Digital Communications and Networks 9 (2023) 1363–1398

Contents lists available at ScienceDirect

Digital Communications and Networks

journal homepage: www.keaipublishing.com/dcan

Decentralized content sharing in mobile ad-hoc networks: A survey

Shahriar Kaisar [a,*], Joarder Kamruzzaman [b], Gour Karmakar [b], Md Mamunur Rashid [c]

[a] Department of Information Systems and Business Analytics, RMIT University, Australia
[b] School of Engineering, IT and Physical Sciences, Federation University Australia, Victoria, Australia
[c] School of Engineering and Technology, Central Queensland University, Australia

ARTICLE INFO

Keywords:
Decentralized content sharing
Mobile ad-hoc networks
Delay-tolerant networks
Flying ad hoc networks
Message forwarding
Content caching
Incentive
Group formation
Misbehavior detection

ABSTRACT

The evolution of smart mobile devices has significantly impacted the way we generate and share contents and introduced a huge volume of Internet traffic. To address this issue and take advantage of the short-range communication capabilities of smart mobile devices, the decentralized content sharing approach has emerged as a suitable and promising alternative. Decentralized content sharing uses a peer-to-peer network among co-located smart mobile device users to fulfil content requests. Several articles have been published to date to address its different aspects including group management, interest extraction, message forwarding, participation incentive, and content replication. This survey paper summarizes and critically analyzes recent advancements in decentralized content sharing and highlights potential research issues that need further consideration.

1. Introduction

Mass penetration of smart mobile devices and widespread use of social networking have changed the way we interact with each other and share contents, such as images, videos, audios, texts, news items or any other information. The shared contents help in spreading information and entertainment, promoting businesses, circulating educational materials, and sharing contents in tourist spot like scenarios. Various Content Sharing (CS) approaches have different effects on the amount of generated Internet traffic and result in different Quality of Service (QoS) outcomes (e.g., delivery success rate and delays) for the end users. Considering the effects of these things, the sharing process can be divided into three approaches: (i) centralized, (ii) decentralized, and (iii) hybrid approach. In centralized content sharing approach, traditional content sharing apps, such as YouTube and Instagram are used where requests are sent to a central server through Internet connection and desired contents are searched and delivered [1,2]. However, it generates a significant amount of Internet traffic, requires constant Internet connectivity and thus incurs cost. In contrast, Decentralized Content Sharing (DCS) approach uses ad-hoc networking capabilities of smart mobile devices within proximity and forms a peer-to-peer network to share contents [3–6]. In his case, users use a content sharing app on top of their operating systems to share contents with nearby users. Although this approach is scalable and fault-tolerant, the mobility of the users carrying the smart mobile devices and intermittent connectivity among them can affect its performance. A hybrid approach uses both Internet connection and ad-hoc networking capability of smart devices to deliver contents [7,8]. In this case, the content is delivered first to a sub-set of users through Internet connection who then disseminate the content to nearby users through peer-to-peer connection. Fig. 1 shows a schematic representation of different content sharing approaches. It shows that in the centralized approach, the request is sent to the content server, which uses an Internet connection to deliver matching content, while in the DCS approach, the request is sent to a nearby neighbor, which uses a peer-to-peer connection to deliver matching content. In the case of a hybrid approach, when multiple co-located users send the same request, the matching content is sent to one of them who delivers it to its neighbors through peer-to-peer connection. The focus of this survey paper is DCS approaches using mobile ad-hoc networks.

DCS schemes can operate in an environment without any infrastructure support and Internet connectivity. They can be used for mobile data offloading to reduce the overhead of cellular networks. DCS also helps maintain communication during situations like natural disasters or battles [9]. Therefore, it has received great attention from the research community in recent years, and further research is required for practical implementation. The main issues related to DCS schemes are: i) how a

* Corresponding author.
E-mail addresses: shahriar.kaisar@rmit.edu.au (S. Kaisar), joarder.kamruzzaman@federation.edu.au (J. Kamruzzaman), gour.karmakar@federation.edu.au (G. Karmakar), m.rashid@cqu.edu.au (M.M. Rashid).

https://doi.org/10.1016/j.dcan.2022.07.002
Received 22 April 2021; Received in revised form 24 June 2022; Accepted 6 July 2022
Available online 15 July 2022
2352-8648/

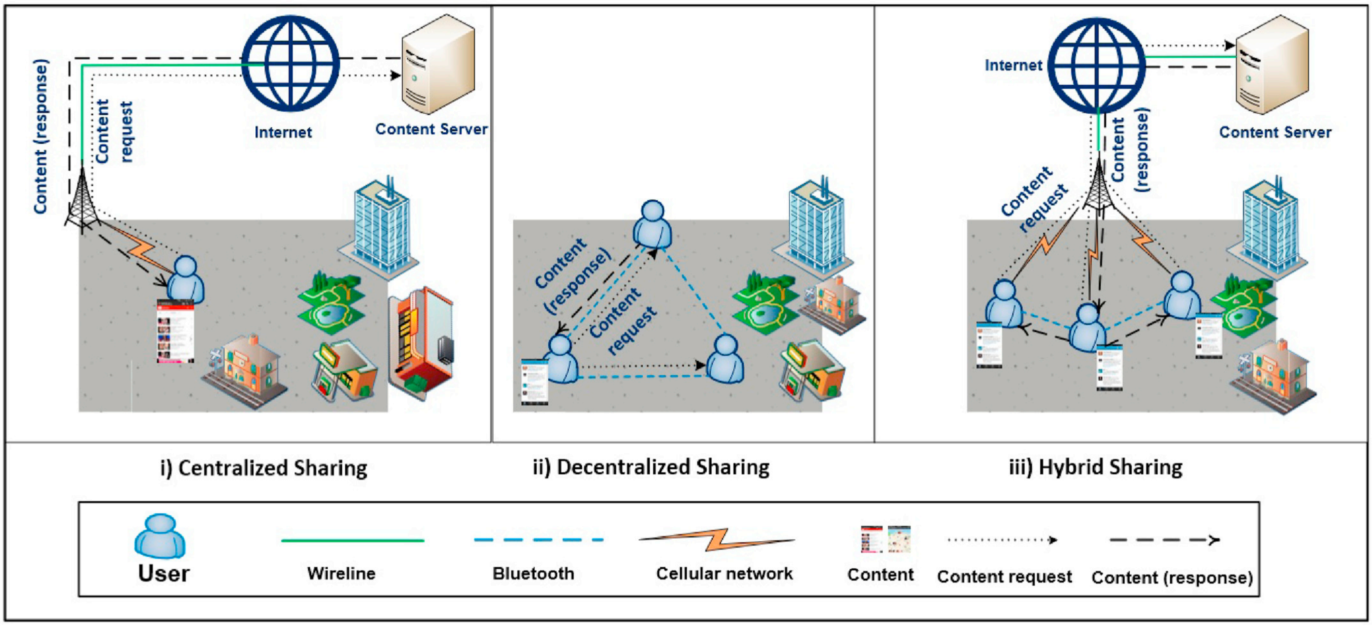

Fig. 1. Principles of content sharing approach: i) Centralized (requesters receive content from central server using Internet connection), ii) decentralized (requesters receive content from nearby users without any Internet using peer-to-peer connection), and iii) hybrid (requesters receive content from both central server through Internet connection and nearby users using peer-to-peer connection).

content is propagated from producers to consumers (i.e., data dissemination); ii) how the devices are grouped together to allow sharing of relevant contents (i.e., group formation and community detection); iii) how to handle device mobility and resource scarcity to deliver content and requests from one user to another (i.e., message forwarding and routing); iv) how the users are motivated to participate in the sharing process (i.e., participation incentive); v) how the misbehaving nodes are identified (i.e., misbehavior detection); vi) how contents are pro-actively placed at strategic locations to provide better service (i.e., content replication and caching); and finally, vii) how the sharing apps have been implemented? To this end, although a couple of survey papers [10–20] have been published to focus on different aspects of decentralized content sharing techniques, they mainly concentrate on a particular aspect of the sharing process, such as routing, data dissemination, incentives, and security, while other important issues, such as group formation, interest extraction, misbehavior detection, and content replication are not addressed.

To the best of our knowledge, the last survey paper to address all the major components of decentralized sharing was published in 2013 [11]. However, they have not addressed many emerging issues such as misbehavior detection, content replication and interest extraction. Interest extraction determines the appropriate interest level of users, which ultimately helps in receiving relevant contents while the content replication methods aim to pro-actively place contents near expected requesters to enhance content delivery. In addition, misbehavior detection schemes play a crucial role in identifying and excluding misbehaving nodes from the sharing process to improve user experience. By integrating the above-mentioned recent advances, in this paper, we have extensively studied recent advancements in the area of decentralized content sharing techniques, and highlighting its main components, such as data dissemination, group formation, message forwarding, participation incentive, misbehavior detection, content replication, and developed application. This paper provides a complete picture of the sharing process highlighting different techniques adopted by researchers. Section 2 discusses the contributions of these relevant survey papers and highlights the need for producing a survey paper encompassing all aspects of recent research in this area as well as potential future challenges. The objective of this survey paper is to give the readership a complete overview of the framework being developed and help them conduct further research in this field.

Summarizing, this paper makes the following contributions:

- Presents a comprehensive literature review on DCS covering all key aspects and state-of-the-art methods proposed in recent literature. The survey articles published in recent years are very limited to certain aspects of DCS and hence have limited appeal to a wide readership. This is the only survey article that covers emerging issues that are shaping recent DCS approaches.
- Provides an in-depth analysis of the various methods highlighting their advantages and limitations, and compares them from possible deployment perspectives.
- Discusses issues such as interest extraction, group formation techniques, sample applications. Also discusses DCS-based techniques to facilitate live streaming of video contents and highlights the use of machine learning techniques in message forwarding. Reflects on the role of new technologies like 5G/6G communication, edge computing, and Software-Dedined Radio (SDR) in advancing DCS implementation. Highlights data sharing techniques proposed for emerging aerial networks. Discussion of these topics has not been addressed in any previous investigative articles.
- Based on the discussion and analysis presented on DCS, major research challenges are identified and possible directions to address them are presented.

The rest of the paper is organized as follows. Section 2 discusses the relevant survey papers in this area and highlights the potential need for further studies. Section 4 presents different content sharing approaches. Recent DCS techniques and their core components are presented in Section 3. Several further research issues are highlighted in Section 6 and finally, Section 7 concludes the paper.

2. Relevant survey works

A few survey papers [10–20] have been published to date to highlight different aspects of DCS, which are listed in Table 1. In 2013, Vastardis and Yang [10] were one of the firsts to publish a notable survey work

Table 1
Relevant survey papers.

Article	Year	Topics surveyed	Not covered
Mobile Social Networks (Vastardis & Yang [10])	2013	MSN architecture, social properties and community detection.	Message forwarding, incentive schemes, content replication and sample applications.
Opportunistic MSN (Jedari & Xia [11])	2013	MSN Categories, MSN characteristics, mobility models, community detection, routing and data dissemination, selfishness and incentive.	Misbehavior detection, interest extraction, content replication, sample applications.
Disruption Tolerant Network (Cao & Sun [12])	2013	Routing techniques for DTNs.	Group formation, incentive and replication.
MSNP (Wang et al. [13])	2014	Relevant research areas, characteristics and challenges, and a sample application.	Group formation, message forwarding, incentive schemes and content replication.
Socially Aware Networking (Xia et al. [14])	2015	Architecture of socially aware network, social properties, routing and forwarding protocols, selfishness and incentive schemes.	Group formation, interest extraction, misbehavior detection and content replication.
Service Discovery (Girolami et al. [15])	2015	Community detection, routing and data dissemination in mobile social network.	Incentive schemes, misbehavior detection and content replication.
Opportunistic Network (Wu et al. [16])	2015	Security and trust management in opportunistic network.	Group formation, message forwarding, incentive schemes and content replication.
Data dissemination (Sobin et al. [17])	2016	Routing and data dissemination in DTNs.	Group formation, Incentive schemes and content replication.
Device-to-Device (Wang et al. [21])	2017	MSNP framework, communication technology, Message forwarding and applications.	Group formation, incentive schemes and content replication.
Information-centric MANET (Liu et al. [18])	2017	Content routing/forwarding strategies.	Group formation, incentive schemes and content replication.
Social-aware data dissemination (Zhao and Song [19])	2017	Data dissemination and incentive schemes.	Group formation, message forwarding and content replication.
Routing protocols in OppNet (Alajeely et al. [22])	2018	Routing protocols in OppNet.	Group formation, incentive schemes and content replication.
Human-centric communication (Jedari et al. [23])	2018	selfish node and misbehavior detection in non-cooperative wireless relay networks, incentive schemes, message forwarding.	Group formation, content replication and sample applications.
Quality of service in DTN (Roy et al. [24])	2018	QoS metrics in DTN, congestion control and incentive schemes.	Group formation, content replication, routing and sample applications.
Content distribution in MSN (Akhtar et al. [25])	2019	Data transmission strategies and routing protocols in mobile social networks.	Group formation, content replication, incentive schemes and sample applications.
Data routing in OppNet (Raghav et al. [26])	2019	Data routing techniques based on social relationships in opportunistic networks.	Group formation, content replication, incentive schemes and sample applications.
Message forwarding in OppNet (Kuppusamy et al. [27])	2019	message forwarding techniques and their performance in opportunistic networks.	Group formation, content replication, incentive schemes and sample applications.
Kaisar et al. (this paper)	2022	DCS architecture and data dissemination techniques, live-streaming content delivery, group formation, message forwarding techniques, interest extraction, participant incentive, misbehavior detection, content replication, and sample sharing applications. Advanced technologies (5G/6G, edge computing, SDN and machine learning) on future DCS. Data sharing in emerging aerial networks.	

emphasizing the characteristics of mobile social networks. They discussed different architectures of Mobile Social Networks (MSN) (i.e., centralized, decentralized, and hybrid) and represented the concepts of most commonly used social metrics, such as social neighbors, social ties and centrality measurements, and community detection methods used in MSN. One of the key works presenting a more complete view of the whole framework of DCS was published by Jedari and Xia [11]. They focused on MSN characteristics, community detection methods, routing and data dissemination, participation incentive schemes, and human mobility model. However, they did not cover other important issues, such as misbehavior detection, content replication, and interest extraction methods. It is worth noting that misbehavior detection is a recent pressing issue and replication methods are crucial for successful sharing. This paper was also published in 2013 and hence it does not include information about recent advances in this area. Girolami et al. [15] investigated service discovery in MSN and presented its different aspects, such as service discovery architecture, service queries, service discovery requirements, and service selection strategies.

Cao and Sun [12] studied routing protocols for Delay Tolerant Networks (DTN), and highlighted their classifications and applications. A similar study focusing on routing and data dissemination protocols for DTN was published in Ref. [17]. In contrast, Liu et al. [18] considered a more traditional Mobile Ad-hoc Networks (MANET) without explicit movement patterns and analyzed existing content routing strategies for such a network.

A review by Wang et al. [13] focused on the concept of Mobile Social Network in Proximity (MSNP), its characteristics, challenges, and design architecture. They further extended this reviews in Ref. [21] by incorporating message forwarding approaches, development frameworks, and typical use of MSNP based applications. In addition, Xia et al. [14] concentrated on the social attributes of participating entities and introduced a socially aware network, where the social relationship among participants is more prominent. They reviewed forwarding protocols, data dissemination techniques, and incentive schemes in such situations. Zhao and Song [19] focused on socially aware data dissemination techniques and highlighted issues related to content source selection and incentive schemes. A few articles also analyzed routing and message forwarding protocols in opportunistic networks [22,25–27], which is one of the highly investigated areas in DCS as the dynamic mobile and social natures of human carrying mobile devices make this problem interesting and challenging.

Privacy, security, and trust management issues have received significant attention from researchers. Wu et al. [16] investigated security and trust management issues in opportunistic networks highlighting authentication and access control mechanisms, the security of routing protocols, and privacy protection. However, they did not address issues related to social selfishness and misbehavior detection. Ferrag et al. [20] extensively studied privacy-preserving schemes for ad-hoc social networks emphasizing different types of attacks that may leak privacy and the proposed countermeasures in the existing literature. Jedari et al. [23] analyzed selfishness and misbehavior detection techniques in non-cooperative networks and highlighted relevant message forwarding protocols to handle this. Another interesting work by Roy et al. [24] presented the Quality of Service (QoS) parameters, incentive schemes, and congestion control techniques commonly used in DTN.

In summary, although several survey papers have been published to address different aspects of the DCS technique, their discussion is limited to only a particular aspect and does not provide a complete overview of the whole framework. In addition, they do not cover some major issues in this field arising from user/device mobility, such as group formation, content replication, and proof-of-concept sample applications (refer to the last column of Table 1). Therefore, there is a gap in existing survey papers for a comprehensive review of the decentralized content sharing approach. Our work in this survey paper investigates the complete framework including all of its major components, such as group formation, interest extraction, message forwarding, incentive mechanism, misbehavior detection, and content replication. We have incorporated recent advancements in this field and highlighted future research challenges which will help researchers conduct further investigation in this area.

3. Decentralized content sharing approaches

Decentralized content sharing approaches are based on ad-hoc communication among nearby nodes using Bluetooth and Wi-Fi, without requiring an Internet connection. Fig. 2 shows a schematic representation of the DCS approach where users within proximity have formed a content sharing group *G*1. Such content sharing groups can be formed among students on university campuses or colleagues in office environments or any other group of people with common interests. User *C* is the administrator of this group and is responsible for maintaining the content list of all group members. User *A* generates a request and forwards it to administrator *C*. After receiving the request, *C* determines that user *D* has matching content and forwards the request to *D*. Whenever user *D* receives this request, it delivers the matching content through its neighbors. For the sake of simplicity, this figure shows a dedicated path from the requester (*A*) to the content holder (*D*). However, in real life, such end-to-end connected paths are mostly unavailable because of node (i.e., user) mobility. This type of network is also called an Opportunistic Mobile Social Network (OMSN) and is considered a paradigm of the Delay Tolerant Network (DTN), which allows a longer delivery period for any content by holding the content for a certain amount of time if there is no connection between a content holder and a requester. Since an Internet connection is not needed for this approach, it does not introduce Internet traffic. DCS has the benefits of scalability and robustness, while the main challenges are content availability and delivery reliability.

Media sharing in urban transport, proposed by McNamara et al. [3], was one of the earlier works proposed for DCS. It suggested that there exists regularity in the movement patterns of people commuting via train services. For example, people who go to work in the morning and/or come back in the evening tend to meet a common group of people, known as *familiar strangers*, while traveling. The authors proposed a content sharing protocol using a co-location prediction method that uses the history of earlier encounters to identify the source for copying content. However, they only used single-hop communication and assumed that often people would be within the communication range of each other to create a history of encounter, which might not be true when trains leave every 5–10 min at a busy station and have many compartments. This work also does not use any concept of grouping. In contrast, work in Ref. [4] proposed a group-based decentralized sharing approach where nodes are divided into groups based on long-term neighboring relationships. The history of previous encounters is used to determine such relationships between nodes.

Content sharing using a decentralized approach employs different data dissemination techniques, such as publish/subscribe, advertisement-based, and query-based approaches to propagate contents from producer to consumers. These approaches are discussed below.

3.1. Publish-subscribe

Publish-subscribe-based DCS approaches consider that mobile devices can play the role of both publisher and subscriber, and are capable of using multi-hop communication for delivering and receiving contents. The publisher devices periodically publish content, such as movies, music, and news, on some channels and the subscribers subscribe to them. In this case, the interests of a subscriber is considered from a coarse level. For example, a user might subscribe to a channel publishing movie or music-related content. Whenever a subscriber node meets any publisher, it first copies contents reflecting the personal interests and then copies the contents that might be of interest to its future neighbors, if meeting time and device memory permit. Such publish/subscribe-based data dissemination has been addressed in Refs. [28–31].

Fig. 3(a) presents a distributed publish/subscribe system similar to the one proposed in Ref. [28]. Here, a single node can also play multiple roles for different contents. Both publishers and subscribers notify broker nodes of their published content and topics of interest, respectively,

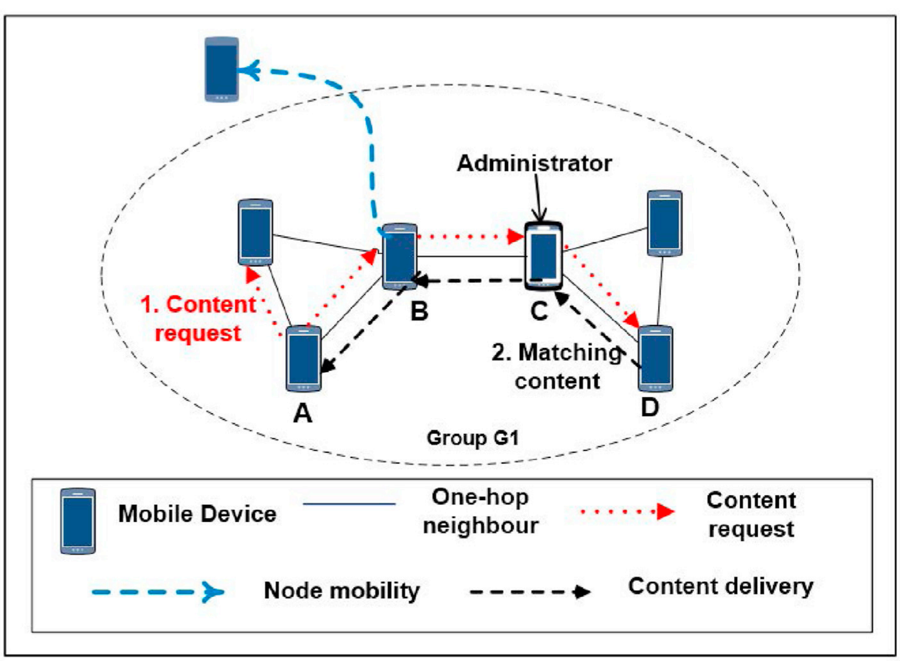

Fig. 2. Decentralized content sharing approach.

which attempt to match published content with subscribers' interests. If any match is found, the broker nodes transfer the contents to the subscriber. The participating nodes were assumed to be part of different communities (i.e., groups) and the node that had the strongest connection with other community members in terms of encounter frequency was selected as a broker.

In contrast, Boldrini et al. [29] used a broker-less publish-subscribe system assuming that a single node can play the role of a publisher and subscriber for different contents and exchange contents on meeting without the presence of a broker. Zhou et al. [31] proposed a similar approach, where at the beginning, each node broadcasts the list of channels it is interested in, which is collected and stored by other nodes to get an overall view of the available channels. Afterward, encountering nodes exchange contents according to their interests and also store some contents for their future neighbors.

Although publish/subscribe schemes are successful in delivering content that matches the interest at a coarse level, they are unable to meet user interests at a finer level and hence might deliver unnecessary content. For example, a user might be interested in 'rock' music; however, he might not be interested to listen to any song by a particular singer. In addition, these schemes do not address request-based content delivery, where users are looking for particular content (e.g., trailer of a particular movie) instead of content designated to a particular channel (e.g., a movie channel).

3.2. Advertisement based

Here, the generated contents can be some sort of advertisement or notification, and the dissemination does not require explicit user subscriptions. Such advertisements are helpful for proximity marketing where some nodes may advertise some promotional offers in stores/restaurants or warn about some natural disasters. Advertisement-based DCS approaches are employed in Refs. [32–34].

Lubke et al. [32] suggested that a user can create and advertise a group, based on his/her interest or some event, which is visible to other users within the proximity. Later, those having matching interests can join the group. After the event is completed, the group members can share their memories (e.g., pictures or videos) related to the event. Another interesting work was proposed in Ref. [33], which addressed the problem of broadcasting some information to the members of different communities (i.e., groups) who are physically separated from each other (3(b)). An advertiser visits several communities to maximize messaging or minimize the delay. The regularity in the participants' movement patterns was used to model user mobility as a semi-Markov process, and then a greedy adaptive routing algorithm was employed to determine the visiting sequence of such communities.

Overall, the advertisement-based content sharing approaches are not suitable for obtaining on-demand content or distributing content according to user interest, as techniques based on advertisements cannot provide such facilities.

3.3. Query-based

This is a request-response-based data dissemination technique where a user generates a request for a particular content specifying its requirement. For example, a request can be for "latest news on coronavirus". Keywords are extracted from such a request to determine related content. In some cases, the requester can also specify keywords rather than a search query. The requests are forwarded to the neighbors of the requesting node. If none of the neighbors hold a matching content, the request is again forwarded by the neighbors. In this way, nodes keep forwarding a request until it reaches a content holder who tries to deliver the content to the requester. In the absence of any administrator (i.e., decentralized approaches without any group and administrator), it is very challenging to forward a request to an appropriate content holder. Another problem is content deliveries, even if the content holder receives

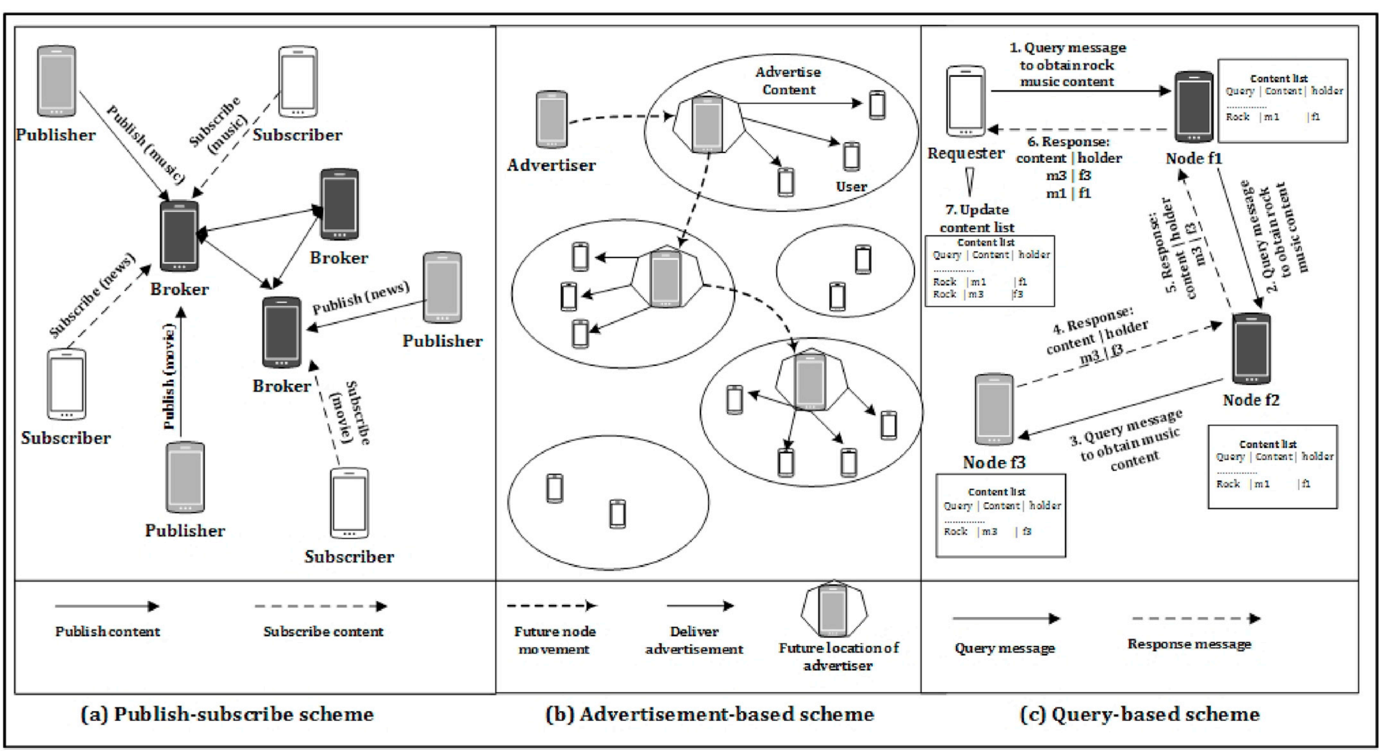

Fig. 3. a) Publish-subscribe scheme. Here, publisher nodes publish different categories of contents, e.g., music and movies, and register them with the broker. The subscribers subscribe to brokers based on their interests. b) Advertisement-based scheme. Here, an advertiser can move around different groups to advertise contents. (c) query-based scheme. Here, a requester node sends a query message and its neighbors respond with meta-data of relevant contents. Afterward, nodes also update their content lists.

the request because everyone in such an environment is dynamically moving.

Query-based content sharing has been employed in several works [3, 5,35–38]. Lindemann et al. [35] proposed that mobile devices can collaboratively create a document indexing service called the Passive Document Index (PDI) for file sharing applications. A mobile device generates a query and forwards it to its one-hop neighbors. Upon receiving the query, the neighbor checks local files and replies with only the identifier (i.e., meta-data of file) of the matching files. The neighbors also forward this query to their other neighbors. If any other node has a matching file, it also replies with the identifier, which is then used by everyone to update their PDI. In this manner, nodes generate a directory for contents held by other nodes. Fig. 3(c) shows a schematic diagram of this approach.

Although the above work provides a generic solution to obtain lists of contents held by other nodes, it does not address the problem of identifying the actual content holder to be selected for fetching content. In this regard, McNamara et al. [3] suggested that the content holder should be selected based on the co-location stay probability. In this case, content holders who expect to stay within the requester's reach for a longer period of time are selected as content sources. This approach assumes that nodes meet frequently at similar times, which is not applicable in all types of environments (e.g., tourist places or disaster scenarios). None of the above approaches uses any grouping technique or an administrator. In contrast, works in Refs. [36,37] used a group-based content sharing approach. Gao et al. [36] suggested that nodes should keep a copy of the content in multiple central nodes (i.e., administrators) that other nodes can easily access and that can get content from them on request. In comparison, a group administrator is used in Ref. [37] for maintaining a list of contents currently owned by group members. Content requests are always forwarded to the administrator who directs them to appropriate content holders. A more detailed description of the group based DCS approaches is provided in Section 4.1.

To summarize, the query-based approach assumes that a requester will have sufficient ideas about the content it wants and will mention that adequately while generating queries. A set of keywords can be extracted from such a query or a requester needs to specify some properties of the content (e.g., content creator, name of the content, tag) which is then compared against the stored contents to identify matching ones. Although this approach requires user input to obtain content, it matches the interests of a user at a fine level and delivers contents that are more useful to the user, it also does not disseminate unnecessary content. Table 2 summarizes the comparative advantages and disadvantages of the three data dissemination techniques.

Content is also delivered differently, such as live and on-demand stored media content, which imposes different constraints and requirements on performance and service. Here, live-streaming media refers to the streaming of live events that are delivered on a real-time or near real-time basis. For example, the real-time video capture and streaming of a disaster area can significantly help the emergency response team to conduct the rescue operation [39]. On the one hand, the delivery of on-demand stored content refers to delivering previously downloaded or saved content when requested. The delivery of live-streaming contents requires significantly higher bandwidth, lower delay and packet loss constraint, and orderly arrival of data packets [39, 40]. Therefore, infrastructure-based centralized or hybrid content sharing approaches (see Fig. 1) are more suitable for this type of delivery as infrastructure can facilitate meeting those requirements. On the other hand, dynamic movement of participating nodes, their frequent disconnection, and the unavailability of a persistent end-to-end path makes DCS applications less suitable for live-streaming contents and hence almost all of the existing works in DCS are focused on delivering on-demand stored media contents. Therefore, those works are mostly highlighted in different subsections of Section 4. A handful of approaches also addressed live-streaming in mobile ad-hoc networks and they are separately highlighted in Sub-section 4.8.

4. Major components and their issues in decentralized content sharing

The major components of DCS include group formation, message forwarding, content replication, participation incentives, and misbehavior detection. The group formation part addresses how groups are formed among the participating devices while the message forwarding part determines the way the messages and contents are delivered to the appropriate node. The incentive mechanism addresses how users are provided with encouragement to actively participate in the content sharing process while misbehavior detection addresses how the misbehaving nodes are handled. The content replication policy addresses when content needs to be proactively replicated, and how many copies need to be replicated, and where (i.e., in which nodes) those copies should be placed. The existing literature has focused on different aspects of these major components and proposed some interesting solutions. Fig. 4 depicts a schematic representation of the major components and issues related to DCS approaches. These components and issues are discussed in detail in the following sections.

4.1. Group formation

Group formation (also called community construction) is one of the most important aspects of DCS as it provides a better way to manage user information and helps provide on-demand content. The group members have common interests and can serve each other. In this case, users within proximity form a content sharing group and exchange content.

It is noted that some of the content sharing approaches do not use any grouping, such as the work proposed in Refs. [3,5]. However, content sharing without a group makes it difficult to find a particular content since no one knows who has which content. In this case, nodes keep forwarding a request until it reaches a node with the matching content. This approach consumes lots of unnecessary resources. It is possible to maintain a distributed content list for all the participating nodes; however, sharing the content list with everyone (i.e., not limiting within the

Table 2
Different data dissemination techniques for DCS.

Data Dissemination Technique	Pros	Cons
Publish-subscribe [28, 29, 31]	• Does not require user input for each content request • Allows users to mention their interests from a coarse level	• Consumes unnecessary resources by delivering additional contents • Users need to know the list of available channels before subscription
Advertisement [32, 33, 34]	• Useful for broadcasting information among users • Helpful in promoting events or businesses	• Not useful for providing on-demand contents • Consumes additional resources to deliver unnecessary contents
Query [35, 3, 5, 36, 37]	• Delivers more user-centric contents to match fine-grained user interests • Only delivers contents when requested by users • Provides contents within a short time if the communication path is available	• Requires user input for each content request • Needs extraction of user profile and other information to provide efficient content delivery service

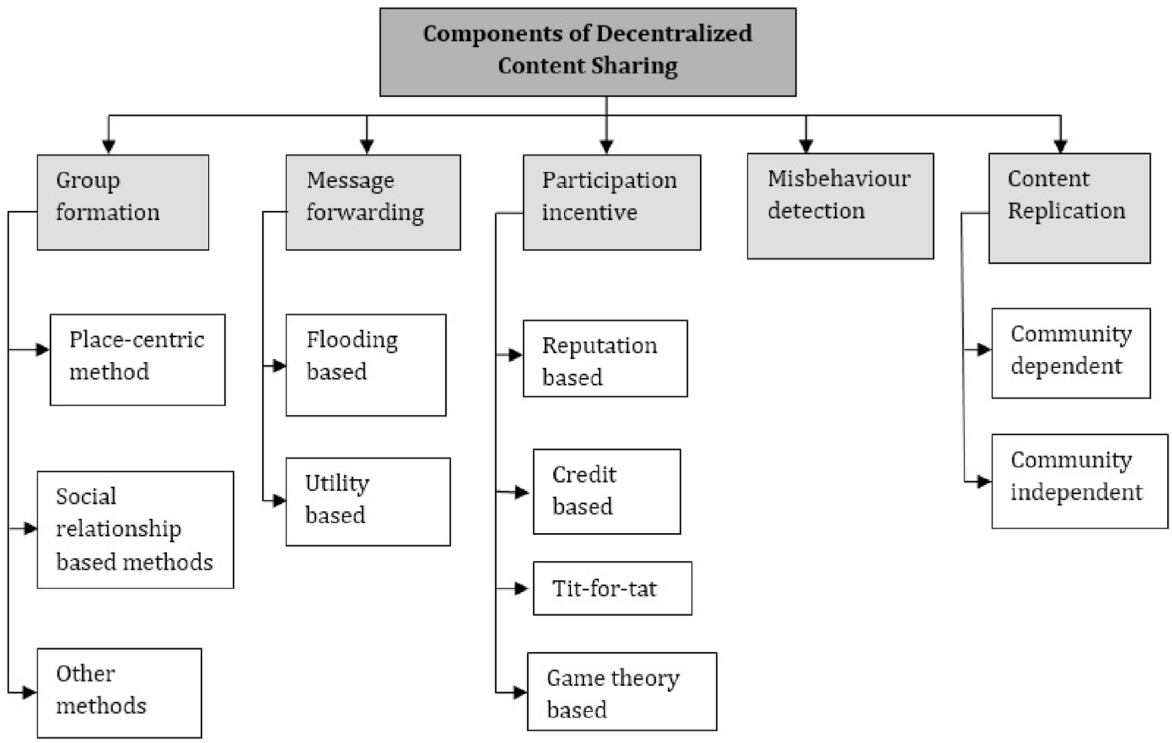

Fig. 4. Major components of decentralized content sharing.

defined group) produces more traffic. Therefore, several group formation methods have been proposed in the literature [32,34,41,42].

For group formation, some of the proposed methods consider the temporal and spatial regularity of movement patterns of nodes while others focus on social relationships, and some works also focus on both as well as common interests. The group formation methods can be broadly categorized into three categories: (i) place-centric, (ii) social relationship-based, and (iii) other methods. Techniques discussed in the first category emphasize nodes visiting common locations more frequently, while the second category focuses on a group of nodes meeting more frequently, regardless of the location. Details of these group formation methods are discussed in the following sections.

4.1.1. Place-centric methods

Place-centric groups are created around specific locations considering that nodes who meet regularly around a particular location are more likely to have some common interests. The argument behind such approaches is that people exhibit a spatial and temporal regularity in their daily life and are expected to meet a common set of people with similar interests at the same place on a regular or semi-regular basis. For example, graduate students meeting on the campus. Nodes spending different amounts of time in different places can be represented by a matrix ($\boldsymbol{LocT^m}$) as in Eq. (1), where l_n^m represents a location visited by user m, and t_n represents time spent at that location. Groups are formed at locations where nodes spend more time than a threshold.

$$\boldsymbol{LocT^m} = ((l_1^m, t_1), (l_2^m, t_2), \ldots, (l_n^m, t_n)) \tag{1}$$

Urbiflocks [41] is a distributed framework proposed for group management where a user initiates a group by indicating the purpose or interests of the group. Afterward, other users are automatically added to this newly created group based on their profiles (e.g., hobbies) and locations. For example, a group created for badminton players would automatically add other users who are nearby, interested in badminton, and/or friends of the group initiator. Once the group is created, the maintenance of the group is automatically handled by the system. MobilisGroups [32] further extended this work by introducing a time restriction along with the location for group formation. For example, they considered a scenario where many participants are interested in a particular event (e.g., BarCamp). An organizer of the event created a group for the event, which was only visible at the event venue four weeks before the event. Participants were only allowed to join the group if they were physically present at the location during the event and shared messages and contents.

Johari et al. [43] also considered creating a group around a base station. The base station was considered as the Point-Of-Interest (POI) and a single group was formed around it. Whenever the number of visits by a user surpassed a pre-defined threshold, it joined the group available there. The underlying assumption of this work is that users who frequently visit a particular location are more likely to meet other users with the same interests at that location. Costa et al. [44] have also considered grouping nodes that are physically close to each other. Similar approaches were employed in Refs. [45–47] where the authors argued that people with similar interests form a group and usually meet at the same place. However, for large outdoor areas where people with similar interests may be far away from each other, the assumption that users are physically close may not be correct. In addition, people with different interests may meet frequently at the same place, while people with the same interest may meet at different places. For example, students frequently meeting on university campuses might have different interests in consuming content. Some students might be interested in news-related content, while others might be interested in sports/music-related content. Likewise, a group of friends who may have common interests can meet at different locations, such as shopping centers, playgrounds, or universities. In this case, their relationship should take precedence over where they meet. This type of variation is not well addressed in the above-mentioned works.

In summary, this type of approach requires repeated visits to certain locations for users to form content sharing groups. While frequent visits to specific locations show a degree of shared interest (e.g., colleagues in the office), other factors, such as online friendships or interactions, may more accurately reflect users' content-sharing characteristics and be considered in the work in the following section.

4.1.2. Social relationship-based methods

This type of group formation method emphasizes social relationships among nodes, regardless of the place of meeting. In this case, frequently encountered nodes usually form a group. For example, a group of friends who meet frequently is more likely to have common interests in sharing content.

Mobile cOmmunity-based Publish/Subscribe scheme (MOPS) [4] is one of the first social relationship-based group formation methods, in which nodes with high intimacy form a group. In this approach, each node (u) records the time and duration of a meeting with another node (v) in the network and calculates a closeness metric ($C_{uv} \in [0, 1]$) to represent the time-space relationship with that node. A higher value of the closeness metric indicates a greater probability of meeting in the future. A training period is needed to calculate the value of such closeness metrics. The closeness between node u and v is measured as,

$$C_{uv} = \exp\left(-\frac{(\overline{D}_{u,v})^2}{2\sigma^2}\right) \tag{2}$$

Here, $D_{u,v}$ represents the average inter-contact period between nodes u and v, and σ shows a scaling parameter for the separation period. The average inter-contact period ($D_{u,v}$)is calculated using the ratio of the total number of times nodes are separated and the number of total separations. Smaller values of $D_{u,v}$ indicate that nodes are separated for a shorter time and hence had stronger ties. When the closeness value exceeds a pre-defined threshold, nodes are considered as local neighbors and forms a group. Similar separation time-based community detection approach is also proposed in Ref. [48] where nodes form temporal communities when their temporal closeness (calculated from average separating time and its variance) is greater than a threshold.

The idea of such local neighbors with direct communication is further extended with the introduction of virtual links that represented an indirect connection. A virtual link between two participating nodes indicates that if direct communication is not available, one of the nodes can be reached from the other through a neighbor. The virtual link between nodes u and v is calculated as,

$$C_{uv} = \max_{p\in P}\left\{\prod_{<x,y>\in p} C_{xy}\right\} \tag{3}$$

where P represents the set of all paths between u and v that are less than or equal to *k-hops* and $< x, y >$ represents an edge in the path. The path closeness for a path p is represented by $\prod_{\langle x,y\rangle\in p} C_{xy}$ which is the product of all edges along the path. Similar to local neighbors, the nodes connected with virtual links form a group when their closeness metric is greater than the threshold. A similar social relationship-based group formation was used in Refs. [28,29,49] where participating nodes were divided into groups, such as family, friends, and familiar neighbors. Group formation based on frequent opportunistic contacts and common interests was explored in Ref. [34]. In this work, broker nodes were first selected based on their popularity among other nodes, calculated as the number of other nodes they encountered during previous time windows. Afterward, the broker nodes performed the responsibility of adding new group members based on mutual interests. Haoran et al. [50] have also used encounter probability to group nodes. When the encounter probability between two nodes exceeded a threshold, they formed a group. This work also considered a change in group membership because of dynamic mobility and change in encounter time and duration among nodes. Similar variability in group membership was also investigated in Ref. [51] suggesting that a node may leave group 'G1' and join another group 'G2' if it increases overall modularization.

Chen et al. [37] also argued that people with similar interests tend to meet each other more often and constructed a group based on interest similarity and meeting frequency. It used the stored content lists in a participant's device to calculate the interests of that user. Whenever two nodes $N1$ and $N2$ met each other, they exchanged information about their current affiliation with groups and their interests. Two distinct cases were considered to handle the group formation task: (i) none of them are part of any existing group and (ii) at least one of them is a part of a group. In the first case, if their interest similarity and meeting frequency were greater than a pre-defined threshold, they formed a new group together. In the latter case, others joined that group if the similarity values exceeded a threshold. Interest similarity value was calculated using the cosine similarity metric as,

$$\mathrm{sim}(\boldsymbol{v1}, \boldsymbol{v2}) = \frac{\sum_{q=1}^{Q} w_{1_q} \times w_{2_q}}{\sqrt{\sum_{q=1}^{Q} w_{1_q}^2}\sqrt{\sum_{q=1}^{Q} w_{2_q}^2}} \tag{4}$$

Here, $\boldsymbol{v1}$ and $\boldsymbol{v2}$ represent two interest vectors from two users, Q represents the total number of common keywords among them, w_{1_q} and w_{2_q} show the weight of the q-th common keyword in $\boldsymbol{v1}$ and $\boldsymbol{v2}$, respectively. This approach also used the concept of a central node (an administrator) for each group to handle group management tasks, such as storing the list of contents of other group members and directing content requests towards appropriate content holders. The administrator nodes were selected based on their centrality value as,

$$D(P_i) = \sum_{v=1, v\neq u}^{G_m} w_{uv} \tag{5}$$

where w_{uv} is the weight between two members of a group and G_m is the total number of members in that group. To select a member with a large number of connections, the value of w_{uv} was set to 1 whenever the contact frequency between two nodes was greater than a threshold.

Juyal et al. [52] suggested that nodes can form or join a group based on trust values. They considered nodes that meet frequently for a longer duration have higher trust values and should form a cluster, i.e., group. They have also considered that the node with the highest trust value should be selected as a cluster-head. In this case, trust value is measured in terms of contact duration, frequency, inter-contact time, and an event state to show whether it is a regular event or not. Another recent work proposed by Jain et al. [53] suggested that nodes with a higher degree value (greater than a threshold) within a neighborhood can be selected as leader nodes (i.e., group administrators or central nodes) and nodes with lower degree value can join a group whose leader possesses the highest degree value.

Similar central nodes were used in other studies for information dissemination, routing, and caching purposes [36,54]. Common social metrics used for central node selection in social relationship-based groups include degree centrality, closeness centrality, and betweenness centrality [54].

In summary, social relationship information obtained from existing social networks or collected over time provides a good platform for creating and managing group membership as tightly knit members can be easily identified. However, groups based on social relationships fail to take into account the importance of locations, which facilitate content sharing among co-located peers. Also, most works assumed the availability of a social network graph or built one over time, which is not always possible due to limited contact. Another problem is the failure to capture the dynamic changes in relationships with respect to places and changes in interests about places, for example, relationships with people may change over time, and static group formation methods fail to incorporate such changes. Likewise, people may be interested in establishing different types of relationships with the same person depending on the context, which requires a dynamic group formation approach. For example, in the workplace, people may want to share work-related content with colleagues, but they may also be interested in sharing different types of content with the same group of colleagues outside the office.

Table 3
Group formation methods in decentralized content sharing schemes.

Method name	Group formation metric	Requirement	Joining criteria	Group initiation
Distributed community (Yoneki et al. [28], 2007)	proximity or common interests	frequent encounters or common neighbors	contact duration or number of common neighbors greater than a threshold	node initiates
MOPS (Li and Wu [4], 2009)	neighboring relationship	frequent encounters	closeness metric greater than a threshold	node initiates
Urbiflocks (Boix et al. [41], 2011)	friendship or physical proximity	✖	matching hobbies and distance within pre-defined limit	manually by user
MobilisGroups (Lubke et al. [32], 2011)	mutual interests, location and time restriction	✖	presence within certain proximity at a particular time	manually by user
CACBR (Johari et al. [43], 2013)	common point interest	frequent visit to a POI	contact strength greater than a threshold	base station initiates
Geo-community (Fan et al. [45], 2013)	common hobbies, social functions, and occupations	frequent visit to particular locations	sojourn time greater than a threshold	not mentioned
Mingle (Costa et al. [44], 2014)	physical proximity	✖	presence at a particular location	base station initiates
CAOR (Xiao et al. [55], 2014)	common interests	frequent visit to particular locations	number of visits greater than a threshold	not mentioned
Socker (Wang et al. [34], 2014)	common social activity	frequent encounters for broker selection	user can manually define	broker initiates
SPOON (Chen et al. [37], 2014)	common interests, frequent meeting	frequent encounters	interest similarity and contact frequency greater than a threshold	node initiates
CS in Tourist spot (Kaisar et al. [56], 2017)	common interests, hop-distance, delivery delay, content availability and delivery probabilities	✖	group maximizing the benefit calculated using defined metrics	node initiates
Community in DTN (Haoran et al. [50], 2018)	encounter probability	frequent encounter	encounter probability greater than a threshold	nodes are initialized with pre-defined communities
Trusted-cluster (Juyal et al. [52], 2020)	encounter frequency, duration, inter-contact time and event state	✖	join the cluster where the cluster head has highest trust value	node initiates
Adaptive community (Jain et al. [53], 2020)	neighboring relationship, degree, encounter frequency and duration	degree greater than threshold to become a leader	having a group leader among neighbors who has the highest degree among neighbors	node initiates

4.1.3. Other methods

There are also a few other noteworthy approaches apart from those mentioned in the previous sections. Tian et al. [57] have suggested the formation of short-term communities, which they call spontaneous community, based on user profiles. The profile consists of attributes such as demographics, current context (location, velocity), interests, and list of permanent friends. The profile of user u_i is represented using a profile vector $\boldsymbol{p_{im}}(t) = (p_{i1}(t), p_{i2}(t), \dots p_{i|\mathcal{F}|}(t))$, where $p_{im}(t)$ represents the value of feature m at time t and $\mathcal{F}$ is the set of all available features. Similarly, each community $Com^k(t)$ is also represented by a community profile vector $\boldsymbol{cp}^k_m(t)$. Whenever a newcomer u_j enters a new location, one of the existing users u_i provides it with the list of available communities and their profile vectors. The newcomer identifies its benefits of joining a particular community. The benefit is calculated using the dissimilarity score of personal profile and community profile as,

$$SC^k(u_j, Com^k(t)) = \sum_{m=1}^{|\mathcal{F}|} W^k_m(t) d_m(\boldsymbol{p_{jm}}(t), \boldsymbol{cp}^k_m(t)) \tag{6}$$

Here, $\boldsymbol{cp}^k_m(t)$ is the received community profile of the k-th community and $W^k_m(t)$ represents the weight of feature m in this community. If the dissimilarity score is smaller than a certain community threshold then the user joins the community. This approach, which requires members to be present within each other's communication range to form a community, also suffers from the initialization problem of the startup group. The system could learn over time and identify important features for different communities based on user behavior, but during the early stage, it requires user inputs for joining communities.

Kaisar et al. [56] investigated DCS in tourist spots-like scenarios arguing that Internet connection is often unavailable in many such places, users demonstrate irregular movement patterns, and mostly meet strangers in those places. They proposed a group formation method considering factors, such as interest fulfillment, content availability, and delivery probabilities, which also used hop-distance and delivery delay as criteria for joining a group.

Table 3 summarizes some key features of the group formation methods. Mutual interest is one of the most important factors for forming a content sharing group, and hence the following section highlights interest extraction techniques used in the literature.

4.1.4. Interest extraction

Social networking platforms such as Facebook and Twitter provide an efficient way of tracking user interest (e.g., music, movies, or news items). In this case, interest is extracted from a user's previous posts, comments, and uploaded contents. For example, one user might post frequent sports updates, which represents a high level of interest in sports-related content, and another user might be interested in rock music and typically upload related content. Such interest extraction mechanisms are very popular for centralized content sharing approaches [58,59] where the central server can track the activity of a user, determines interests for different content categories, and dynamically updates the level of interest (i.e., interest score). For a decentralized approach, since there is no centralized server, the content sharing application installed in a user's device can determine interests based on the past activity of that user. Work in Refs. [60–62] proposed such activity-based interest extraction from the history of content access patterns of a user. It is also possible to obtain interests directly from the user through input, which is explored in publish-subscribe-based content dissemination [31,63] discussed in Section 3.1. Another interesting work also used meta-data from of stored content lists in a user's device to extract interest information [37].

Most of the above-mentioned approaches fail to take into account the dynamic nature of user interests, which is expected to change based on the context (e.g., location, surrounding neighbors). To address this issue, Tian et al. [57] proposed an interest extraction technique where users showed different levels of interest in different communities. A community-aware profile was maintained by a user's device to reflect the interests in different content categories inside a community. Such community-aware profiles were updated based on the reaction of the user in response to published content as,

$$p_{im}^{k}(t+1) = \begin{cases} (1-\delta_s)p_{im}^{k}(t) + a_m\delta_s, & \text{if } a \text{ is interesting to } u_i \\ (1-\delta_s)p_{im}^{k}(t) - a_m\delta_s, & \text{otherwise} \end{cases} \tag{7}$$

where $p_{im}^{k}(t)$ represents the interests of user i for interest feature m inside community k during time t, a_m is a content with feature m and δ_s is a weighting factor. Although the proposed approach indicates that a user's interests may change depending on the context, it only relies on the publication of relevant content to capture this. Considerations of features or facilities available in a particular area can more accurately capture the dynamic change of user interests. To address this, kaisar et al. [64] proposed an interest extraction technique where nodes calculate their interests using information from a personal profile, online recommendation, and place-centric experiences. They considered that the interests of a user is likely to vary based on the recommendation received from online sources as well as the availability of particular facilities in an area which leads the final interest score calculation as,

$$S_i = \beta_i(1-\sigma_i) + \sigma_i(\gamma_i + \delta_i)/2 \tag{8}$$

Here, S_i indicates interest score in category i (i.e., fishing, camping, or other types of activity or content). β_i, γ_i, and δ_i indicate interest score for i obtained from a personal profile, online recommendation, and place-centric experience, respectively. σ_i shows the standard deviation of interest scores obtained from different sources (e.g., personal profile, online recommendation, and place-centric information). Although the above work presents an intuitive approach to measure user interests, it lacks proper validation using real-world traces.

4.2. Message forwarding

Message forwarding plays a major role in successful content delivery. It is very challenging in DCS as there is no fixed end-to-end path from source to the destination due to node mobility. Therefore, mostly a store-carry-and-forward method [65] is used to handle this, where nodes keep carrying a message until they meet another forwarder node (i.e., relay node) or the destination node. The aim of message forwarding techniques is twofold: the first part focuses on forwarding a content request to an appropriate content holder, while the second part deals with delivering the matching content back to the requester. The concept is somewhat similar to the techniques proposed for a delay tolerant network [66], the main difference being DCS deals with forwarding the request to an appropriate content holder, which is not addressed in the former. In a group-oriented DCS approach with the presence of an administrator, the first part becomes manageable, since the administrator can maintain the content list of all group members so requests can be forwarded to the appropriate content holder, however, due to intermittent connectivity, it is still challenging between nodes. The DCS method without any grouping mechanism has difficulty handling the first part, because in this case content requests must be forwarded blindly until they reach a node with matching content. Since the size of the content request is smaller (generally $\leq 1-2$ KB), making multiple copies of a request and sending them over different paths does not consume much network resources.

The problem is more prominent for the second part of the message forwarding, as the content size is generally significantly larger than the request. Although forwarding multiple copies increases the probability of successful delivery, it also consumes more network resources (e.g., bandwidth, energy). The forwarding approach for DTN is the same as the delivery of content from a content holder to the requester. Therefore, this section also highlights the forwarding methods for DTN, which are extensively studied in the existing literature.

The existing message forwarding techniques can be broadly classified into two categories: (i) a flooding-based approach and (ii) a utility-based approach. In a utility-based approach, a message is forwarded to the next node (i.e., relay or forwarder node) based on some context or suitability of that node. Both of these message forwarding techniques are discussed below.

4.2.1. Flooding-based approach

One basic and representative message forwarding scheme is called epidemic routing [67], where a node carrying a message forwards it to every other node it meets that does not have a copy. Although epidemic routing yields the most successful deliveries with low latency, it requires a high amount of resources and creates unnecessary copies in the network which, in turn, increases network congestion.

The problem of making redundant copies of the same message is termed as the ‘broadcast storm problem’ in Ref. [68] and several strategies are proposed to handle this. The proposed strategies include forwarding based on a probabilistic metric, a counter, distance, and location. In a probabilistic metric-based scheme, nodes only rebroadcast a message when a randomly generated number is greater than some pre-defined threshold while the counter-based scheme uses a counter and compares it with a threshold value to determine whether a message should be forwarded. When a node receives the message for the first time, the counter value is initialized with 1. During the subsequent reception of the same message from other nodes, the counter value is incremented by 1 and the message is dropped if the counter value exceeds the threshold. In the case of a distance-based scheme, a node only rebroadcasts if the distance from the source node, calculated from signal strength, is greater than some distance threshold. In contrast, a location-based scheme considers the location of the transmitting host and the additional coverage it can provide before rebroadcasting a message. However, the selection of an appropriate threshold is a challenge in all cases.

In [69], each message was initialized with a fixed counter value, which was decremented after every successful transfer to subsequent nodes. The forwarding process ends when the value becomes *zero*. In contrast, Pitkanen et al. [70] considered the number of hops the message has already traveled to control the message propagation. Similar hop-limited flooding was also investigated in Ref. [71] to determine its efficiency in varying network conditions. Lu et al. [72] proposed a method where the broadcast transmission range is controlled considering energy consumption and delivery predictability to gain better energy efficiency. Another interesting work recently proposed by Chancay--García et al. [73] suggested that the sender can divide the message into multiple chunks before forwarding and a smaller chunk has a better possibility to reach the destination as the contact duration among nodes is short enough to transfer the whole message.

Spray-and-Wait [74] is another notable work that spreads a specific number of copies (R) of a message in the network. In this method, whenever a node meets another node with $m > 1$ copies available for forwarding, it forwards $\lfloor \frac{m}{2} \rfloor$ copies and keeps $\lceil \frac{m}{2} \rceil$ copies for itself. If any node has only a single copy available, it holds on to that copy until it meets the destination. Fig. 5 shows the working procedure of the Spray-and-Wait forwarding approach. Here, node A has 5 copies of a message available at time t_1. When it meets nodes B and C at time t_2, it transfers 2 copies to each of them. Afterward, node B transfers 1 copy to node D while node C transfers the same to node E during interval t_3. In this manner, a source node distributes copies of a message in the network. However, determining the appropriate value of R (i.e., no. of copies) at the initial stage in a network with unknown parameters (i.e., the total number of nodes) is difficult since the estimation requires periodic contacts and a significant learning period. A variation of this approach was investigated in Ref. [75], where a node with a single copy of the message forwards the copy to a better relay node if it does not meet the destination. Recently, Wu et al. [76] proposed an updated version of the spray-and-wait algorithm suggesting that the social relationship among nodes should be considered in the spray phase. In this case, messages are forwarded to a node belonging to the same social circle as the destination node in the spray phase. They have also proposed limited replication of message copies in the wait phase to improve successful delivery. Similar to the work proposed in Ref. [74], Grossglauser et al.

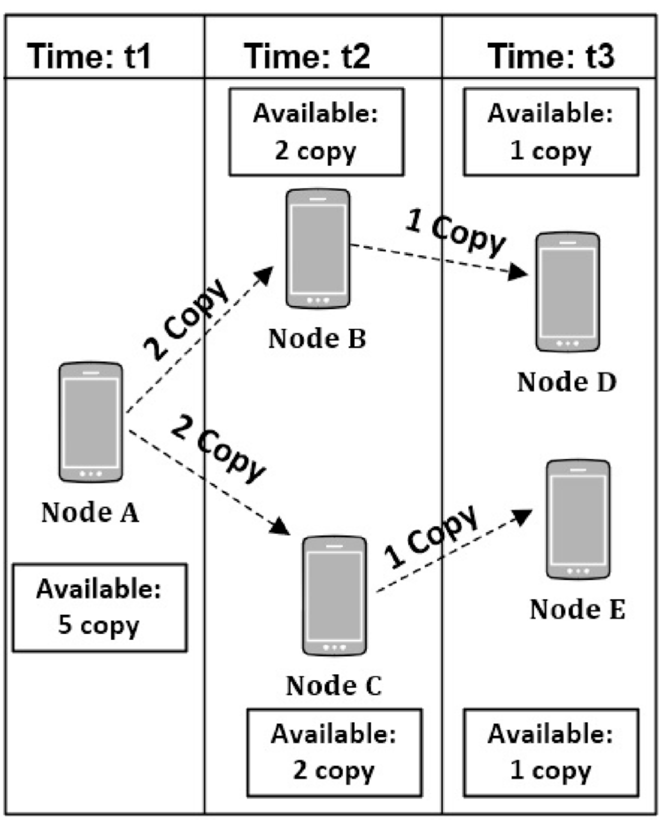

Fig. 5. Spray-and-Wait message forwarding protocol with $R = 5$.

[77] explored a two-hop flooding approach, where the source node distributes m copies of a message to relay nodes who hold on to them until they meet the destination. The delivery from source to destination happens via two-hop communication. Niu et al. [78] proposed a forwarding method where each relay node is also permitted to spread an additional k number of copies of the same message.

A major concern of these methods is to choose appropriate values for initial propagation under dynamic network conditions with different numbers of nodes and their movements. Wu et al. addressed this in Ref. [79] and proposed a copy-limited epidemic message forwarding approach where all the nodes are divided into multiple communities and the source node determines the optimal number of copies required in different communities to achieve a certain delivery success rate within the tolerable delay. They formulated a classical combinatorial optimization problem using the above constraints and solved it using a constrained non-linear optimization solver. Li et al. [80] proposed another interesting work to control the spread of information. They used the concept of 'Turf', which was considered as a logical location of the receiver in the temporal and spatial domain. Receivers who were located within the same 'Turf' as the sender (i.e., co-located for a longer time or remained within close distance) were allowed to receive all the information. Otherwise, no information was passed.

To summarize, flooding-based approaches spread multiple copies and hence achieve a high success rate, but consume a high amount of resources resulting in a significant energy drain. Determining the appropriate number of copies to spread in the network is also challenging without any global observer and a dynamic network. In addition, these approaches do not consider the suitability of a particular node for relaying messages. To address this issue, utility-based forwarding approaches are proposed, which will be discussed in the following section.

4.2.2. *Utility-based approach*

In this approach, whenever two nodes meet, they first forward a message destined for the other node, and then, they exchange the summary of the currently carried messages and their utility (e.g., delivery probability or expected delay). For any message, if other nodes have higher utility, it is selected as a relay node and forwards the message. The utility value is measured in terms of various aspects. Some approaches utilize frequent encounters with the destination to select a relay node. Another type of approach employs social attributes such as common interests with the destination, or popularity of a node for utility calculation. Physical contexts, such as mobility patterns and the location of the nodes, were also used in a few approaches. Different utility-based approaches are discussed in the following sections.

4.2.2.1. Contact pattern-based forwarding approach. This type of approach considers the frequency or recency of meeting with other nodes in the network and predicts the probability of successful delivery of a message to its destination. Fresher encounter search (FRESH) [81] is an early encounter-based forwarding approach where every node keeps track of the encounter time with other nodes and the node with the most recent encounter with the destination is selected as the relay node. Probabilistic Routing Protocol using History of Encounters and Transitivity (PROPHET) [82] is one of the prominent works that considers the probability of meeting other nodes based on the frequency of previous encounters. In this case, each node maintains a metric called *delivery predictability* denoted as $P_{(a,b)} \in [0, 1]$, the probability of node a successfully delivering a message to node b. The value of $P_{(a,b)}$ is updated whenever node a meets node b. Fig. 6 depicts the working principle of this approach. In this figure, node A is the source, and node D is the destination. When node A meets node B, it forwards the message to B as its delivery predictability is higher. Similarly, B forwards the message to C upon encounter and finally, C delivers the message to D. Although PROPHET considers delivery predictability, it does not account for available buffer space or the remaining energy of the relay node to make

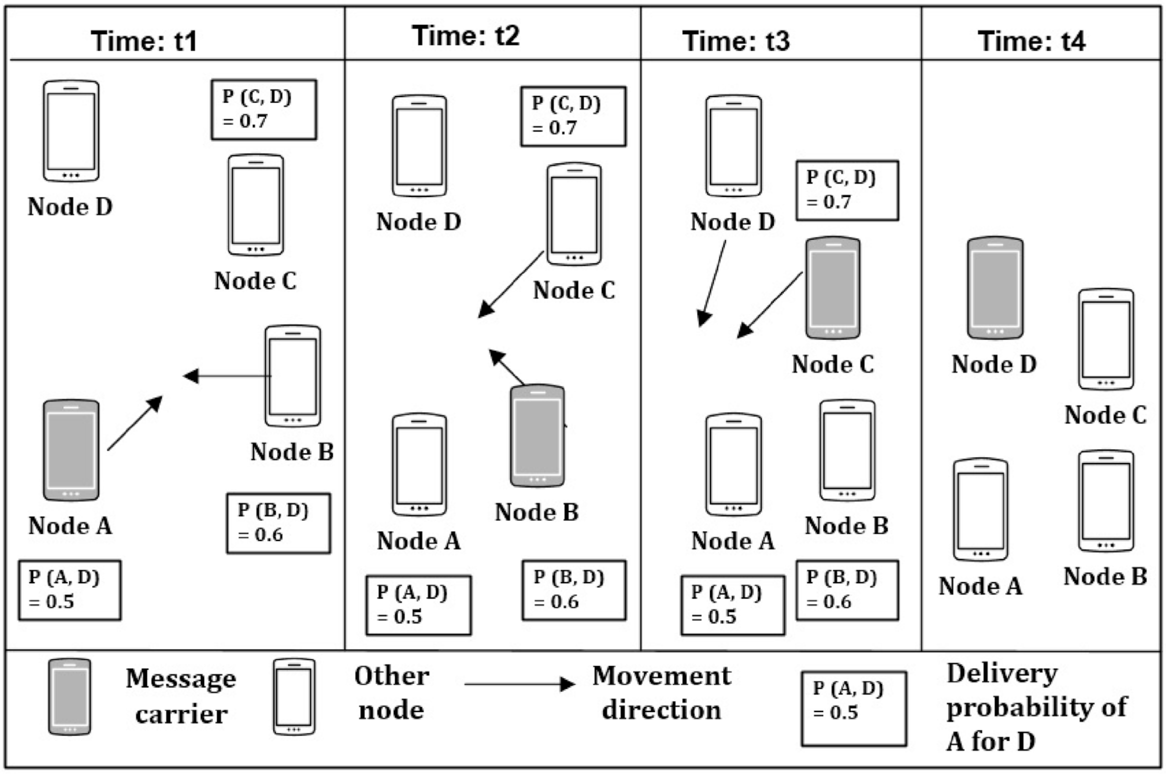

Fig. 6. Probabilistic Routing Protocol using History of Encounters and Transitivity (PROPHET). Here, *A* is the source node and *D* is the destination node.

forwarding decisions. To address this issue, a few approaches have been proposed [83–85] that use available buffer space and remaining energy along with delivery predictability. Another interesting work recently proposed by Ayub and Rashid [86] considers the inactivity of the destination node along with available buffer space to make forwarding decisions. In contrast, Mir and Hu [87] used a regular and sporadic link to differentiate between contact patterns among a pair of nodes. In this case, a node only creates a regular link with another node if the frequency of meeting within a time window is greater than a threshold, otherwise, the link is considered sporadic and this information is used while making forwarding decisions.

A similar encounter-based forwarding approach is also adopted in Refs. [88–92]. Burgess et al. [88] prioritize packets for transmission as well as deletion. Each node maintains and updates the probability of encountering other nodes (f^{u_i}) using incremental averaging (i.e., $\sum_{u_i} f^{u_i} = 1$). The cost of delivering a packet is calculated considering the sum of probabilities of encountering all the nodes in the path as,

$$cost(u_i, u_j, \ldots, u_d) = \sum_{u_k=u_i}^{u_d-1} \left[1 - \left(f_{u_k+1}^{u_k}\right)\right] \quad (9)$$

Here, $f_{u_k+1}^{u_k}$ shows the path cost from u_k to u_k+1 and u_d is the destination node. Finally, the path with the lowest cost is selected and packets are sorted using this cost value. During a transfer opportunity, higher-ranked packets are transferred first. Packets with higher hop-count are also deleted first in this approach when the buffer is full. Spyropoulos et al. [89] proposed a single copy-based forwarding approach where each node maintains a utility value for delivering content to every other node in the network. This utility value decreases according to the last encounter time. Nodes only forward a message whenever they meet another node with a higher utility. Localcom [90] considers that nodes are part of different communities, and their frequent encounter history is used to detect and identify gateway nodes that meet more frequently with members from multiple communities. In this method, intra-community message forwarding employs higher similarity and short hop-distance among community members, while inter-community communication uses the gateway nodes to send a message to the community of the destination node and later performs intra-community message forwarding to deliver the message.

The performance of Localcom was evaluated through a test-driven simulation where two datasets were used, namely (i) Haggle [93] and (ii) reality-mining [94] dataset. In the former dataset, the movement of 41 students in a conference environment was collected while the latter consists of the movement pattern of 97 students and staff. To analyze the performance of the forwarding method, 1000 packets were used where the source and destination were randomly selected, the performance of Localcom was compared with epidemic routing [67] and PROPHET [82]. A successful delivery rate of 30–40% across all approaches was reported for the Reality mining dataset while the Haggle trace produced 80–85% successful delivery. Localcom achieved a higher successful delivery rate than PROPHET while epidemic routing produced the best result. Inherently, the epidemic routing also produced the highest number of message exchanges than other approaches and hence consumed the highest amount of resources.

Context-aware Adaptive Routing (CAR) [95] is another forwarding protocol that uses a Kalman-filter-based prediction technique to determine a node's utility for carrying a message. In CAR, utility value depends on future co-location and the change in the degree of connectivity. If two nodes are co-located during the current time interval, the possibility of their co-location in future time intervals increases. Similarly, a node with a more dynamic neighbor-set (i.e., more unique nodes) is assigned a higher utility value. Finally, the best relay node is selected using these utility values and the Kalman-filter-based prediction technique. The performance of CAR was compared with epidemic routing [67] where 200 nodes generated 1000 messages for random destinations and the simulation was run for 8 h. The reported delivery success rate for epidemic routing and CAR was 62.7% and 49.9%, respectively.

Although the above approaches consider contact frequency, they neglect the fact that the contact opportunity might be short to complete a message transfer. To address this issue, Kim et al. [98] and Gondaliya et al. [99] proposed a contact duration aware forwarding approach. In Ref. [98], it is suggested that, since the contact duration might be insufficient to transfer the whole message, a *forwarding failure* occurs when part of the message cannot be delivered due to time constraints. Therefore, nodes can divide a message into several fragments and independently forward each fragment to the destination to utilize all contact opportunities and avoid total *forwarding failure*. A more simplified forwarding approach is proposed in Ref. [99] where a relay node for intra-community forwarding is selected based on both the frequency and duration of encounter with the destination node. If a node belongs to the same community as the destination node and has a higher contact frequency with a longer duration than the current message carrier node, it is selected as the relay node. In the case of inter-community forwarding, the global centrality of a node is used, which is calculated using the encounter frequency and duration of a node with all other nodes in the network, regardless of their community membership.

Ravei et al. [101] suggested that nodes can be part of multiple communities and their contact pattern may vary for different communities. Therefore, the time spent in different communities was considered for utility calculation. In contrast, Lobiyal et al. [102] suggested that contact duration varies based on location and hence used location information along with contact duration to determine the utility of a relay node. Recently, Le and Gerla [103] proposed a contact duration aware approach, which uses message fragmentation to increase delivery success rate during a short contact period.

Gao et al. [96] exploited transient social contact patterns to undertake forwarding decisions. They considered that the contact patterns might vary during different times of the day. For example, classmates might encounter more frequently during daytime compared to nighttime. Therefore, instead of considering the cumulative contact distribution, they focused on transient contact distribution to identify nodes that are more likely to meet within a certain period. A similar approach by Zhang et al. [100] suggested that information about fine-grained contact patterns, i.e., meeting time and week of the day needs to be considered to calculate encounter probabilities as nodes may follow a weekly and daily pattern for the meeting.

Community-aware Opportunistic Routing (CAOR) [55] employed the idea of the home community and the presence of a static virtual throwbox in each community. A home community is assigned to each node based on its visiting frequency to particular locations. It is also argued that nodes are expected to meet at their home community more often than at other places. The message forwarding between a pair of nodes is then converted into forwarding between two communities and the relay nodes are selected based on the expected minimum delivery delay using a reverse Dijkstra algorithm. A similar home community-based forwarding approach is proposed in Ref. [104], where a message is forwarded to the node, which has an affiliation to the highest number of home communities among co-located neighbors. Another interesting work proposed by Abdelkader et al. [97] provided a mathematical formulation for optimal forwarding strategy assuming the presence of a global observer in the network. The global observer collected encounter patterns among all the nodes and accordingly selected the best forwarding path considering limited available resources (e.g., buffer space, contact opportunity). A heuristic-based forwarding protocol was also proposed in Ref. [97] using the average contact rate among participating nodes. Their simulation results indicated that, in terms of successful delivery, their proposed forwarding protocol SGBR (60–90%) outperformed epidemic routing [67] (35–70%), PROPHET [82] (45–85%), Spray-and-Wait [105] (45–85%) and MaxProp [88] (60–90%). However, it is difficult to obtain the presence of a global observer in an intermittently connected network that is frequently disconnected. A congestion-aware and buffer-management-based forwarding scheme is proposed in Ref. [106] where a sender node calculates the optimal transfer size considering the available buffer size, point of congestion, and delivery probability. Afterward, the sender applies a scheduling policy to efficiently manage the available bandwidth during a contact with a potential forwarder to increase delivery probability.

The above approaches achieve a higher delivery success rate and lower latency when nodes frequently meet each other regularly, which provides an opportunity for predicting future contact and message delivery options. Table 4 shows some key features of the contact pattern-based approaches. Please note that DCS uses smart mobile devices for sharing contents, which has limited energy and buffer space. Although recent advancement of smartphones with greater memory and battery capacity is likely to encourage users to participate in the sharing process, available energy and buffer space remain a major concern for the users for adopting DCS and hence these metrics were used for comparison in Table 4. These approaches do not consider any social attribute or characteristic of a user (e.g., popularity in the society or tie strength) for making forwarding decisions. Inspired by such social attributes of the participants, researchers have investigated several forwarding approaches, which are discussed in the following section.

4.2.2.2. Social attribute-based forwarding approach. This category of forwarding approaches analyzes the underlying social alliance among participating nodes and leverages it for improving the delivery service. The social alliance is usually captured using popularity or similarity metric. In the case of a popularity metric, the basic idea is to forward the message to the most popular node who is more likely to meet the destination. In contrast, the similarity metric-based approaches identify a relay node that has more commonality with the destination node. Daly et al. [54] were among the first to explore the social relationships among nodes to undertake forwarding decisions. They employed social similarity and centrality to calculate a node's utility for forwarding a message. The utility value obtained from the social similarity of a node u for delivering a message to destination v in comparison to node k is calculated as,

$$SimUtil_u(v) = \frac{Sim_u(v)}{Sim_u(v) + Sim_k(v)} \tag{10}$$

Similarly, the betweenness centrality is also used to calculate a utility value as,

$$BetUtil_u = \frac{Bet_u}{Bet_u + Bet_k} \tag{11}$$

Finally, using these two values, the utility value of node u in comparison to node k is calculated as,

$$SimBetUtil_u(v) = \varphi_{sim}\ SimUtil_u(v) + \varphi_{bet}\ BetUtil_u \tag{12}$$

Here, φ_{sim} and φ_{bet} are tunable parameters to assign a weight to the components of the utility calculation. Finally, a node with a higher utility value was selected as the relay node for carrying the message. This idea was further extended in Ref. [107] where another metric called *tie strength* was introduced for utility calculation which measured the intensity of a relationship calculated in terms of frequency, recency, and duration of the encounter. PeopleRank [108] is another approach that is inspired by the PageRank [109] algorithm used by Google to rank web pages. PeopleRank assigns higher rankings to the most popular and highly connected nodes in the network, then forwards messages from lower-ranked nodes to higher-ranked nodes, assuming higher-ranked nodes have a better chance of encountering other nodes.

LABEL [110] proposed that each node has a 'label' associated with it that expresses its affiliation. The relay nodes were selected based on having similar affiliation (i.e., labels) as the destination node. This idea was further extended in BUBBLE RAP [111] which is a prominent social attribute-based message forwarding protocol. This approach considered that nodes can be associated with multiple groups and have different rankings (i.e., popularity) in different groups. Each node is assigned a global ranking and a local ranking (i.e., ranking inside the community).

Table 4
Contact pattern-based message forwarding approaches.

Protocol name	Metric for utility calculation	Community	Energy of relay considered?	Buffer space of relay considered?	No of Message copies
FRESH (Ferriere et al. [81], 2003)	recent contact time	✖	✖	✖	multiple
PROPHET (Lindgren et al. [82], 2004)	contact probability	✖	✖	✖	multiple
MaxProp (Burgess et al. [88], 2006)	contact probability	✖	✖	✖	multiple
Seek-and-Focus (Spyropoulos et al. [89], 2008)	recent contact time	✖	✖	✖	single
Localcom (Li and Wu [90], 2009)	encounter history similarity	encounter-based	✖	✖	multiple
CAR (Musolesi and Mascolo [95], 2009)	co-location and connectivity	✖	✖	✖	single
User-centric (Gao and Cao [91], 2011)	contact patterns and interest	✖	✖	✓	multiple
Transient (Gao et al. [96], 2013)	transient contact pattern	frequent contact-based	✖	✖	multiple
SGBR (Abdelkader et al. [97], 2013)	meeting frequency	encounter-based	✖	✖	multiple
Contact duration aware (Kim et al. [98], 2014)	contact duration	✖	✖	✖	multiple
CAOR (Xiao et al. [55], 2014)	visiting frequency	visiting pattern-based	✖	✖	single
Contact frequency (Gondaliya et al. [99], 2016)	contact frequency duration	k-clique distributed	✖	✖	multiple
Ea-PROPHET (Bista and Rawat [83], 2017)	contact probability, energy consumption and available buffer space	✖	✓	✓	multiple
Fine-grained contact pattern (Zhang et al. [100], 2017)	contact duration, and time	✖	✖	✖	multiple
CAF (Ravaei et al. [101], 2018)	contact duration, and time, TTL, community membership	encounter-based	✖	✖	single
NEEP (zhao et al. [92], 2018)	encounter frequency and time, energy, TTL	interest-based	✓	✓	single
LCTEE (Lobiyal et al. [102], 2019)	contact duration, location, buffer space	✖	✖	✓	single
FDR (Le and Gerla [103], 2019)	contact duration and time, inter-contact time, TTL and fragmented data size	✖	✖	✓	single
InD (Ayub and Rashid [86], 2020)	encounter time interval, encounter frequency, average time interval, message size, and available buffer	✖	✖	✓	multiple
RSCR (Mir and hu [87], 2020)	encounter time and period, inter-contact time and TTL	✖	✖	✓	multiple

The ranking of a node was calculated using a degree and betweenness centrality. For message forwarding, a node with a higher global rank is initially selected until the message reaches a member of the same group as the target node, after which the local rank in that particular group is used to spread the message among group members, hoping that members who are more popular in the group are more likely to reach their destination. The method is illustrated in Fig. 7. Here, the source node continues to send a message via nodes with a higher global ranking. Finally, when the message is received inside the sub-community of the destination node, ranking inside that community is used for delivering the message. Similarly, various combinations of degree centrality, betweenness centrality, and tie-strength measures were used in Refs. [112–114] to select a relay node.

Xia et al. [115] were inspired by an artificial bee colony algorithm, where bees can identify a nectar source with maximum density, and proposed a forwarding approach where nodes can determine density in a group (i.e., degree centrality or the number of unique nodes seen) and keep track of the tie strength (i.e., amount of time spent with group members). For inter-community message forwarding, density values were used while intra-community message forwarding utilized social tie

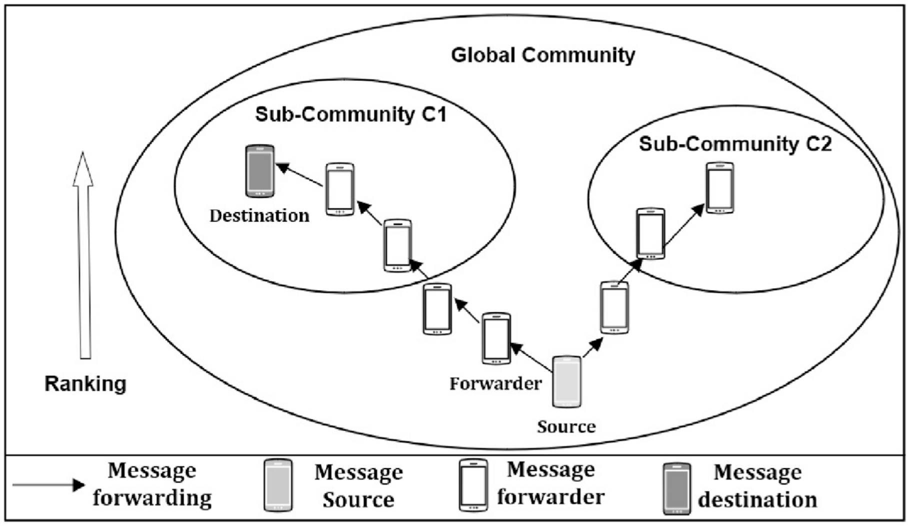

Fig. 7. Bubblerap forwarding. Messages are forwarded from lower-ranked nodes to higher-ranked nodes until they reach the destination.

values. To evaluate the performance of this approach, a simulation was performed using an area of 4.5×3.4 km^2 and 40 nodes where the size of the contents was varied within 500–1024 KB. Simulation results indicated that this approach achieved a 55–75% delivery success rate while outperforming epidemic routing [67] (35–65%) and PROPHET [82] (35–55%). Although these types of social popularity-based approaches are likely to yield successful delivery, they also might result in congestion near the popular node whose energy will drain due to communication from other nodes.

SocialGreedy [116] approach assumed that social profiles of users are readily available and can be used for taking message forwarding decisions. They calculated the social distance between two users using attributes such as nationality, language, affiliation, city, country, and interest/hobbies collected from their social profile. Finally, the relay node was selected that had a shorter distance (i.e., more similarity) with the destination. However, the selection of appropriate social features (i.e., attributes) was not investigated. To address this issue, Wu and Wang [117] proposed that important social features can be extracted using the Shannon entropy formula as,

$$E(F_i) = -\sum_{k=1}^{n} P(x_k) log_2 P(x_k),\ \ (i = 1, 2, \ldots, m') \tag{13}$$

Here, $E(F_i)$ shows the entropy of the i-th feature F_i, $P(.)$ depicts the probability of mass function of F_i and $\langle x_1, x_2, \ldots, x_n \rangle$ are the possible values of F_i. Social features may include physical feature, e.g., gender, or logical features, e.g., membership in a group. They also proposed two forwarding approaches, namely (i) node-disjoint routing and (ii) delegation-based routing. In node-disjoint forwarding, feature difference with the destination node was resolved in a step-by-step manner (i.e., one feature at a time) to forward the message. In the delegation-based routing method, feature closeness with the destination was checked to select an appropriate relay node. However, this approach is difficult to implement in a decentralized environment as there is no fixed global entity to collect feature information from everyone and then identify important features for further processing. In contrast, Xu et al. [118] considered the name, workplace, address, friends, and hobbies as social features, which are recorded by nodes during the encounter and used social similarity and transition of nodes in different communities to select an appropriate relay node. SPOON [37] also proposed a social attribute-based forwarding approach, which used interest similarity and meeting frequency among participants for making forwarding decisions, arguing that people with similar interests tend to meet each other more frequently than others. Whenever a node has a message to forward, it calculates the fitness score ($\boldsymbol{F}$) of the neighbors using the following equation

$$\boldsymbol{F} = \varphi\, sim(v_{dest}, \tilde{v_u}) + (1-\varphi)\, sim(v_{dest}, v_{H_u}) \tag{14}$$

Here, $\tilde{v_u}$ represents u's interest vector while v_{H_u} represents the interest of other nodes seen by node u in the past. $sim(v_{dest}, \tilde{v_u})$ measures node u's interest similarity with the destination, and $sim(v_{dest}, v_{H_u})$ shows the interest similarity of node u's expected future neighbors with the destination. Whenever a node meets a neighbor with a higher fitness score ($\boldsymbol{F}$), it forwards the message to that node. Yu et al. [119] used interest similarity along with residual energy and message Time-To-Live (TTL) to select a forwarder node. However, it can be argued that people with similar interests might form a community but they might have different activity levels inside the community. To address this, Li et al. proposed a Local Activity and Social Similarity (LASS)-based forwarding technique [46]. They suggested that the activity level of a node varies in different groups. Therefore, both social similarity and local activity within a group should be used to calculate forwarding utility. For a higher TTL (>1 week), LASS [46] achieved a better delivery success rate (55–70%) and outperformed epidemic routing [67] (22–42%), PROPHET [82] (28–38%), BUBBLE RAP [111] (40–50%) and Simbet [54] (30–35%).

Social-aware Networking (SANE) [120] considered interest as a social attribute of the users and interest similarity among them as a metric for selecting a forwarder node. The interest profile of a user was represented using an m-dimensional vector where each component indicated a user's level of interest in a topic and m represented the total number of interests (i.e., topic). A cosine similarity metric was used to identify interest similarity among two encountered nodes. Finally, considering that a node's interest also determines its movement in the network, a node with a higher interest similarity with the destination is selected as a forwarding node. In contrast, Jang et al. [121] used similar contact frequency with neighbors to define social similarity and incorporated position similarity information to select a relay node. Another recent work by Yu et al. [122] suggested that since there might be some selfish nodes in the network, the selection of relay nodes should consider the social relations between nodes and their probability of meeting and cooperation.

Yuan et al. in Ref. [123] used both betweenness centrality and social similarity along with a personality value to calculate a forwarding utility, which was finally used to select relay nodes. Unlike previous works [123], calculated the above social attributes from GPS traces considering that people visit a particular set of hotspots more regularly. The top-k hotspots were mutually identified by a collaborative exchange of visiting records among users. Nodes who visited popular hotspots more often attained higher centrality values while nodes with similar visiting patterns achieved higher similarity values. In addition, the individual's habits for visiting these hotspots were taken into account to calculate a personality value. Finally, a utility value called a 'Hotnet' metric was calculated considering all the above components. The Hotnet metric of node u for destination v is calculated as [123],

$$Hotnet_{u,v} = per_u \times gra_{u,v} \tag{15}$$

Here, per_u shows u's personality score and is calculated using Shannon entropy. $gra_{u,v}$ shows the gravitation between node u and v, and calculated as,

$$gra_{u,v} = \boldsymbol{G}\frac{B_c^u B_c^u}{Sim(u,v)^2} \tag{16}$$

where $\boldsymbol{G}$ represents the gravitational constant, B_c^u shows the betweenness centrality of u, and $Sim(u, v)$ depicts the similarity between u and v. The performance of Hotnet was assessed using two real-world datasets (KAIST and NCSU [125]) showing human movement patterns in an urban scenario, and compared against Simbet [54] and PeopleRank [108]. Simulation results indicated that Hotnet achieved a higher success rate (40–80%) than Simbet (38–60%) and PeopleRank (22–62%). A recent work proposed by Zhang et al. [124] suggested that destination-aware betweenness centrality is more important for utility calculation, which only considers the paths connecting the destination node than paths between every pair of nodes in the network.

Some key features of the social attribute forwarding approaches are highlighted in Table 5. Social attribute-based forwarding approaches require the extraction of social metrics from existing social networks or building them over time from regular social contexts. Therefore, they are more appropriate in scenarios where such relationships already exist through available social networks or are easily understood in *workplace-type* scenarios between classmates or colleagues. However, these approaches usually do not consider the current physical context of

Table 5
Social attribute-based message forwarding approaches.

Protocol name	Metric for utility calculation	Community	Energy of relay considered?	Buffer space of relay considered?	No of Message copies
Simbet (Daly and Haahr [54], 2007)	betweenness centrality and similarity	✖	✖	✖	single
LABEL (Hui and Crowcroft [110], 2007)	similar affiliations	✖	✖	✖	multiple
SimbetTS (Daly and Haahr [107], 2009)	betweenness centrality, similarity and tie strength	✖	✖	✖	multiple and single
PeopleRank (Mtibba et al. [108], 2010)	popularity	✖	✖	✖	single
SocialGreedy (Jahanbakhsh et al. [116], 2010)	social similarity tie-strength	✖	✖	✖	single
BUBBLE RAP (Hui et al. [111], 2011)	global and local popularity	k-clique distributed	✖	✖	single
Hypercube (Wu and Wang [117], 2014)	social feature and social closeness	✖	✖	✖	multiple
SPOON (Chen et al. [37], 2014)	interest similarity	interest similarity and meeting frequency	✖	✖	multiple
LASS (Li et al. [46], 2014)	social similarity and activity	geographic proximity	✖	✖	multiple
Beeinfo (Xia et al. [115], 2015)	density and tie-strength	interest-based	✖	✖	multiple
SANE (Mei et al. [120], 2015)	interest similarity	✖	✖	✖	multiple
Hotnet (Yuan et al. [123], 2015)	social similarity, betweenness centrality personality	✖	✖	✖	single
PaSS (Jang et al. [121], 2016)	encounter frequency, social similarity and position similarity	✖	✖	✖	multiple
SAPR (Zhao et al. [112], 2017)	degree centrality and betweenness centrality in different regions	geographic	✖	✖	multiple
Interest community-based (Yuan et al. [113], 2017)	centrality within and outside community, buffer space	interest-based	✖	✓	single
EIAD (Yu et al. [119], 2019)	interest similarity, residual energy, TTL	✖	✖	✓	multiple
PSOR (Xu et al. [118], 2019)	social similarity, social activity	geo-location -based	✖	✖	single
DAS (Zhang et al. [124], 2019)	destination-aware, betweenness centrality	✖	✖	✖	multiple
SAS (Paul et al. [114], 2020)	tie strength, social similarity, betweenness centrality	✖	✖	✖	single

participants (e.g., instantaneous movement or current location) which might provide faster delivery options. To address this issue, another type of forwarding protocol is proposed as discussed below.

4.2.2.3. Physical context-based forwarding approach. This type of forwarding protocol analyzes the current physical context, such as movement direction, location, mobility pattern, and current time, to assign a utility value for forwarding a message and accordingly selects a relay node. Meeting-and-Visits (MV) routing [126] is one of the earliest works in this category that used frequency of visits to particular locations to assign a utility value. Static destinations are considered in this work, and nodes maintain a probability metric for visiting those destinations which are calculated by counting the number of past visits within a particular period. For example, node k maintains a probability metric $P_0^k(R_i)$ depicting its probability of delivering a message in region R_i which is calculated as, $t_{R_i}^k/t$, that is the ratio of the number of rounds k visited region R_i to the total number of rounds. If k visited region R_i higher number of times, it is likely that it will visit that place again. However, assumptions of such static destinations are unrealistic in DCS. To address this issue, Leguay et al. proposed another mobility pattern-based forwarding approach called MobySpace [127]. In this approach, participating nodes maintain the history of their past visits considering the frequency and duration of visits to particular places. They identified that it follows a power-law distribution which essentially indicates that there are only a few locations that people visit more frequently. In this approach, each node maintains a K-dimensional metric called MobySpace to record the list of their top K visited locations and the probability of visiting them. The similarity between the mobility patterns of the two nodes is calculated using the Euclidean distance. Finally, a node with a higher similarity value with the destination is selected as the relay node.

Although the similarity between mobility patterns indicates that the nodes are likely to meet again, it does not guarantee that these nodes will meet soon to enable faster delivery. Therefore, Huang et al. [128] proposed a technique where the distance and the moving direction of a node are taken into account. In this method, a node that has a smaller distance with the destination and is moving towards it is selected as the relay node. A message dropping policy is also proposed where messages that have traversed more hops are dropped first if the buffer becomes full. A similar distance-based forwarding approach is also proposed in Refs. [129–134]. However, these approaches mostly consider static destinations or the location of the destination is known a priori, which is usually not the case for DCS.

Predict-and-Relay (PER) [135] is a prominent message forwarding technique that uses predictable movement patterns to identify a relay node. This approach considers that nodes follow a semi-deterministic trajectory by visiting a particular set of locations called landmarks regularly and a time-homogeneous semi-markov model was employed to illustrate the transition of nodes from one landmark to another. The transition probability between landmarks as well as the sojourn time in a particular landmark was calculated using historical data. Whenever nodes encountered each other, such information was exchanged so that nodes were aware of each other's movement patterns in the network. Finally, a message forwarding utility was calculated considering the contact probability between nodes and message delivery delay. The approach is demonstrated in Fig. 8. In this figure, node A is the source, and node C is the destination. Based on the forwarding utility, node A forwards the message to node B at time $t1$ in landmark $L1$, who ultimately delivers the message to node C in landmark $L2$ during time $t2$. Note that nodes have changed position due to movement from time $t1$ to $t2$. A similar movement pattern-based forwarding approach was also proposed in GeoDTN [136] where nodes shared their mobility pattern as well as the mobility pattern of their neighbors (reachable within 2-hop). A confidence value for movement history indicating the recency of the information was also used. Simulation results in Ref. [136] show that GeoDTN achieved an 85% delivery success rate similar to Simbet [54] and SimbetTs [107] while Epidemic routing [67] and PROPHET [82] achieved a higher rate (90–100%).

The above approaches require maintenance of the mobility history of all the encountered nodes which introduces message overhead and consumes significant network resources. To solve this, Talipov et al. [5] proposed Discover-Predict-Deliver (DPD) method where each node only maintains its mobility history and does not share this with its neighbors. While generating a content request, a node calculates its mobility information that includes future locations at different time intervals and adds this information with the request. This mobility information is used by a node to calculate message delivery probability (i.e., utility). For example, if the mobility information of the destination node v and another node u is represented by $M_v = l_{v,t}, l_{v,t+\delta}, \ldots, l_{v,t+k\delta}$ and $M_u = l_{u,t}, l_{u,t+\delta}, \ldots, l_{u,t+k\delta}$, respectively, then the utility value of node u for delivering a message to node v can be calculated as,

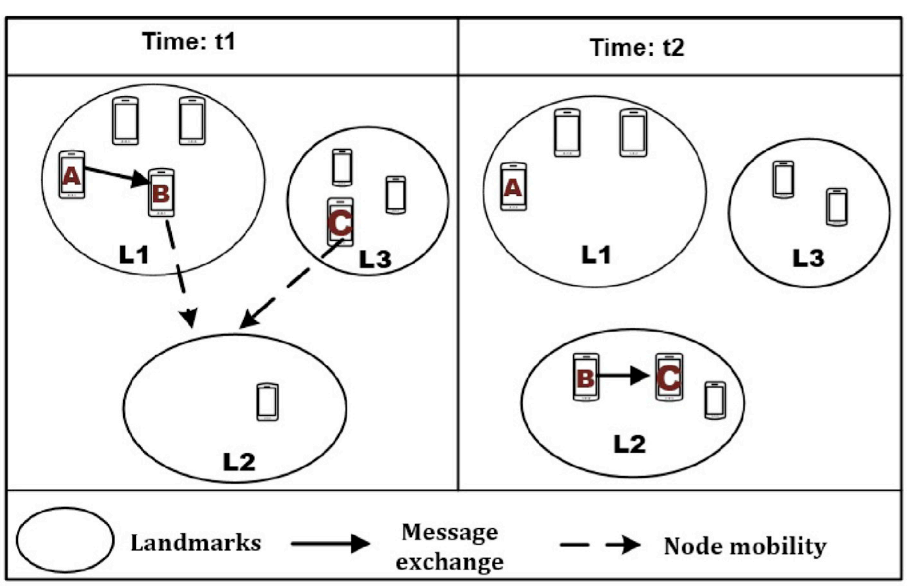

Fig. 8. Predict-and-Relay (PER) forwarding. Here, A is the source node and C is the destination node and nodes move around landmarks following their mobility pattern.

$$Util_u(v) = \sum_{m=t}^{t+k\delta} U_m, \quad U_m = \begin{cases} \frac{t}{m}, & \text{if } |l_{u,m} - l_{v,m}| \leq R_{u,v} \\ 0, & \text{otherwise} \end{cases} \tag{17}$$

Here, $R_{u,v}$ represents the radio communication range of u and v within which they can detect the presence of each other and successfully communicate. The performance of DPD was assessed using trace-driven simulation with 100 nodes for 72 h where the movement of nodes was dictated using the working day movement model [137] and 10 nodes randomly generated content request every 30 min. DPD achieved a delivery success rate of 80–85% in different scenarios. Kaisar et al. [138] proposed a forwarder selection policy based on co-location stay probability and connectivity values calculated from the number of co-located nodes. Another interesting work proposed by Xie et al. [139] used perceived cooperation willingness where each node records the number of messages forwarded by their neighbors and selects the one with the highest number of forward.

Dsearching [140] divides the entire area under consideration into sub-areas assuming that a particular sub-area can only contain at most one popular spot that is frequently visited by all nodes (e.g., library or dormitory in a university campus). Since mobile devices have built-in GPS, they can easily identify their locations and determine the sub-area they are currently in. Nodes maintain and update their visiting records to generate a mobility history. A set of nodes called 'host' nodes are selected for each sub-area that is more likely to stay longer in that region. Unlike [135], in this work mobility information is shared with only the host nodes in a sub-area. Mobility information of a destination node collected from such host nodes is used for reaching them. Alhasanat et al. [104] proposed a home-community aware message forwarding approach where nodes visit multiple home locations and share this information with other nodes. For message forwarding, if the destination node's home location is known a priori, a node with the same home-location is selected as the forwarder, otherwise, a node with the highest number of home location is selected. Furthermore, a bitmap-based weighted tree is employed in Ref. [141] where each node maintains a bitmap to store its location and connection with other nodes and uses it for message forwarding decisions. Another interesting work proposed by Zhang et al. [142] suggested that the use of a node position server to record the location information of the participating nodes. In this case, each node share their potential future location and visiting time with the location server in advance and update the server if there is a sudden change. Nodes can also inquire about the potential location of other nodes to make forwarding decisions. However, in an opportunistic network without any infrastructure support, management of such as location servers can be difficult.

Although sharing mobility patterns with other nodes provides a faster way to deliver content, it also raises privacy concerns. To overcome these issues, Lu et al. [143] proposed that nodes should only record their mobility pattern without sharing it with other nodes. They also considered that mobility patterns vary across different time slots due to variation of movement during weekdays and weekends. Using this information, each node calculates its utility value for forwarding a message to a particular destination. In this case, only the identity of the destination is used to calculate the utility value, and a node with a higher utility value is selected as the relay node. ALERT [144] is another protocol that provides anonymity protection by hiding node identity and routes from outsiders. It provides identity protection by using a collision-resistant SHA-1 hash function to hash a node's MAC address and current time to generate its identity rather than simply using its MAC address. In this way, an outsider is unable to determine whether a particular MAC address holder is present in the network. For message forwarding, it dynamically selects an intermediate node in every step of the forwarding. To achieve this, ALERT performs hierarchical region partitioning, which continuously divides the entire region into alternate horizontal and vertical partitions until the target node is not on a separate region. After that, a temporary destination is selected which is a node in the same zone as the destination and a message is forwarded to that node.

Table 6 represents some key features of the physical context-based approaches. These approaches require the existence of regular movement patterns of participating nodes, where they visit some set of locations regularly and spend similar amounts of time in them. This routine is easily accomplished in our daily lives, as people typically visit their homes, offices or college campuses on some predictable schedule. However, learning this predictable pattern requires a learning period and a regular or semi-regular schedule that participants follow. Recently, Machine Learning (ML) and Deep Learning (DL) techniques have emerged as effective tools for handling classification and prediction-related tasks in many domains. In this regard, researchers in DCS are using them to predict user movement patterns to facilitate message forwarding decisions. Such machine learning-based approaches are highlighted below.

4.2.2.4. Message forwarding using machine learning. Sharma et al. [145] considered message forwarding as a classification problem and employed a machine learning technique to address this in opportunistic networks with intermittent network connectivity. They suggested that nodes can be trained with machine learning models, such as K-Nearest Neighbor (KNN) to make message forwarding decisions. In this case, a node can be trained with features, such as available buffer space, time-out ratio (i.e., duration of a message in the buffer compared to a maximum time), hop count, the distance of the neighbor to destination, speed of neighbor, and interaction probability to decide whether to forward a message (i.e., class 1) or not (class 0) when it encounters a neighbor. Simulation results showed that their proposed KNNR protocol outperformed the state-of-the-art message forwarding protocols, such as PROPHET and Epidemic routing. Along a similar line [146], suggested the use of Decision Tree (DT) and Neural Network (NN) based machine learning model to train nodes to make forwarding decisions. In this case, the authors proposed a machine learning-based PROPHET model called the MLPROPH model, which considers the output of forwarding a message to different hops and checks if it leads to successful delivery to the destination in the training phase. In contrast, an ensemble-based Cascaded Machine Learning model (CAML) was proposed in Ref. [147] which used a simple logistic regression classifier at the first stage and a Multi-Layer Perception Neural Network (MLPN) classifier at the second stage to make the forwarding decision. The proposed CAML model outperformed MLPROPH [146] and KNNR [145] in terms of message delivery probability, average hop count, and network overhead ratio. A further extension was explored in Ref. [148] by considering the opportunistic environment as a Markov decision process and solving it using the dynamic programming-based iterative algorithm to improve delivery performance.

In contrary to the above-mentioned works, where the message forwarding "action" has been used as different classes, works in Refs. [149–151] used machine learning techniques to classify "nodes" to make the forwarding decision. Souza et al. [149] used the Naive Bayes classifier to classify nodes into friends, acquaintances, and unknown nodes, and based on the friendship strength made the message forwarding decisions. In addition, a random forest classifier was used in Ref. [150] to classify nodes as reliable and non-reliable forwarders and in Ref. [151] as benign and malicious forwarders, and then the classification outcome was used to make the message forwarding decision.

Vashishth et al. [152] used a Gaussian mixture model-based unsupervised machine learning technique for message forwarding in the opportunistic network. They considered a soft clustering mechanism where a node may be associated with different clusters at different times. Their proposed technique works in two stages, the first stage involves

Table 6
Physical context-based message forwarding approaches.

Protocol name	Metric for utility calculation	Community	Energy of relay considered?	Buffer space of relay considered?	No of Message copies
MV (Burns et al. [126], 2005)	visiting frequency	✖	✖	✖	multiple
Mobyspace (Leguay et al. [127], 2005)	similar visiting pattern	✖	✖	✖	single
DAER (Huang et al. [128], 2007)	distance and moving direction	✖	✓	✖	multiple
POR (Li et al. [129], 2008)	distance and message size	✖	✖	✖	multiple
MPAD (Zhu et al. [130], 2008)	speed, current moving direction and distance	✖	✓	✖	multiple
PER (Yuan et al. [135], 2009)	landmark transition and sojourn time probability	✖	✖	✖	single
GeoDTN (Link et al. [136], 2011)	visiting pattern and confidence score	✖	✖	✖	multiple
LOOP (Lu et al. [143], 2012)	mobility record including location, time slot and day type	✖	✖	✖	multiple
DPD (Talipov et al. [5], 2013)	movement pattern similarity	✖	✖	✖	multiple
HBPR (Dhurandher et al. [131], 2015)	movement pattern history	✖	✖	✖	multiple
SGFL (Jaiswal et al. [132], 2016)	movement speed, distance	✖	✖	✖	multiple
CWAR (Xie et al. [139], 2016)	message forwarding history, priority and encounter probability	✖	✖	✖	multiple
UBF (Kaisar et al. [138], 2016)	co-location stay, probability, connectivity, energy and buffer space	interest -based	✓	✓	multiple
LIBR (Wang et al. [133], 2017)	movement direction, location and TTL	✖	✖	✓	multiple
RATP (Zou et al. [134], 2019)	node mobility, and location	✖	✖	✖	multiple
Home-community (Alhasanat et al. [104], 2019)	number of home community, delay and hop-count	✖	✖	✖	single
AMOR (Zhang et al. [142], 2020)	message priority, location of source and destination, activity range, energy, centrality, incoming and outgoing degree, and movement pattern	designation -based in simulation	✓	✖	both single and multiple

training nodes with extracted network features, the second stage assigns nodes to different clusters, and message forwarding occurs when candidate nodes belong to the same cluster as the target node. Another interesting work proposed by Dhurandher et al. [153] used the fuzzy logic-based q-learning model to select the optimal forwarder node based on available energy, buffer space, and movement. On the other hand, Borrego et al. [154] used machine learning models to estimate the future value of a node's centrality metric to select an appropriate forwarder node.

Overall, the proposed machine learning-based message forwarding techniques require extraction of network features, training nodes with those features, and finally, use a machine learning model to select appropriate forwarder nodes. Machine learning models have also been used for user movement tracking and prediction in different scenarios [155,156]. It can be concluded that the evolution of high-powered smart mobile devices will allow the incorporation of such techniques in DCS for message forwarding to improve delivery performance.

In summary, flooding-based message forwarding techniques blindly spread multiple copies of a message in the network and hence are likely to consume unnecessary resources. In contrast, utility-based message forwarding techniques require frequent encounters regularly, social relationships among participants built over time, or scheduled movement patterns to calculate the utility value and select an appropriate relay node. Most of the existing approaches do not consider the remaining energy or buffer space of the relay node before selection, which is an important indicator of a node being capable of successfully carrying and delivering the content. In addition, the above approaches assume that nodes are cooperative and help each other in carrying and delivering contents. However, in real life, selfishness is common among participants and some sort of incentive is needed to encourage them. To address this, several incentive schemes are proposed in the literature that is discussed in the following section.

4.3. Participation incentive

The message forwarding approaches discussed in the previous section rely on the altruistic behavior of participating nodes suggesting that they work collaboratively for carrying and delivering content for other nodes. However, such altruistic behavior might not be found in reality as users are more likely to act selfishly without some form of incentive. The reasons behind such selfish behavior may be due to the nature of the use of the device, saving battery life, or the privacy concerns of the users about taking part in the sharing process. To handle such selfish behaviors, different incentive schemes have been proposed in the literature to induce users to participate in different phases of the content sharing process. The proposed incentive schemes can be broadly categorized into (i) reputation-based, (ii) credit-based, (iii) tit-for-tat, and (iv) game-theory-based schemes, which are discussed in the following sections.

4.3.1. Reputation-based

This type of scheme monitors the behavior of participating nodes, identifies well-behaved and misbehaving nodes, and accordingly calculates a reputation score. In this regard, a higher reputation score indicates the superiority of a node for message forwarding and/or its trustworthiness. Whenever any node forwards a packet for another node, the reputation score increases, and a higher reputation score ensures priority for obtaining a service. In contrast, whenever a node misbehaves, its reputation score decreases and when the score falls below a certain threshold, that node is usually excluded from the network.

He et al. [157] were among the first to adopt reputation-based incentives, using neighbor monitoring, where a node can overhear a forwarding node's transmissions and identify if it forwarded a message. The reputation score of a node is calculated using the ratio of the number of messages forwarded by that node to the number of total messages sent to it for forwarding. Reputation scores are also shared in the neighborhood to employ indirect observation. Finally, messages generated from misbehaving nodes with lower reputation scores are not forwarded by their neighbors to punish them. Although this scheme provides a basic framework for employing reputation-based incentives, it fails to address the fact that in this kind of network nodes are likely to move away and become unable to overhear the transmission to identify successful forwarding. Consequently, some nodes will be unduly punished even if they provide the service. Uddin et al. [158] addressed this issue and proposed that the destination node can send a delivery report for successful delivery that includes a list of all forwarder nodes. Such reports are flooded in the network to help everyone to assign a ranking (i.e., reputation score) for the forwarder nodes. A further improvement is proposed in Ref. [159], where an intermediate forwarder node sends positive feedback after receiving a message. Nodes also exchange their list of encountered nodes in the past. Finally, this list along with the feedback message is used to identify nodes that had an encounter opportunity but did not forward. A similar scheme is presented by Bigwood and Henderson [160], where nodes exchange their list of encountered nodes. Upon meeting the destination, this allows a sender node to identify a misbehaving forwarder node that did not forward a message.

The above schemes suggest that nodes should monitor their neighbors and maintain a reputation score for them, which requires excessive message passing among neighboring nodes. The amount of message overhead also increases to maintain a consistent score across all nodes. To this end, MobiID [161] suggested a more user-centric approach where nodes maintain their forwarding evidence and demonstrate it when required. In this case, whenever a node forwards a message for another node, it receives a reputation certificate which it later uses as proof of delivery. This allows a node to keep track of its reputation score. Along a similar line, Mei and Stefa [162] suggested that a forwarder node should forward a message to at least two other nodes in the network and keep the proof of delivery. Upon meeting a sender node, a forwarder node should show the proof of delivery or of still having the message in the memory in case it did not have any opportunity to forward. If a forwarder node fails to provide any proof, the sender node reports the issue to a central authority which verifies the incident and punishes the misbehaving node by excluding it from the network. However, the maintenance of such a central authority is an issue with this approach. The simulation results showed that this approach was able to detect 60–90% misbehaving nodes within 10–60 min across different settings.

Another interesting work is presented in Ref. [163], where nodes mostly rely on their individual experience to determine the selfishness of a node rather than reports received from their neighbors. In this case, nodes only consider whether other nodes have forwarded their messages rather than their neighbors' messages. It is argued that a node may behave differently with different nodes due to its underlying social relationship (e.g., more helpful towards a friend than a stranger), and hence personal experience should be given more weight than indirect observation reported by other nodes. This work also considered that a forwarder node might decide not to forward a message due to a low battery and thereby should not be punished for this. However, this method requires the extraction of social relationships from online social network information or frequent encounters among nodes to identify the same, which is unavailable in tourist spots-like scenarios. In addition, the list of past forwards must be exchanged, which is likely to create message overhead in the network. Furthermore, a node might cheat to gain unfair benefits by providing false claims of successful message forwarding, which is not addressed in this work. In contrast, Kaisar et al. [56] proposed a reward-based incentive scheme where the administrator of a group maintains an incentive score for the group members. The score is increased for participating in the successful delivery of contents that is reported by the content receiver. A node with a higher incentive score gets priority processing for getting service (i.e.., receiving contents). However, a malicious node may cheat such a system by not reporting successful delivery, which is not addressed in this work.

Overall, a reputation-based incentive scheme requires direct and indirect observation from participating nodes to be shared in the network to maintain a reputation score. However, without the presence of a central authority, such schemes will result in inconsistent reputation scores for the same node as not everyone receives the same report due to intermittent connectivity. Furthermore, an aggressive punishment scheme will discourage nodes to participate at all in the sharing process. Therefore, a credit-based scheme is proposed in the literature where a central server provides an appropriate incentive to the participants for their service to ensure fairness, which is presented in the next section.

4.3.2. Credit-based

A credit-based incentive scheme employs the notion of virtual currency or credit for rendering the message forwarding service. Forwarder nodes earn some credits for participating in the successful delivery of a message, which is paid by the sender node. A node can also utilize its earned credit to obtain some services in the future. A generic assumption in this approach is that a Trusted Third Party (TTP) is available for credit management. Another issue is different types of cheating attacks by selfish nodes to gain an undue advantage [14].

SMART [164] is a multi-layer credit-based incentive scheme that uses an offline security manager for key distribution and a Virtual Bank (VB) for credit management. It is based on the idea of a layered coin approach where the sender node generates a base layer and forwards the message. The intermediate forwarder nodes generate an endorsed layer using the previous layered coin. Each node periodically submits its collected layered coins to the VB to obtain credit that verifies the submitted coins, calculates the credit for the forwarder nodes, and accordingly charges the sender. The amount of credit is calculated using the size of the message. In this scheme, credit is only given for successful delivery. Lu et al. [165] further extended this and suggested that nodes should also be given some incentive for unsuccessful delivery in the form of reputation, where the reputation score of a node increases if it participates in an attempted but unsuccessful delivery. It is also shown that nodes with a higher reputation are more likely to get help from other nodes. The amount of reward for forwarding a message is calculated based on the distance it is carried by a node.

A similar VB-based credit management scheme is employed by Chen et al. [166]. They proposed two incentive schemes, namely the Earliest Path Singular Rewarding (EPSR) and the Earliest Path Cumulative Rewarding (EPCR). The former gives rewards to the forwarding nodes that participate in the earliest delivery path (i.e., delivery within minimum time), while the latter gives rewards to nodes for their participation in any delivery path. The reward is given considering the time a forwarder carries a message before forwarding again. In contrast, Wang et al. [167] consider that the reward should be inversely proportional to the total hop count in the delivery path. A multi-receiver scenario is considered in this work where multiple nodes are interested in receiving a single message. Nodes try to select a forwarder who is more likely to meet more receivers for benefit maximization. The performance of this approach was also evaluated using MIT reality mining [94] and Haggle [93] dataset where the average size of the content was set to 250 Kb. This approach achieved a delivery success rate of 60–85% across different scenarios. A similar virtual credit-based approach was also used in Refs. [168,169]. Another interesting work by Wu et al. [170] used the idea of an overdraft where nodes with insufficient virtual credit can avail forwarding service from other nodes and return the overdraft when they have sufficient virtual currency. A recent work proposed by Esfandiari et al. [171] used demand-supply-based microeconomic theory to motivate users to participate in the forwarding process. In this case, each source node broadcasts a summary of the message and the budget associated with forwarding it. In response, the neighboring nodes send an acknowledgement message to show their willingness or a negative acknowledgement otherwise. The source node selects an optimal set of nodes to forward its message using the Genetic Algorithm (GA). However, management of virtual currency or dispute resolution is not highlighted in this work.

Ning et al. [172] proposed a Copy Adjustable Incentive Scheme (CAIS) where nodes are divided into communities based on their social relationships. Two types of credit, namely social and non-social credit, are employed in this work. Social credit is obtained for relaying the data of the community members while the other is gained for carrying non-members' data. Similarly, a node can use its earned social credit for intra-community forwarding and the non-social one for inter-community message forwarding. Simulation results indicate that this method outperformed PROPHET [82] in terms of successful delivery ratio, delivery time, and cost when selfish nodes are present in the network. CAIS achieved a 70–85% successful delivery ratio across all reported experiments.

In summary, the credit-based incentive schemes employ a virtual bank or a central server for credit management. Such a virtual bank or central authority is difficult to establish for decentralized sharing as the considered scenario lacks Internet connectivity to maintain an uninterrupted connection. Therefore, reciprocity-based incentive schemes are proposed, which do not require a central authority to provide a management service and consider that nodes show reciprocal behavior and only help those nodes who help them in return. Such reciprocity based incentive schemes are discussed in the following section.

4.3.3. Tit-for-Tat

A Tit-for-Tat (TFT) scheme considers that the amount of service provided to a node should be equal to the service received from that node. In the case of message forwarding, every node forwards as much traffic as the other node has forwarded for it. This is a popular technique in wired networks but difficult to employ in a decentralized setting as there is no central authority to monitor node behavior. Another issue is the bootstrapping and cold start problem as the scheme needs to handle the situation when two nodes meet for the first time.

Shevade et al. [173] proposed a pair-wise TFT scheme for rewarding well-behaved nodes. Instead of keeping track of the misbehaving nodes, this scheme keeps track of the good behaviors of a node that helped in forwarding in the past. In this case, if node u carries some packets for node v, it expects that v will also carry the same amount and otherwise stops cooperation. Initialization is an important issue in this context as nodes need to forward a message first to observe reciprocal behavior. Using generosity in this case, each node initially forwards some packets for the other node and then observes reciprocity, however, the system may run into difficulties when the two nodes provide different services. For example, node u may be a good relay node for v to forward multiple messages to nodes w and x. In addition, node v is not an appropriate relay node for node u and hence can not guarantee the same amount of service. To address this, Krifa et al. [174] proposed a trading based TFT scheme for buying, storing, and trading contents where transitive forwarding behaviors are assessed. For example, a node may also carry content for transactional purposes, in which case the node uses a history of past request patterns and a list of encountered nodes to identify what it needs to carry to maximize utility in future encounters value. A similar transaction-based technique is also proposed in Ref. [31], where encountered nodes initially obtain content reflecting personal interests and use the remaining time to obtain content reflecting the interests of neighbors they expect to encounter in the future. The utility value for carrying a particular content is calculated considering the number of interested nodes expected to be met before the TTL expires. In contrast, Socievole et al. [175] proposed a social relationship based incentive scheme where messages are forwarded based on degree centrality, interest similarity, and social-tie strength, and cooperation is ensured by punishing selfish nodes with a service disruption when their selfishness score exceeds a pre-defined threshold.

Li et al. [176] were the first to address Social Selfishness (SS) suggesting that nodes are more willing to provide service to other nodes with whom they have stronger social ties. In this scheme, nodes consider their social tie with the previous-hop from whom they receive a message or with the sender of a message to determine their willingness to further carry it. The idea of such social selfishness is also employed in Refs. [177–179]. Wei et al. [177] employed social selfishness along with similarity between users' profiles to determine whether to carry a message for another node. In contrast, Yu et al. [178] argued that resources available at a node also dictate the decision of carrying a message as node u might have stronger ties with another node v, but resource scarcity (e.g., low battery or storage space) at u will make it not carry any message. Another interesting work proposed by Liu et al. [180] suggested that a node should consider its social relationship with a community rather than individual members to decide whether to carry a message. The idea is that if a node u helps any members of a community by carrying its messages, all the members of that community will also carry its messages in return. The performance of this approach was analyzed using trace-driven simulation where the message size was varied within 500–1024 KB and the simulation results indicated that a delivery success rate of 80–85% was achieved in different scenarios.

A service priority-based incentive scheme is proposed in Ref. [181] where a Secure Management Authority (SMA) is considered for the allocation of such priority. Nodes can send their service claim to SMA after providing a service to another node. The SMA assigns new priority for the provided service and broadcasts this value to update everyone. The role of SMA is similar to the VB used in a credit-based scheme and hence difficult to establish in a decentralized sharing.

Although the proposed TFT schemes ensure fairness as nodes only get the amount of service they provide to others, they also require repeated encounters. In addition, calculating content utility in a distributed manner is also difficult since the encounter information available at a node may only give a partial view and lead to inaccurate calculation.

4.3.4. Game theory-based

This category of incentive scheme employs game theory [185] to handle selfish nodes, considering them as rational players who try to maximize their profit. Nodes try to select a strategy for gaining personal benefit and hence the proposed mechanism tries to reach Nash equilibrium where no node can unilaterally change its strategy to gain unfair benefits. Most of the game theory-based schemes adopt a credit-based method while a few use reputation-based incentives and Tit-for-Tat.

Li et al. [186] were among the first to employ a game-theoretic model to deal with node selfishness. They considered a principal-agent model where both the sender and the receiver of a message were termed as principals who were interested in exchanging a message through the intermediate relay nodes termed as agents. In the beginning, the sender collects the cost of sending a message from the relay nodes and selects the path with the lowest cost. In this work, a hidden information game is adopted, in which the cost of carrying the message is only known by the agent, and the principal cannot determine whether the agent intentionally discard the message. To facilitate honest responses by agents about costs, the method uses a proof-of-policy payment scheme and achieves a sub-game perfect equilibrium, which states that relay nodes must provide their promised quality of service in order to be rewarded. However, their assumption of static nodes makes this approach ineffective for a dynamic network with node mobility.

Mobicent [187] is another credit-based game-theoretic model that addresses the path selection from a source to destination for downloading content. It used a Trusted Third Party (TTP) for verification and payment, and assumed that helper nodes help mobile clients to download their content and get paid for their service. Initially, a mobile client contacts TTP to determine the cost of the download. After receiving information about available paths, a client decides whether to minimize transmission cost or delay using a path auction game. Finally, the mobile client receives the content in an encrypted format, which can only be decoded after payment by contacting the TTP that provides the key. Mobicent was evaluated using Haggle [93] and DieselNet [188] datasets. The former represents human movement while the latter depicts a vehicular network in an urban scenario. Mobicent achieved 20–80% delivery success rates for a hop-limit of 2–3 and a delivery delay of 100–600 min across both datasets. In contrast, Haq et al. [189] formulated the pricing strategy among two nodes as Rubinstein bargain model and suggested that nodes should decide the pricing and cooperation level based on their remaining energy, social strength, and the value of the message. A recent work proposed by Nazih et al. [183] also used virtual credit for message exchange and formulated a evolutionary bargaining game to motivate users into participation. In this case, sender and receiver bargain in multiple rounds to reach an agreement on the price of the message forwarding. Along a similar line, Wang et al. [184] also used evolutionary game model to encourage participation in opportunistic social network. They suggested that nodes should receive reward for providing service to others while a punishment in the form of negative credit should be applied for non-cooperation, which may result in disruption of service if the credit score decreases below a threshold.

In contrast [190,191], employed a reputation-based and TFT-based scheme, respectively using a game-theoretic model. Wei et al. [190] propose a user-centric scheme where nodes can store their reputation and display it as proof when needed. It uses a Bayesian game approach to design reasonable cost and reward to ensure fairness. Buttyán et al. [191] devised a message exchange scheme among encountering nodes as a non-cooperative game and showed that the overall message delivery rate can be improved if nodes follow Nash equilibrium. In this case, the exchange occurs in a message-by-message manner where node u transfers a message to node v and waits until it gets another message in exchange from v before transferring the next one.

Ning et al. [192] studied the data dissemination issues in DTN and proposed a credit-based incentive scheme using a two-person cooperative game. They employed direct and indirect interest and considered that nodes are willing to pay for content related to their direct interest. Since multiple nodes might be interested in the same content, this scheme calculates the expected reward and utility for carrying a content using past encounter history to determine the number of nodes expected to be met who have interest (both direct and indirect) in this content. When two nodes meet with each other, they try to maximize their utility using the Nash equilibrium. They further extended this idea in Ref. [193] and proposed a technique to encourage node participation for ad dissemination in MSN. This method assumed that an ad provider can issue a virtual check for propagating advertisements which are carried by participating nodes for getting virtual credits. When an intended receiver receives such an ad for the first time, it signs the check, which is cashed by the relay node to earn virtual credits from the ad provider. Such virtual credits can be later used by a node for disseminating its ad. Another extension of this work in Ref. [182] considered that virtual checks can be traded for real credits and used an online auction model to do so.

Social selfishness and game theory-based techniques were employed together in some studies [194,195]. Xia et al. [194] investigated a signaling game approach to study the impact of uncertain cooperation among cooperative and socially selfish nodes. They utilized the Bayesian Nash equilibrium to analyze the initial interaction between encountering nodes and a perfect Bayesian equilibrium to determine their response strategies during subsequent communication. In contrast [195], applied a bargaining game among socially selfish rational nodes to buy the forwarding service of each other using virtual currency. This method also incorporated the idea of reputation and Tit-for-Tat as the buyer with a higher reputation gets some discount for buying a service and nodes were forced to follow a 'give one to get one' policy.

Table 7 highlights some of the key features of the existing incentive schemes. Overall, the incentive schemes available in the existing literature require an authority to monitor node behavior in reputation-based schemes while the credit-based schemes mostly depend on the availability of a trusted third-party server. In contrast, a TFT scheme requires frequent encounters to ensure fairness. Therefore, employing a proper incentive scheme in decentralized sharing remains a challenging issue.

Some of the above-mentioned schemes already employ a misbehavior detection method to protect against users to ensure that they do not get any unfair benefits. Additionally, some approaches specifically address trust management issues in content sharing and they are discussed in the next section.

4.4. Misbehavior detection

In DCS, misbehaving nodes are those who try to gain an unfair advantage from others without actually providing any service in return. In this regard, we use the term 'trust' to indicate the reliability of a node for providing a service or making a claim for providing a service. For example, a trustworthy node is expected to forward a packet when its energy and contact opportunity permits. Again, a trustworthy node will only make an honest claim for the services it provides. In contrast, a misbehaving node will try to cheat the system by intentionally dropping messages or spreading malicious content. Additionally, misbehaving nodes can also make false claims for some services that they are not involved in at all. The purpose of a trust management scheme is to identify such trustworthy and misbehaving nodes. Since there is no centralized authority in DCS, trust management emphasizes detecting misbehaving nodes collaboratively. Existing misbehavior detection schemes are explored below.

Misbehavior detection is mainly performed through a node monitoring or watchdog approach. In this case, nodes usually observe the behavior of their neighboring nodes to determine their trust level and assign a trust score. A misbehaving node is punished by its neighbors and the punishment is usually provided in the form of service disruption or blacklisting.

SReD [196] is an early work for misbehavior detection where each node uses its own experience and information from its neighbors to determine the nature of the surrounding nodes. A node calculates its neighbor's trust score using a local trust value that the node itself calculates, and a local reputation value that is reported by other neighbors. The local trust value is assigned according to the forwarding behavior and cryptographic operation capability. It is assumed that a node can

Table 7
Incentive schemes to encourage participation in DCS.

Method name	Reward type	Punishment strategy	Calculation metric	Technique used
SORI (He et al. [157], 2006)	✖	service disruption	Percentage of forwarded message	neighbor monitoring and indirect observation
SMART (Zhu et al. [164], 2009)	virtual credit	✖	TTL and earliest delivery path	profit sharing
RELICS (Uddin et al. [158], 2010)	message priority	✖	number of forwarded message	delivery report flooding
RADON (Li and Das [159], 2010)	✖	dropping message	increment and decrement of trust score using a constant	direct observation
MobiID (Wei et al. [161], 2011)	✖	blacklisting	number of forwarded message	sharing reputation information
IRONMAN (Bigwood et al. [160], 2011)	cooperation from neighbors	dropping message	increment and decrement of trust score using a constant	neighbor monitoring
MobiTrade (Krifa et al. [174], 2011)	cooperation from neighbors	✖	size of content	content trading
Give2get (Mei and Stefa [162], 2012)	✖	service disruption	proof of delivery user's interest	direct observation and reporting to CA
MuRIS (Wang et al. [167], 2014)	virtual money	✖	hop-count	path information sharing
Com-BIS (Liu et al. [180], 2015)	cooperation from neighbors and members of other communities	✖	available resource	monitoring other nodes
EPSR and EPCR (Chen et al. [166], 2016)	virtual credit	✖	contribution time earliest delivery path	TTP-based monitoring
SIS (Xie and Zhang [181], 2016)	service priority	✖	number of bundles forwarded	SMA based monitoring
CAIS (Ning et al. [172], 2017)	virtual credit to spread multiple copies of a message	✖	number of messages forwarded	self-assessment
Incentive (Ning et al. [182], 2017)	virtual credit and	✖	probability of meeting nodes with particular interest, amount of virtual credit expected, TTL	two-person cooperative game
NISOVCM (Wu et al. [170], 2018)	virtual currency	✖	available energy and cache size, message size and TTL	message trading
SORSI (Socievole et al. [175], 2019)	cooperation from neighbors	dropping message	degree centrality, social-tie strength and interest similarity	direct observation
Fixed reward (Nguyen et al. [168], 2019)	virtual reward	✖	cost of receiving, delivering and carrying message, inter-contact time	bayesian game
OPCCD (Esfandiari et al. [171], 2020)	virtual credit	✖	message size, utility, budget, cost, number of hops, and number of neighbors	Genetic algorithm and economic theory of demand and supply
EBIS (Nazih et al. [183], 2020)	virtual credit	✖	TTL, cost of sending and receiving message, bargaining cost, and utility	Evolutionary bargaining game
Evolutionary game (Wang et al. [184], 2020)	virtual credit	service disruption	connectivity, fitness, satisfaction, reward and punishment factor	Evolutionary game model

observe its neighbors' forwarding behavior in promiscuous mode and determine the fraction of the messages forwarded by that neighbor. The cryptographic operation capability is assessed by checking whether a received cipher text from a neighbor can be correctly decrypted using a symmetric key. Information about a neighbor's trust score is also collected from other neighbors and considered as local reputation value. Finally, these values are used by a node to calculate its neighbors' overall trust score. However, in decentralized sharing, the forwarding operation might be delayed because of intermittent connectivity and it is not always feasible to monitor the forwarding behavior of a neighboring node. Therefore, Li et al. [197] proposed a positive feedback message-based approach to calculate trust. After forwarding a message, each node sends a feedback message to the previous-hop that uses this to monitor forwarding behavior. This approach employs both direct and indirect observation to calculate belief, disbelief, and uncertainty about the forwarding behavior of a node. Simulation results indicated that when 10–40% of malicious nodes were present in the network this method achieved 65–70% delivery success rates while the baseline method without any trust mechanism achieved a 50–55% delivery success rate.

A similar behavior monitoring-based approach is also investigated in Refs. [198–201]. Salehi et al. [198] used the idea of a positive feedback message as in Ref. [197] and further proposed that nodes can periodically broadcast their trust value, which will essentially help other nodes to update their trust score. Simulation results indicated that when 20% of malicious nodes were present in the network, this method achieved a 75% delivery success rate, while the baseline method without any trust management scheme achieved a 50% delivery success rate. Yang et al. also proposed a direct and indirect trust-based approach where opinion of neighbors is considered as indirect trust and used in the calculation of a comprehensive trust score. In this case, the direct score of a node is initially determined using interest similarity, movement pattern similarity and friendship similarity, which is later updated based on feedback received from participants. In addition, Ahmed et al. [200] suggested that nodes can calculate the expected number of messages from their neighbors in a particular period and accordingly classify them as cooperative and selfish nodes based on their actual contribution. In Ref. [201], the authors proposed that while forwarding a message, nodes can add their IDs and sign it with their keys and the destination node can check against this signed list to verify if everyone participated in the forwarding process. The destination node also sends an acknowledgement message, including the list of forwarder nodes, which is used by everyone to update their trust values. In contrast [202], suggests that nodes can keep their record of forwarding behavior and exchange it with other nodes upon encounter. From this record, a node can decide about the selfishness of other nodes. Additionally, this approach also considers that nodes might be unable to forward a message because of low resources, which should not be considered as selfishness. However, a malicious node might cheat the system by generating fake records.

As alluded to before, misbehaving nodes can also make false claims or forge forwarding evidence to indicate their participation. To address such cheating behavior, in Ref. [203] it is assumed that a Trusted Authority (TA) that can verify the forwarding evidence. It considers that the TA can periodically arrive in the network and probabilistically check a subset of forwarding evidence to determine if the forwarders are generating fake evidence or making false claims. Similar TA-based misbehavior detection is also proposed in Ref. [204] where the Sybil attackers (i.e., nodes that change their identities to gain an unfair advantage) are identified. However, such a trusted authority is difficult to establish and maintain in a decentralized setting without an Internet connection.

Waluyo et al. [205] proposed an interesting approach where each node maintains its personalized trust score of another node. They argued that different nodes might be interested in different Quality of Service (QoS) metrics. For example, node u_i might be interested in transmission delay while node u_j is more interested in the quality of received content and hence they will assign different scores for the same forwarding action of node u_k. They considered four QoS, namely (i) transmission delay (T_d) (ii) accuracy of reported resource (A_r), (iii) quality (Q_r), and (iv) maliciousness of received content (M_r) to determine a node's trust. Since each node has its own QoS requirement, the trust value of node v is calculated by other nodes as,

$$Ts_v = \frac{\sum_{j=1}^{J} [T_d A_r Q_r M_r / 4]}{J} \tag{18}$$

where J shows the number of services provided by node v as perceived by other nodes. However, this approach requires a node to contact all of its neighbors before assessing another node's trust score for each transaction, which will introduce significant message overhead in the network. Kaisar et al. [56] proposed a community-based trust management system where the administrator of each group maintains a trust score for the group members. Each member is initialized with a trust score of 0.5, which is updated every time they submit a service claim for delivering/forwarding contents. The trust score increases for an honest claim while a false claim decreases the trust score.

In summary, the above-mentioned approaches use behavior monitoring to identify misbehaving nodes where nodes share their experience with other nodes by flooding the network. Frequent exchange of such messages inherently increase message overhead and cause network congestion, while infrequent exchanges might lead to delayed detection. In addition, an attacker node might propagate false recommendations to gain an unfair advantage.

4.5. Content replication and cooperative caching

Content replication and cooperative caching strategies are adopted to enhance the content delivery service by increasing content availability and reducing delivery latency. The basic idea is to identify potential requests and proactively push matching contents near the prospective requesters. Existing strategies can be broadly categorized into (i) community independent strategies and (ii) community-based strategies. The community-independent replication strategy does not consider the existence of the community, but the node decides whether to replicate the content according to the interests of individuals and neighbors. In contrast, community-based strategies consider the existence of communities among participating nodes and and propose a replication strategy to help community members receive requested content. Both of these are discussed in the next section.

4.5.1. Community independent strategies

Nodes are considered as individual entities and they replicate contents based on their observed request patterns or that of their neighbors, performing replication to reduce overall content access latency and improve content availability.

PodNet [206] is one of the first community independent replication strategies that suggest that nodes should divide the available buffer space into private and public space. The private buffer space is used for storing contents of personal interest, while the public buffer space is utilized for replicating contents that might be of interest to future encountering nodes. Once contacted, nodes first exchange content that reflects their interest, then use the remaining time to copy the content in the common buffer space. To determine the contents to be replicated in the public buffer space, four solicitation strategies are proposed, namely (i) most solicited, (ii) least solicited, (iii) uniform, and (iv) inverse proportional. The first strategy replicates the most popular contents while the second one selects the least popular ones to increase diversity. The popularity of contents is calculated considering the past request patterns observed by a node. In uniform solicitation, nodes randomly select content using uniform distribution while the fourth strategy suggests that the solicitation probability should be inversely proportional to content popularity. Ma et al. [207] further extended this work by considering meeting probability with the potential requesters along with their personal preference. They considered that movement patterns of participating nodes are non-random in nature and used meeting probability. In addition, nodes broadcast their request summaries and personal preferences towards a particular content. Finally, the replication is performed jointly considering the probability of meeting a potential requester, content popularity (calculated from the request summary), and personal preference. An extended version of this work is presented in Ref. [208] where a pair-wise solicitation strategy is considered, suggesting that encountering nodes can jointly determine the optimal strategy for replicating content. Simulation results indicate that the Cooperative Cache-based Content Delivery Framework (CCCDF) proposed in Ref. [208] outperformed the method proposed in Ref. [207] in terms of successful content deliveries and delays. CCCDF could successfully deliver 75–95% contents for a cache size of 6–8 contents per node in across various simulation scenarios while [207] achieved 60–85% successful delivery for the same.

Xuyuan et al. [209] proposed a caching policy where nodes calculate their cooperation willingness value in terms of available storage and local message generation rate, and exchange this value with their neighbors upon encounter. Finally, nodes with higher cooperation willingness value cache the content of the other node. Gao et al. [36,210] proposed a scheme for a Mobile Ad-hoc Network (MANET) where contents are replicated in multiple central locations called Network Central Locations (NCL), which are selected based on a probabilistic metric that evaluates data transmission delay in delay tolerant networks. In this case, the central location simply reflects the ease of access to other nodes, and does not represent a way of centralized replication, but rather the choice of such multiple locations to place the replicated content. Whenever a node generates some content, it replicates the content in the nearest NCL. If the buffer space at the NCL is full, then another node closer to the NCL in terms of hop-distance is selected as the temporary cache node. For content access, requests are forwarded to NCL, who delivers the content to the requester. Although this scheme ensures that the requester can easily access the NCL to upload and download content, it also indicates that when multiple nodes request content at the same time, the NCL will be congested. This method was evaluated using user movement patterns obtained from MIT reality trace [94] and the simulation results showed that this method achieved a 200% performance improvement in terms of delivery success rate and delay when compared to a method without any caching.

Zhao et al. [211] argued that the encounter duration among nodes is usually short to replicate the whole content, and hence they proposed a packet-level replication strategy where content can be divided into multiple packets and a node can selectively replicate a sub-set of such packets. The benefits of replicating content are determined by its popularity, current availability, and the likelihood of delivering it to other nodes. Popularity is calculated as the ratio of the number of pending requests to the total number of pending requests observed for the content. Nodes share their list of available content to calculate current availability, and use historical contact rates between nodes to determine delivery probability.

Moualla et al. [212] proposed another interesting strategy where a node proactively pushes contents to its neighbors' cache. The potential contents are identified using their popularity, which is calculated using the number of copies available in the network. A higher number indicates higher popularity. The potential candidates for pushing the replicated content are identified using social proximity where a user with the same contents is considered more similar and given higher preference. In contrast [213], suggested that the access points can proactively push popular content in a user's device to reduce delivery latency. However, their simplified assumption of nodes with identical mobility, cache capacity, and request pattern is unrealistic. Wang et al. [214] further improved this and proposed a mobility aware content replication strategy where a node replicates content from a nearby edge-network device (e.g., access point) considering the gain achieved by carrying it. The gain is calculated using the social popularity of a content and mobility pattern of the node. This method considers that contents have varying popularity in different regions. Therefore, social popularity is calculated using this variation and the influence of the user who generated or shared this content. In addition, this method also uses past visiting patterns to determine the probability of visiting a particular region. Simulations results indicated that this method achieved 2–4 times performance improvement when compared with two baseline methods based on mobility and popularity. However, this approach deployed a coordinate server for gain calculation, which is difficult to establish in real-time decentralized sharing without an Internet connection.

A few other works have also used content popularity to identify the contents to be replicated [215, 217]. Ioannidis et al. [215] proposed a voting mechanism-based policy where each user independently determines the utility value of caching content and reports this to its encountered node. The utility value is calculated using the number of pending requests observed for content and the reports received from other nodes. Upon meeting an access point, a node replicates the contents with higher utility. Similar to this approach, Chen et al. [217] proposed that encountering nodes should replicate contents based on their priority value calculated in terms of the number of requests received and the size of the content. They also considered meeting frequency among nodes and available resources (buffer space) for replication. Simulation results showed that this method achieved around 80% hit rate (i.e., percentage of successfully resolved queries) and outperformed CacheDTN [210] across various request rates.

Recently, Li et al. [221] proposed a content caching strategy for edge computing scenario suggesting that the joint optimization problem of content caching at small base stations (SBS) and allocation of the users to those base stations is an NP-hard problem. To address this, the authors proposed a smart content caching policy based on the observed content request pattern aiming to reduce the content download latency. A dynamic user allocation policy was also proposed in Ref. [221]. Another interesting work by Xia et al. [222] suggested that mobile devices can offload their computational tasks to edge cloud servers to effectively manage their energy consumption, which can be also utilized for cache management.

In summary, most of the proposed strategies use observed content request patterns or content popularity as the main criteria for replication. Although content popularity is an important indicator, other issues, such as a user's interest or preference for accessing contents, need proper consideration for accurate request estimation. In addition, the proposed approaches do not consider community membership among nodes, which is important in decentralized settings as nodes are more likely to form communities based on their mutual interest and eventually will only help fellow community members by replicating content for them. Such community-based replication strategies are explored in the next section.

4.5.2. *Community-based strategies*

ContentPlace [29] is a prominent community-based content replication strategy that suggests that a node may belong to several communities (e.g., working or family community). Each node visits such communities frequently, which can be used to determine the probability of visiting a particular community. The utility value of content varies in different communities and should be calculated considering the visiting sequence of a node. In addition, the utility value of content also depends on its access probability, availability, and size. A node uses its interest to calculate local access probability. A binary value is used to show the access probability as 0 or 1. Whenever two nodes encounter, they first exchange their content list and local access probability values. Afterward, they update the utility value of all the contents in their combined content list. If any node identifies that the other has some contents with higher utility than its currently owned contents, it replicates those contents. Considering the visiting sequence of a node, this method investigated five different strategies, namely (i) most frequently visited, (ii) most likely next, (iii) future, (iv) present, (v) uniform social. The first strategy gives more weight to contents that are popular in the frequently visited community while the second one considers the contents likely to be consumed in the community the node is expected to visit next. Similarly, the third one ignores the contribution of the present community in the utility calculation while the fourth strategy only considers content consumption in the current community. Finally, the last strategy assigns an equal weight for all communities.

Zhuo et al. [216] proposed a community-based replication policy which suggests that the contents should be replicated at nodes with higher centrality. The centrality value of a node was calculated using its inter-meeting time with other nodes of the same community. A node with higher encounter rates was assigned a higher centrality value. They proposed that when a node with lower centrality meets a node with higher centrality, it should replicate contents in that node. However, they did not suggest which contents should be replicated or how many replicas should be created. Along a similar line, Cabaniss and Madira [223] suggested that a node's ranking in a group depends on its encounter frequency with other nodes and their request patterns. If a node u meets other nodes frequently who generate a greater number of requests, u should be assigned a higher rank. Nodes with a higher rank are considered as the social repository or throwbox and carry contents for all group members. When a repository node meets another node with a higher rank, it transfers the whole repository (i.e., all contents). The performance of this method was evaluated using trace-based simulation and the results indicated that using a single throwbox increased the delivery success rate up to 80%. GCC [224] is another community-based strategy

Table 8
Replication or caching strategies in DCS.

Method name	Community structure	Cache selection	Content selection	Cache replacement
Podnet (Lenders et al. [206], 2008)	✖	everyone caches	popularity	not mentioned
ContentPlace (Boldrini et al. [29], 2008)	visiting sequence and frequency	Each node decides based on its own utility calculation	access probability, size and availability	not mentioned
CCCDF (Ma et al. [208], 2010)	✖	pairwise decision using node mobility and interest	popularity, preference and delivery probability	not mentioned
PSEPHOS (Ioannidis et al. [215], 2010)	✖	each user decides based on personal preference, resource availability, and mobility	observed request patterns	personal preference and request frequency of neighbors
DAC (Zhuo et al. [216], 2011)	k-clique based on contact rate	based on centrality metric	not addressed	using a greedy algorithm
NCL (Gao et al. [36], 2014)	✖	multiple central locations based on data transmission delay	all contents	utility-based method using content popularity
OFRR (Chen and Shen [217], 2015)	✖	each node selects one of its neighbors to replicate based on meeting probability	popularity and size	priority calculated from nodes meeting probabilities
DARA (Zhao et al. [211], 2016)	✖	each node decides distributedly whether to become a cache	popularity, delivery probability and availability	using replication benefit
Propagation and mobility (Wang et al. [214], 2017)	✖	a subset of users based on social influence and mobility	popularity	not mentioned
CWAC (Xuyuan et al. [209], 2018)	✖	pairwise decision using cooperation willingness calculated using available storage space and message generation rate	all contents	using cooperation willingness value of creator
DCDS (Kaisar et al. [218], 2019)	mutual interest	utility based on demand coverage and medium access contention	demand and supply of content	not mentioned
MobileCopy (Yan et al. [219], 2019)	meeting probability based	community head selects a subset of members based on meeting ability	popularity	not mentioned
SACC (Wu et al. [220], 2020)	interest similarity -based	pairwise decision based on social tie strength, trustworthiness and encounter probability	popularity	popularity-based replacement

that maintains a single replica of a content considering the recency of the request. Whenever a node u receives content for another node v as a response to v's previous request, node u checks whether any other community members have already replicated it and keeps this copy otherwise. Another interesting work by Yan et al. [219] proposed a data loss resistant replication policy. They suggested that random replica placement may result in complete data loss if correlated node failure occurs and the set of replica holder fails. They used file popularity to calculate the number of replicas, and the replica holders are selected in a way so that their presence is limited within a single community and they are well spread within the network.

Wu et al. [220] proposed a social-aware strategy where contents are replicated based on their popularity at nodes with higher sharing abilities calculated in terms of social tie strength, encounter probability, and trustworthiness. Kaisar et al. [218, 241] proposed a community-based demand-and-supply aware economic model for proactive content distribution. In this approach, the administrator determines the demand and supply for each content available among members and accordingly replicates the ones with higher demand and shorter supply. The demand calculation uses user-interest, content popularity, and event-specific content access into account while the supply considers resource availability and connectivity of content holders. Finally, the distribution is done using estimation of future demand coverage and medium access contention. However, this method did not address cache management, i.e., how to replace items in buffers.

Overall, the community-based strategies usually require frequent meetings to develop communities and a dedicated administrator to handle replications, which may collapse because of single node failure. Such administrator nodes may also get exhausted to handle a high number of requests and/or provide storage facilities. Table 8 highlights some key features of existing content replication policies.

4.6. *Implementation and developed applications*

The evolution of wireless communication technology, such as Bluetooth and Wi-Fi, and the introduction of Wi-Fi direct technology have

Table 9
Developed applications for decentralized content sharing.

Apps name	Platform	Wireless connectivity	Operation	Evaluation
Peer2Me (Wang et al. [225], 2007)	J2ME	Bluetooth	Message exchange and file sharing	✖
Tourist MSN (Arnaboldi et al. [226], 2011)	Android	Wi-Fi ad-hoc	Information sharing	✖
WiFi-Opp (Trifunovic et al. [227], 2011)	Android	Wi-Fi Tethering	Not mentioned	✖
E-SmallTalker (Champion et al. [228], 2013)	JAVA ME	Bluetooth	Message exchange	Testbed with six devices
Android P2P (Shahin et al. [229], 2014)	Android	Wi-Fi Direct	Group messaging	Testbed with four devices
AllChat (Wang et al. [230], 2014)	Alljoyn (supports Android, Os/X and windows)	Bluetooth and Wi-Fi Direct	Message exchange and file sharing	✖
DirectSpace (Park et al. [231], 2014)	Android	Wi-Fi Direct	Group messaging and resource sharing	✖
Haggle (Nordstrom et al. [232], 2014)	C\C++ (supports Android, iOS and Windows	Bluetooth and	Photo sharing	User study with 10 users
iTrust (Lombera et al. [233], 2014)	Android	Wi-Fi Direct	Information sharing	Testbed with three devices
Oppline (Turkes et al. [234], 2016)	Android	Wi-Fi hotspot and Wi-Fi infrastructure	Message exchange	Testbed with 20 devices
SMART Campus (Kadadha et al. [235], 2016)	Android	Wi-Fi Direct	File sharing	Testbed with four devices
TeamPhone (Lu et al. [236], 2017)	Android	Wi-Fi ad-hoc	Message exchange	Testbed with four devices
SMART Group (Casetti et al. [237], 2017)	Android	Wi-Fi Direct	Content exchange	Testbed with four devices
Opptain (Ippisch et al. [238], 2018)	Android	Wi-Fi infrastructure	Message and file sharing	Real world experiment with 26 users
Floater (Bonvin et al. [239], 2019)	Android	Google Nearby API	Message and image sharing	✖
SURAKSHIT (Paul et al. [240], 2019)	Android	Wi-Fi Adhoc	text and multimedia message sharing	user study with 4 participants

leveraged the implementation and development of proof-of-concept for DCS applications. Table 9 highlights the mobile applications developed for various platforms and their key attributes.

Peer2ME [225] is one of the earlier apps, which is implemented on the J2ME platform and facilitates file sharing and message exchange through Bluetooth communication. The introduction of the Android operating system and smart mobile devices with Wi-Fi technology have further aided the development of sample applications. Arnaboldi et al. [226] developed a context-aware middleware platform called CAMEO for opportunistic mobile social networks and implemented an Android application on top of this for tourists to share content using Wi-Fi ad-hoc communication technology. In contrast, Trifunovic et al. [227] argued that using Wi-Fi in tethering mode to connect to nearby devices is energy efficient than connection via Wi-Fi ad-hoc mode. They developed the Wi-Fi-Opp as a proof-concept application on Google Nexus One phone running Android 2.3.4. Their simulation results demonstrated that the use of Wi-Fi tethering is 10 times energy efficient compared to Wi-Fi Ad-hoc communication. However, a testbed evaluation of the actual application is not presented in Ref. [227]. To this end, E-SmallTalker [228] application was developed using the JAVA ME platform and had a testbed evaluation with six devices. Bluetooth was used for communication and nearby devices were discovered within 10–20 s. The successful device discovery rate ranged from 80 to 100% with varying numbers of devices. The reported power consumption showed that a 60-s peer discovery interval resulted in a battery life of 29 h, which is encouraging for future development. However, the range of Bluetooth communication is quite low (i.e., around 10 m) and hence nodes need to be present within a shorter distance for successful communication.

The introduction of Wi-Fi direct technology on the Android platform has played a major role in the development of content sharing applications. Wi-Fi direct allows single-hop communication and able to achieve a data rate of 250 Mbps. Several applications have been developed on Android using this Wi-Fi direct technology, such as Android P2P [229], AllChat [230], DirectSpace [231], SMART Campus [235], and SMART Group [237]. The functionalities of these apps include file sharing, group messaging, and information exchange. Most of them are evaluated using a testbed scenario with three to four devices. In contrast, Turkes et al. [234] used Wi-Fi hotspot and Wi-Fi infrastructure mode for communication in their Oppline application and performed a testbed evaluation with 20 smartphones. They varied the interval for message generation and measured the ratio of successful delivery and latency. For a message generation interval of 240 s, their method achieved nearly 80% successful delivery with an average delay of 180 s. Ippisch et al. [238] developed the opptain application on the android platform to evaluate the performance of opportunistic networks in real-life settings. They conducted a user study with 26 participants for 5 h and concluded that 60.85% of contents were successfully delivered with an average delay of 23 min. Their results are encouraging but limited to a small user population.

Lu et al. have developed TeamPhone [236] for providing communication facilities during natural disasters. They used Wi-Fi in Ad-hoc mode for connecting devices which allowed them to achieve multi-hop communication. Along a similar line, SURAKSHIT [240] was developed on the Android platform to enable message and file exchange during crisis management after a disaster. Bonvin et al. [239] developed the Floater application using Google nearby service for enabling communication in post-disaster situations. Please note that similar applications can also be used for enabling communication in battlefield scenarios. The above-mentioned applications are primarily developed using the android platform and hence does not work on iOS, and Windows phones. In this

Table 10
Optimization techniques used in DCS.

Optimization Technique	Technique used for
Artificial bee colony	message forwarding [242]
Barter game	discourage selfish behavior [191]
Bayesian game	strategic message delivery [168]
Dynamic programming	content caching [36]
Evolutionary Game	negotiate credit amount [183] and stimulating cooperation [184]
External optimization	community partition [50]
Expectation-maximization algorithm	model parameter estimation [134]
Greedy algorithm	message forwarding [116] and adaptive route selection [33]
Genetic algorithm	content distribution [171]
Hill climbing	message forwarding [136]
Integer linear programming	message forwarding [97]
Kalmn filter	congestion prediction [106]
Knapsack algorithm	forwarding service allocation [180] and content caching [29]
Lagrangian multiplier	buffer allocation [243]
Multi-objective control	message forwarding [126]
Non-linear optimization solver	message forwarding [79]
Perfect Bayesian Equilibrium (PBE)	response strategy selection [194]
Rubinstein bargain model	content price calculation [189]
Simulated annealing	message forwarding [244]
Subgame Perfect Equilibrium (SPE)	maximize social utility [195]
Two-person cooperative Game	nodal message communication [193, 172]
Vickrey-Clarke-Groves (VCG) auction	induce truthfulness [186] and relay selection [245]
Weighted sum method	utility maximization [95]

regard, Haggle [232] is a notable project which is implemented using C/C++ language and capable of running on different platforms, such as Android, iOS, and Windows-based mobile devices. This application was tested in a real-life environment with 10 users carrying the phones for 6 h. Simulation results obtained from this experiment reported a successful delivery ratio of 43%, where 60% of the highly relevant contents were delivered within 3 h. The authors reported an Android bug that reduced the battery life up to 6 h and recommended fixing the bug to improve battery life beyond 16 h.

Although a few proof-of-concept applications have been developed to measure the performance of content sharing applications, a large scale real-life study is yet to be performed in this field to obtain better insight. The evolution of new communication technologies, such as LTE direct and mobile devices with higher battery capacity will help further development of DCS applications.

4.7. Optimization techniques used in DCS

Researchers have used various optimization techniques to address different issues, such as group formation, message forwarding, incentive, misbehavior detection, and content replication in DCS. Several works used mathematical optimization and simulation-based performance evaluation while a few highlighted different techniques listed in Table 10. Game-theory-based models have been very popular for dealing with incentive issues.

4.8. Delivering live-streaming contents in MANET

Delivery of live-streaming contents in resource-constrained MANET is significantly challenging as the devices are mobile, there are intermittent connections, and there is no reliable end-to-end path to ensure the required QoS. Xing et al. [246] considered a scenario where family members or friends within vicinity can simultaneously watch videos and conducted an early study to compare the performance of Wi-Fi Ad-hoc and infrastructure modes. Their results suggested that Wi-Fi Ad-hoc mode produced better performance. Such collaborative streaming applications in home networks were also studied in Refs. [247,248]. Tang et al. [40] considered live video streaming over multi-hop wireless networks and suggested that the pre-selection of traditional wireless routing protocols (e.g., Ad-hoc On-demand Distance Vector (AODV) and Optimized Link State Routing (OLSR)) may lead to poor performance due do the dynamic nature of wireless link. The performance can be improved by incorporating Reinforcement Learning-based Opportunistic Routing (RLOR) techniques, which uses dynamic calculation of Expected Any path Delay (EAD) metric. Although these studies provided some insights of sharing live-streaming contents, they only considered static nodes in their scenarios which limits their applications.

To address mobility issues, Fleury et al. [39] considered a dynamic scenario with moving nodes and highlgihted the challenges related to video streaming over MANET. They suggested that the use of video encoding techniques, such as Multiple Description Coding (MDC) or Scalable Video Coding (SVC) technique with multi-path delivery makes it feasible to stream the videos on such networks. They also reported that the video quality and Quality of Experience (QoE) depend on the speed and density of nodes. In contrast, Lochin et al. [249] highlighted the challenges of using streaming services in DTN and suggested that the use of on-the-fly coding scheme can produce a reliable service.

Mohideern et al. [250] proposed the use of Multi-State Video Coding (MSVC) technique and zone routing-based multi-path propagation methods to improve the delivery latency and packet overhead in MANET-based video streaming applications. However, the considered all nodes to have the same speed in their performance evaluation, an assumption that often does not hold in practice. In contrast, Thakur et al. [251] presented a software platform and developed a mobile application to enable video streaming over opportunistic networks. However, the developed applications used computers to process the video at the source and destination ends. They further extended this work in Ref. [252] to enable the application to run entirely on android platform. Overall, most of the works focused on employing video coding techniques in conjunction with multi-copy delivery techniques to achieve better performance. The use of machine learning techniques to predict user movement and its incorporation in the delivery path selection should be further investigated in this regard. Readers may also refer to a recent articles highlighting resource allocation issues for video streaming in vehicular networks [253].

The content-sharing approaches presented in this paper in the previous sections are based on Mobile Ad-hoc NETworks (MANETs). Additionally, in recent times research has focused on the emerging aerial networks, such as Flying Ad-hoc NETworks (FANETs) and Internet of Drones (IoD), and a few approaches have been proposed for sharing contents and data using their communication architecture. The following section presents an overview of such emerging approaches.

5. Data sharing in emerging aerial networks

The rapid advancement in telecommunication and sensor technology has enabled the development and deployment of Unmanned Aerial Vehicles (UAVs), which are capable of monitoring and surveilling large areas and becoming increasingly popular in different scenarios including wildfire monitoring, military applications, and search and rescue operations [254,255]. FANET and IoD are examples of such aerial networks. Fig. 9 shows a schematic representation of the data sharing scenario in aerial networks. In this case, the UAVs communicate with each other for sharing data, which is ultimately transmitted to a ground station for further processing. The packet forwarding, routing, and scheduling techniques employed in FANET and IoD are different than those of MANETs as the formers suffer from more frequent disconnection, network partition, and dynamic network topology [255]. Therefore, the techniques proposed in the literature for data sharing in aerial networks are separately highlighted below in this section.

Rosati et al. [256] proposed a predictive OLSR (P-OLSR) algorithm to facilitate communication among UAVs. Their work was based on the conventional Optimized Link State Routing (OLSR) protocol where nodes maintain a list of their neighbors and select the next forwarding hop based on their connectivity degree. However, the work considered the relative speed of nodes in the calculation of their Expected Transmission count (ETX) metric to select the best path. A few other works also used different variations of the OLSR algorithm to determine the best route [257–259]. A Link-quality and Traffic load Aware OSLR (LTA-OLSR) protocol is proposed in Ref. [257], where the link qualities among neighboring nodes and the congestion within the network are used to select the best path. In addition, Xie [258] proposed that the link expiration time and residual energy of nodes should be used for selecting the next relay node. In contrast, Dong [259] suggested that the link layer congestion should be considered along with residual energy of nodes and the link connection time to select the next node.

The above-mentioned approaches consider that each node maintains path information to other nodes in a routing table and keeps updating it whenever there is a change within the network. In contrast, a reactive routing protocol is proposed by Gankhuyag et al. in Ref. [260]. They modified the standard Ad-hoc On-demand Distance Vector (AODV) routing protocol based on the characteristics of FANET and proposed a Robust And Reliable Predictive routing (RARP) strategy. RARP considers both directional and omnidirectional transmission along with dynamic angle adjustment for improving performance. It also considers that UAVs are equipped with GPS to obtain and exchange more accurate three-dimensional position information. Along a similar line, Usman et al. [261] suggested improvement of network lifetime by selecting an appropriate forwarder node and utilizing their position information. They introduced the concept of forwarding zone, which is calculated using the current position of the candidate relay nodes and their forwarding angle with the destination node. The forwarder node is selected based on the remaining energy of the candidate nodes and their forwarding angle.

Although the reactive approaches can determine the path to destination on-demand, they often suffer from longer delays in establishing this path. To address this issue, Li et al. [262] proposed Link Stability Estimation-based Preemptive Routing (LEPR) protocol where multiple paths are recorded during the route discovery phase, and a route maintenance mechanism is proactively initiated to handle probable link failure or disconnection. This process enables LEPR to minimize the number of broken connections and reduce delivery latency. However, other matrices, such as delay, remaining energy, the number of hops from source to destination, and node mobility are not considered in this work. To address these issues, a few strategies [263–265] are proposed in the literature.

Oubbati et al. [263] proposed energy-efficient connectivity-aware data delivery (ECaD) protocol for FANETs where nodes participate in the route discovery process based on their remaining energy and multiple routing paths are established during the discovery phase for a destination node. The protocol also considers connectivity expiration time and delivery delay while selecting a path. In addition, Kumar et al. [264] proposed a modified version of the well-known Location-Aided Routing (LAR) protocol where an optimal route between UAVs for information dissemination is selected based on the residual energy of the forwarder, movement direction of nodes, and their distance. In contrast, Lee et al. [265] proposed a fuzzy logic-based routing protocol suggesting that the broadcast of route discovery messages within a network may lead to a broadcast storm problem. To address this and reduce the number of control messages they suggest nodes should only rebroadcast a message if their personal score is higher than a threshold calculated using their movement direction, residual energy, link quality, and node stability. The protocol also uses a fuzzy-logic-based route selection method where parameters, such as delay, hop count and fitness are used. The simulation results suggest that their approach outperforms LEPR and ECaD approaches in terms of energy consumption, end-to-end delay, packet delivery rate, and route stability. However, the above-mentioned works assume the existence of an end-to-end path from source to destination for packet delivery. Due to high node mobility in FANETs, this might not always hold true as the network may be partitioned into separate parts and an end-to-end path may not exist. To address this issue, Pu and Carpenter [266] proposed a hybrid routing protocol where an end-to-end path is selected using node speed and movement direction when this information is available, otherwise a DTN-based forwarding scheme is used. In the latter case, the source node forwards the data packet to a ferry node moving towards the ground destination. If no such ferry nodes are available, the source node itself moves to the ground station to deliver data packets.

In [267], Pu proposed an interesting packet forwarding algorithm for FANET where a forwarder node is selected stochastically from a set of candidate nodes. In this case, when a sender needs to forward a data packet, it considers various network metrics to assign a weight called forwarding probability to each candidate node. Afterward, the sender node generates a random number and compares it with the forwarding probability of a candidate node. If the random number is lower than the forwarding probability, that candidate node is selected as the forwarder. Otherwise, another random number is generated and another candidate node is considered. An extension of this work is employed in a real-life testbed with two DJI Mavic 2 Pro drones to evaluate the performance of this approach [268]. Another recent work by Pu and Carpenter [269] proposed a priority-based service scheduling scheme for the IoD networks. They suggest that, due to dynamic network environments, drones have limited communication bandwidth to transmit/receive data from the Zone Service Providers (ZSP). In this case, a scheduling scheme can be employed to prioritize services based on different parameters, e.g., request deadline, data size, and data popularity.

A few works have also proposed bio-inspired routing strategies for FANET. Emulating ant colony behavior, Rango et al. [270] proposed a routing strategy to find an optimal route from source to destination by jointly considering the path length and load balancing parameters. Along a similar line, Khan et al. [271] also used the ant colony optimization technique to select the best path. Additionally, they considered energy consumption to improve network lifetime and quality of service parameters. Bhardwaj et al. [272] proposed a cluster-based routing protocol for FANETs. They used a Chaotic Algae Algorithm (CAA) for selecting the clusters, and the cluster heads are selected using a dragonfly algorithm. In this case, the cluster heads are responsible for intra-cluster and inter-cluster communication.

Recently, Q-learning-based routing protocols are also employed in FANETs. Liu et al. [273] proposed a Q-learning-based multi-objective optimization routing protocol for FANETs to select a path that concomitantly aims to lower delay and energy consumption for forwarding a packet. However, the protocol requires re-evaluating the neighborhood relationship for selecting a path rather than depending on historical information. Along a similar line, Da Costa et al. [274] also proposed a

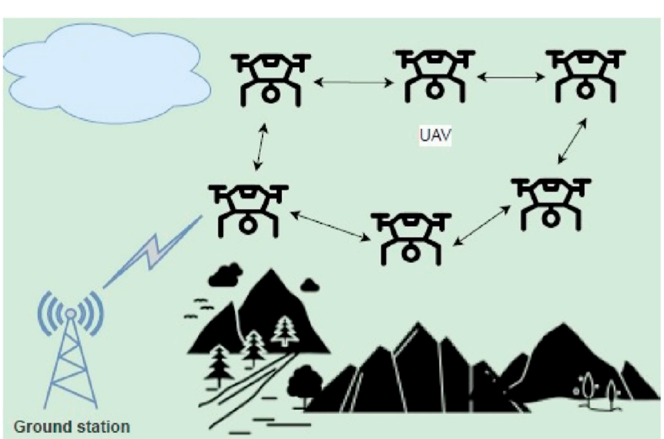

Fig. 9. Data sharing using emerging aerial networks.

Q-learning-based routing protocol to reduce the delay in FANETs suggesting that consideration of only the immediate past episode may lead to imprecise decisions, rather a finite number of past episodes and their relative weights leads to a more accurate routing decision for dynamic networking scenarios like FANET and IoD. They also considered channel conditions while selecting the optimal path.

In summary, the routing, packet forwarding, and scheduling approaches in emerging networks should consider different QoS and QoE requirements to manage data sharing tasks. Some applications require higher bandwidth while others focus on delivery delay. It will be interesting to see the development of a hybrid approach where the routing protocols can dynamically change and adapt their strategy based on the requirements of the underlying applications.

6. Future research issues

The decentralized content sharing approach is evolving as a promising alternative for delivering content. This section presents several open research challenges in this area that need to be addressed in future and provides some guidelines to addresses those challenges.

- *Group management:* The current group formation techniques primarily focus on the individual user for identifying their interests and movement patterns. Although similar interest and movement patterns are important for forming groups, important aspects, such as content availability, probability of successful delivery, and observed delays are often overlooked in this regard. It will be interesting to see the impact of these metrics on group management. In addition, sometimes a large group of users (i.e., herd) such as classmates, co-workers, or friends can move together and may engage in group activities. Although individuals might not be interested in a particular topic/content yet, since they are co-located with other members of the same herd they might be subject to word-of-mouth propagation, and become interested in that particular content. Such herding behavior can be further utilized in interest calculation and lead to forming groups. In this case, some new issues need to be investigated that can exploit a user's affinity towards such herding activity, the probability of engaging in such activity during the current session, and how such engagements may impact the overall interest of the user. In addition, the behavior of a user might change based on the relationship with other members of the herd. For example, a user might become easily interested in a topic while staying with friends but may be reluctant to do so while accompanied by co-workers. Investigating such herding behavior and how those can be used in the DCS mechanism is worth investigating.

Again, users' interest can also vary with time. For example, friends attending university together might be interested in educational materials while visiting university campus, however, they might be more interested in entertainment or sports related contents while meeting outside the campus at different times. Investigating such time varying user interest is likely to produce interesting result for interest extraction and group formation.

- *Multi-channel communication:* The surveyed literature indicates that the current content sharing applications use a single channel for communication. Allocating non-overlapping channels for adjacent groups is expected to improve the performance. However, channel assignment in IEEE 802.11 is an NP-hard problem and a complex task [275]. One way to address this would be through group administrators who can mutually communicate to assign a channel based on its utility for the respective group in terms of contents' demand, request frequency, and their size. For channel allocations, factors such as the channel interference, dynamic distribution of contents considering channel utility and group members' mobility need to be considered.
- *Message forwarding:* Though message forwarding issues have been widely investigated for DCS, existing methods are ineffectual in tourist spots like scenarios where people demonstrate spontaneous movements and mostly meet strangers. Although a few works (e.g., Ref. [138]) have addressed this issue, further research is needed devising efficient message forwarding approach to obtain a better result for the practical adoption of content sharing system. Identifying potential movement of tourists including the places they are likely to visit and the sequence of such visits will certainly help to select an appropriate forwarder for successful message delivery. However, predicting such instantaneous movement patterns is a complex and challenging task. Another important aspect which has been often overlooked in existing literature is the available energy and remaining buffer space of a relay node. Although smart mobile devices nowadays offer substantial storage space and adequate battery capacity, the increased size of the shared content can still pose challenges. New message forwarding approaches must consider factors like content size, available buffer space and remaining energy in selecting a forwarder node.
- *Fair incentive schemes:* The incentive schemes presented in Section 4.3 require the presence of a trusted third-party server or a virtual bank or repetitive meetings to ensure fairness. However, the availability of such servers/banks can not be guaranteed in DCS application scenarios. In addition, participants should also be given some reward for unsuccessful deliveries to ensure fairness as they use their resources though the attempt ends in failure. In addition, this might increase the fraudulent behavior as a deceiver node might intentionally drop a message and claim a reward for this. It will be challenging to verify such claims due to intermittent connectivity and the absence of any static impartial trusted entity. In this regard, further investigation is required to implement a suitable approach.
- *Traditional security implications:* A major concern of DCS is the security implication as a malicious node can easily spread a virus or harmful contents in response to a content request. One way to encounter this cyber-threat is to run the received content in a sandbox environment first to check for any malicious activity. Contents can be stored in local memory only if they are found safe. Another approach can be once a misbehaving node is detected, its signal can be jammed using a technique where a node(s), acting a friendly jammer(s), will send jamming signal to only block the misbehaving node without hampering other legitimate communication [276]. Although a few key-based encryption techniques are proposed in the literature [277–280], they are difficult to implement without any central authority to manage and distribute digital certificates and keys. In addition, key-based encryption techniques consume significant amount of resources. Therefore, developing a lightweight but suitable encryption and authentication technique for DCS remains a challenging research issue.
- *Joint trust management of the content, nodes and communication channels:* In DCS, contents are shared among neighbors and exchanged through the free radio (ISM) band of the wireless communications system (e.g., Bluetooth, Wi-Fi). For such dynamic and infrastructure-less communication systems, any node can join the group any time and start requesting or delivering the requested content instantly. The complexity and dynamicity of the deployment environment of a decentralized content distribution system and computationally expensive encryption technique limits the adoption of encryption-based strong security mechanisms to protect content, communication channels, and participating nodes including administrative nodes (group leaders) from cyberattacks or misbehaving nodes. Moreover, key management becomes a challenging issue as if any nodes and communication channels are breached, keys are compromised and thus the application of encryption techniques becomes ineffective. Note, ISM band and nodes are exposed to cyberattacks. Besides, misbehaving or compromised nodes can change the content as well. Such severe security threats and limited efficacy of encryption-based

security mechanism for the distributed content sharing demands the estimation of the overall trust level of the distribution system on the fly i.e., the joint trustworthy measure of content, communication channels and participating nodes. The trust estimation for content (e.g., numeric data [281], image [282]), nodes [56], data and nodes [283], and communication and data [284] has already been investigated. However, joint trust estimation of content, nodes and communication channels are yet to be introduced.

- *Performance evaluation:* Existing literature mostly used a network simulator for evaluating the performance of the proposed methods. Although simulation tools provide a faster way to obtain a better understanding and can accommodate a larger number and variation of devices, results obtained from real-world implementations are more valid for the practical adoption of a system. In addition, there has been no standard dataset or real-world traces to demonstrate the content sharing behavior of participating users. Researchers have primarily used a variety of statistical distributions to simulate content request patterns. In this regard, the collection and adoption of a standard dataset will certainly provide a better way to compare competing methods. In addition, large scale real-world user study of DCS applications will encourage future research in this domain and provide a better understanding of relevant issues and practical challenges.
- *The role of 5G/6G technologies in shaping the future:* We believe that the 5G/6G technology will have a significant impact on DCS approaches. 5G/6G technologies possess increased coverage (about 100% 6G coverage in all places across the world envisaged) and low latency. They have key technologies like millimeter-wave and terahertz frequencies, small cell, and software-defined networks [285]. These enhanced capabilities and key technologies will accelerate the use of centralized and hybrid content sharing, especially in remote areas where currently limited or no coverage is available. This rising usage trend will reduce the gap between infrastructure-based and decentralized content sharing approaches. 5G/6G enabled DCS with AI-assisted mobility prediction and resource allocation will be better equipped for live-streaming of contents. Additionally, further advancement of wireless technologies like Wi-Fi and Bluetooth technologies [286] will drive DCS further. Besides, increased IoT and edge devices and their improved computation and communication capability will make more mobile relay stations available and thus will increase the connectivity and adoption of decentralized content sharing. It will be interesting to see how approaches developed for one platform can be deployed in others, although a hybrid sharing approach is likely to produce the best outcome.
- *Improving data sharing techniques for emerging networks:* Although existing literature has shed some light on data sharing in emerging networks, such as FANETs and IoDs, a few issues require further investigation. The proposed sharing strategies mostly assumed availability of end-to-end connections and paths from source to destination. However, in a dynamic network with moving drones, network partition is likely to occur in different scenarios especially due to high-speed node mobility, weather conditions, or mountain areas. Although a handful of approaches proposed DTN-type routing strategies to address this, further research is needed to provide a more adaptive solution. Most approaches used simulation for performance evaluation. Although an appropriate simulation can provide us with insights into practical implementation, a real-world testbed evaluation will lead to better insight for practical adoption. Current works used mobility models proposed for traditional MANET to replicate node movement in their simulation. However, a customized 3-D mobility model considering the unique characteristics of FANETs/IoDs is required to emulate real node movement in aerial topology. Research should also address how data exchange can be scheduled when multiple drones with competing priorities and limited resources initiate contact with the ground station.

7. Conclusion

Decentralized content sharing approaches have attracted significant attention of researchers in recent times due to convenience that mobile-based applications and services offer nowadays. DCS approaches do not require an Internet connection or support from a centralized server to deliver contents, and hence they have the potential for a wide scale adoption among users if issues such as, timely delivery of relevant contents, resource scarcity, user privacy and security, and participation incentives are properly addressed. This survey paper presented a comprehensive review of existing literature on DCS approaches, its architecture, major components, comparative analyses and major unresolved issues. Although DCS provides a fault-tolerant and scalable solution, its performance is also impacted by the dynamic nature of the underlying network and selfish behavior of participants. Several existing works have addressed these issues and highlighted some potential solutions. These approaches and their contributions were compared and contrasted in this paper. Our analysis revealed that the predictability of user movement patterns has received most attentions, while issues such as appropriate buffer/cache space management, available energy of participating devices, and functionality enhancement of the sharing apps in tourist spot like scenarios have received less attentions, and thus require further investigation. Although the emergence of smart devices with greater memory and battery power is likely to solve some of their resource constraint issues, the potential increase in the content size due to the quality of the shared contents (e.g., 4 K/8 K) videos) and the emerging topology like aerial networks still present many challenges for the adoption of these approaches. Many researchers have used a proof-of-concept application to support their claims and evaluated their performance, which are also summarized in this paper. However, a large-scale real-life user study with an intelligent application, and the experience of the users learned from such a study will be invaluable in this research area. Finally, the paper is concluded with potential research directions for future studies.

References

[1] S. Gaonkar, J. Li, R.R. Choudhury, L. Cox, A. Schmidt, Micro-blog: sharing and querying content through mobile phones and social participation, in: Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services, ACM, 2008, pp. 174–186.
[2] A. Gupta, A. Kalra, D. Boston, C. Borcea, Mobisoc: a middleware for mobile social computing applications, Springer Mob. Netw. Appl. 14 (1) (2009) 35–52.
[3] L. McNamara, C. Mascolo, L. Capra, Media sharing based on colocation prediction in urban transport, in: Proceedings of the 14th ACM International Conference on Mobile Computing and Networking, ACM, 2008, pp. 58–69.
[4] F. Li, J. Wu, Mops: providing content-based service in disruption-tolerant networks, in: Proceedings of the 29th IEEE International Conference on Distributed Computing Systems, IEEE, 2009, pp. 526–533.
[5] E. Talipov, Y. Chon, H. Cha, Content sharing over smartphone-based delay-tolerant networks, IEEE Trans. Mobile Comput. 12 (3) (2013) 581–595.
[6] G. Rizzo, N.P. Palma, M.A. Marsan, V. Mancuso, Storage capacity of opportunistic information dissemination systems, IEEE Trans. Mobile Comput. 21 (10) (2021) 3773–3788.
[7] M. Papadopouli, H. Schulzrinne, Effects of power conservation, wireless coverage and cooperation on data dissemination among mobile devices, in: Proceedings of the 2nd ACM International Symposium on Mobile Ad Hoc Networking & Computing, ACM, 2001, pp. 117–127.
[8] M. Taghizadeh, K. Micinski, S. Biswas, C. Ofria, E. Torng, Distributed cooperative caching in social wireless networks, IEEE Trans. Mobile Comput. 12 (6) (2013) 1037–1053.
[9] S. Kaisar, Emergency response and post-disaster recovery using smartphone-based applications, in: IGI Global Digital Services in Crisis, Disaster, and Emergency Situations, RMIT University, 2021, pp. 31–49.
[10] N. Vastardis, K. Yang, Mobile social networks: architectures, social properties, and key research challenges, IEEE Commun. Surv. Tutorials. 15 (3) (2013) 1355–1371.
[11] B. Jedari, F. Xia, A survey on routing and data dissemination in opportunistic mobile social networks, IEEE Commun. Surv. Tutorials, (2013) 1–25.
[12] Y. Cao, Z. Sun, Routing in delay/disruption tolerant networks: a taxonomy, survey and challenges, IEEE Commun. Surv. Tutorials, 15 (2) (2013) 654–677.
[13] Y. Wang, A.V. Vasilakos, Q. Jin, J. Ma, Survey on mobile social networking in proximity (msnp): approaches, challenges and architecture, Springer Wireless Netw. 20 (6) (2014) 1295–1311.
[14] F. Xia, L. Liu, J. Li, J. Ma, A.V. Vasilakos, Socially aware networking: a survey, IEEE Syst. J. 9 (3) (2015) 904–921.

[15] M. Girolami, S. Chessa, A. Caruso, On Service Discovery in Mobile Social Networks: Survey and Perspectives, vol. 88, Elsevier Computer Networks, 2015, pp. 51–71.
[16] Y. Wu, Y. Zhao, M. Riguidel, G. Wang, P. Yi, Security and trust management in opportunistic networks: a survey, Wiley Online Lib. Secur. Commun. Netw. 8 (9) (2015) 1812–1827.
[17] C. Sobin, V. Raychoudhury, G. Marfia, A. Singla, A survey of routing and data dissemination in delay tolerant networks, Elsevier J. Netw. Comput. Appl. 67 (2016) 128–146.
[18] X. Liu, Z. Li, P. Yang, Y. Dong, Information-centric Mobile Ad Hoc Networks and Content Routing: a Survey, vol. 58, Elsevier Ad Hoc Networks, 2017, pp. 255–268.
[19] Y. Zhao, W. Song, Survey on social-aware data dissemination over mobile wireless networks, IEEE Access 5 (2017) 6049–6059.
[20] M.A. Ferrag, L. Maglaras, A. Ahmim, Privacy-preserving schemes for ad hoc social networks: a survey, IEEE Commun. Surv. Tutorials. 19 (4) (2017) 3015–3045.
[21] Y. Wang, L. Wei, A.V. Vasilakos, Q. Jin, Device-to-device based mobile social networking in proximity (msnp) on smartphones: framework, challenges and prototype, Elsevier Future Generat. Comput. Syst. 74 (2017) 241–253.
[22] M. Alajeely, R. Doss, A. Ahmad, Routing protocols in opportunistic networks–a survey, Taylor & Francis IETE Tech. Rev. 35 (4) (2018) 369–387.
[23] B. Jedari, F. Xia, Z. Ning, A survey on human-centric communications in non-cooperative wireless relay networks, IEEE Commun. Surv. Tutorials. 20 (2) (2018) 914–944.
[24] A. Roy, T. Acharya, S. DasBit, Quality of Service in Delay Tolerant Networks: A Survey, vol. 130, Elsevier Computer Networks, 2018, pp. 121–133.
[25] R. Akhtar, Y. Shengua, Z. Zhiyu, Z.A. Khan, I. Memon, S. Ur Rehman, S. Awan, Content distribution and protocol design issue for mobile social networks: a survey, Springer J. Wirel. Commun. Netw. 2019 (1) (2019) 128.
[26] N. Raghav, A. Bhola, D. Kumar Sharma, Survey paper on data routing techniques based on social relationship in opportunistic networks, Int. J. Inform. Syst. Manag. Sci. 2 (1) (2019) 226–232.
[27] V. Kuppusamy, U.M. Thanthrige, A. Udugama, A. Förster, Evaluating forwarding protocols in opportunistic networks: trends, advances, challenges and best practices, MDPI Future Internet 11 (5) (2019) 113.
[28] E. Yoneki, P. Hui, S. Chan, J. Crowcroft, A socio-aware overlay for publish/subscribe communication in delay tolerant networks, in: Proceedings of the 10th ACM Symposium on Modeling, Analysis, and Simulation of Wireless and Mobile Systems, ACM, 2007, pp. 225–234.
[29] C. Boldrini, M. Conti, A. Passarella, Contentplace: social-aware data dissemination in opp. networks, in: Proceedings of the 11th International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, ACM, 2008, pp. 203–210.
[30] H. Jafarpour, S. Mehrotra, N. Venkatasubramanian, A fast and robust content-based publish/subscribe architecture, in: Proceedings of the Seventh IEEE International Symposium on Network Computing and Applications, IEEE, 2008, pp. 52–59.
[31] H. Zhou, J. Chen, J. Fan, Y. Du, S. Das, Consub: incentive-based content subscribing in selfish opportunistic mobile networks, IEEE J. Sel. Area. Commun. 31 (9) (2013) 669–679.
[32] R. Lubke, D. Schuster, A. Schill, Mobilisgroups: location-based group formation in mobile social networks, in: Proceedings of the IEEE International Conference on Pervasive Computing and Communications Workshops, IEEE, 2011, pp. 502–507.
[33] J. Fan, J. Chen, Y. Du, W. Gao, J. Wu, Y. Sun, Geocommunity-based broadcasting for data dissemination in mobile social networks, IEEE Trans. Parallel Distr. Syst. 24 (4) (2013) 734–743.
[34] Z. Wang, X. Zhou, D. Zhang, Z. Yu, D. Zhang, Socker: enhancing face-to-face social interaction based on community creation in opportunistic mobile social networks, Springer Wireless Pers. Commun. 78 (1) (2014) 755–783.
[35] C. Lindemann, O.P. Waldhorst, A distributed search service for peer-to-peer file sharing in mobile applications, in: IEE Peer-To-Peer Computing, 2002, pp. 73–80.
[36] W. Gao, G. Cao, A. Iyengar, M. Srivatsa, Cooperative caching for efficient data access in disruption tolerant networks, IEEE Trans. Mobile Comput. 13 (3) (2014) 611–625.
[37] K. Chen, S. Member, H. Shen, S. Member, H. Zhang, Leveraging social networks for p2p content-based file sharing in disconnected manets, IEEE Trans. Mobile Comput. 13 (2) (2014) 235–249.
[38] S. Kaisar, J. Kamruzzaman, G. Karmakar, I. Gondal, Content sharing among visitors with irregular movement patterns in visiting hotspots, in: Proceedings of the 14th International Symposium on Network Computing and Applications, IEEE, 2015, pp. 230–234.
[39] M. Fleury, D. Kanellopoulos, N.N. Qadri, Video streaming over manets: an overview of techniques, Springer Multimed. Tool. Appl. 78 (16) (2019) 23749–23782.
[40] K. Tang, C. Li, H. Xiong, J. Zou, P. Frossard, Reinforcement learning-based opportunistic routing for live video streaming over multi-hop wireless networks, in: Proceedings of the 19th International Workshop on Multimedia Signal Processing (MMSP), IEEE, 2017, pp. 1–6.
[41] E.G. Boix, A.L. Carreton, C. Scholliers, T. Van Cutsem, W. De Meuter, T. D'Hondt, Flocks: enabling dynamic group interactions in mobile social networking applications, in: Proceedings of the 2011 ACM Symposium on Applied Computing, ACM, 2011, pp. 425–432.
[42] D. Zhang, Z. Wang, B. Guo, X. Zhou, V. Raychoudhury, A dynamic community creation mechanism in opportunistic mobile social networks, in: Proceedings of the Third International Conference on Privacy, Security, Risk and Trust and 2011 IEEE Third International Conference on Social Computing, IEEE, 2011, pp. 509–514.
[43] R. Johari, N. Gupta, S. Aneja, Cacbr: context aware community based routing for intermittently connected network, in: Proceedings of the 10th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, sensor, & ubiquitous networks, ACM, 2013, pp. 137–140.
[44] C.A. da Costa, D. Zaupa, J.L.V. Barbosa, R. da Rosa Righi, J. de Camargo, N. Daroit, A.C. Yamin, A spontaneous social network based on mobile devices, Springer Soc. Netw. Anal. Min. 4 (1) (2014) 158.
[45] J. Fan, J. Chen, Y. Du, W. Gao, J. Wu, Y. Sun, Geocommunity-based broadcasting for data dissemination in mobile social networks, IEEE Trans. Parallel Distr. Syst. 24 (4) (2013) 734–743.
[46] Z. Li, C. Wang, S. Yang, C. Jiang, X. Li, Lass: local-activity and social-similarity based data forwarding in mobile social networks, IEEE Trans. Parallel Distr. Syst. 26 (1) (2014) 734–743.
[47] M. Xiao, J. Wu, L. Huang, Community-aware opportunistic routing in mobile social networks, IEEE Trans. Comput. 63 (7) (2014) 1682–1695.
[48] M. Ruan, H. Zhou, D. Li, X. Liu, Q. Deng, Detection of temporal communities in mobile social networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2020, pp. 1021–1026.
[49] P. Hui, E. Yoneki, S.Y. Chan, J. Crowcroft, Distributed community detection in delay tolerant networks, in: Proceedings of 2nd ACM/IEEE International Workshop on Mobility in the Evolving Internet Architecture, ACM, 2007, pp. 1–8.
[50] S. Haoran, W. Muqing, C. Yanan, A community-based opportunistic routing protocol in delay tolerant networks, in: Proceedings of the 4th International Conference on Computer and Communications (ICCC), IEEE, 2018, pp. 296–300.
[51] J. Wu, Z. Chen, M. Zhao, Weight distribution and community reconstitution based on communities communications in social opportunistic networks, Springer Peer-to-Peer Netw. Appl. 12 (1) (2019) 158–166.
[52] V. Juyal, R. Saggar, N. Pandey, An optimized trusted-cluster–based routing in disruption-tolerant network using experiential learning model, Wiley Online Lib. Int. J. Commun. Syst. 33 (1) (2020) 1–15.
[53] S. Jain, N. Chauhan, P. Choudhari, Adaptive approximate community detection algorithm for bubble rap routing protocol, in: Advances in Communication and Computational Technology, Springer, 2020, pp. 865–878.
[54] E.M. Daly, M. Haahr, Social network analysis for routing in disconnected delay-tolerant manets, in: Proceedings of the 8th ACM International Symposium on Mobile Ad Hoc Networking and Computing, ACM, 2007, pp. 32–40.
[55] M. Xiao, J. Wu, L. Huang, Community-aware opportunistic routing in mobile social networks, IEEE Trans. Comput. 63 (7) (2014) 1682–1695.
[56] S. Kaisar, J. Kamruzzaman, G. Karmakar, I. Gondal, Decentralized content sharing among tourists in visiting hotspots, Elsevier J. Netw. Comput. Appl. 79 (2017) 25–40.
[57] Z. Tian, N. Samaan, A novel approach for modeling and managing spontaneous social communities over manets, Springer Soc. Netw. Anal. Min. 3 (3) (2013) 685–700.
[58] D. Li, Q. Lv, X. Xie, L. Shang, H. Xia, T. Lu, N. Gu, Interest-based Real-Time Content Recommendation in Online Social Communities, vol. 28, Elsevier Knowledge-Based Systems, 2012, pp. 1–12.
[59] D. Palsetia, M.M.A. Patwary, K. Zhang, K. Lee, C. Moran, Y. Xie, D. Honbo, A. Agrawal, W.-k. Liao, A. Choudhary, User-interest based community extraction in social networks, in: Proceedings of the 18th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, ACM, 2012, pp. 1–5.
[60] H. Wirtz, J. Rüth, T. Zimmermann, K. Wehrle, Interest-based cloud-facilitated opportunistic networking, in: Proceedings of the 8th ACM MobiCom Workshop on Challenged Networks, ACM, 2013, pp. 63–68.
[61] K. Thilakarathna, A.C. Viana, A. Seneviratne, H. Petander, Mobile social networking through friend-to-friend opportunistic content dissemination, in: Proceedings of the Fourteenth ACM International Symposium on Mobile Ad Hoc Networking and Computing, ACM, 2013, pp. 263–266.
[62] A. Iamnitchi, M. Ripeanu, E. Santos-Neto, I. Foster, The small world of file sharing, IEEE Trans. Parallel Distr. Syst. 22 (7) (2011) 1120–1134.
[63] R.-I. Ciobanu, R.-C. Marin, C. Dobre, V. Cristea, Interest-awareness in Data Dissemination for Opportunistic Networks, vol. 25, Elsevier Ad Hoc Networks, 2015, pp. 330–345.
[64] S. Kaisar, J. Kamruzzaman, G. Karmakar, I. Gondal, Content exchange among mobile tourists using users' interest and place-centric activities, in: Proceedings of the 10th International Conference on Information, Communications and Signal Processing (ICICS), IEEE, 2015, pp. 1–5.
[65] T. Small, Z.J. Haas, Resource and performance tradeoffs in delay-tolerant wireless networks, in: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, ACM, 2005, pp. 260–267.
[66] K. Fall, A delay-tolerant network architecture for challenged internets, in: Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications, ACM, 2003, pp. 27–34.
[67] A. Vahdat, D. Becker, EPidemic Routing for Partially Connected Ad Hoc Networks, Technical Report CS-200006, Duke University.2000.
[68] Y.-C. Tseng, S.-Y. Ni, Y.-S. Chen, J.-P. Sheu, The broadcast storm problem in a mobile ad hoc network, Springer Wireless Netw. 8 (2/3) (2002) 153–167.
[69] N.B. Chang, M. Liu, Controlled flooding search in a large network, IEEE/ACM Trans. Netw. 15 (2) (2007) 436–449.
[70] M. Pitkanen, T. Karkkainen, J. Greifenberg, J. Ott, Searching for content in mobile dtns, in: Proceedings of the 2009 International Conference on Pervasive Computing and Communications, IEEE, 2009, pp. 1–10.
[71] M. Vojnović, A. Proutiere, Hop limited flooding over dynamic networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2011, pp. 685–693.

[72] Y. Lu, W. Wang, L. Chen, Z. Zhang, A. Huang, Distance-based energy-efficient opportunistic broadcast forwarding in mobile delay-tolerant networks, IEEE Trans. Veh. Technol. 65 (7) (2016) 5512–5524.
[73] L. Chancay-García, E. Hernández-Orallo, P. Manzoni, A.M. Vegni, V. Loscri, J.C. Cano, C.T. Calafate, Optimising Message Broadcasting in Opportunistic Networks, Elsevier Computer Communications, 2020, pp. 162–178.
[74] T. Spyropoulos, K. Psounis, C.S. Raghavendra, Spray and wait: an efficient routing scheme for intermittently connected mobile networks, in: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, ACM, 2005, pp. 252–259.
[75] T. Spyropoulos, K. Psounis, C.S. Raghavendra, Spray and focus: efficient mobility-assisted routing for heterogeneous and correlated mobility, in: Proceedings of the Fifth Annual IEEE International Conference on Pervasive Computing and Communications Workshops, IEEE, 2007, pp. 79–85.
[76] L. Wu, S. Cao, Y. Chen, J. Cui, Y. Chang, An Adaptive Multiple Spray-And-Wait Routing Algorithm Based on Social Circles in Delay Tolerant Networks, vol. 189, Elsevier Computer Networks, 2021 107901.
[77] M. Grossglauser, D. Tse, Mobility increases the capacity of ad-hoc wireless networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2001, pp. 1360–1369.
[78] J. Niu, D. Wang, M. Atiquzzaman, Copy limited flooding over opportunistic networks, Elsevier J. Netw. Comput. Appl. 58 (2015) 94–107.
[79] J. Wu, Y. Zhu, L. Liu, B. Yu, J. Pan, Energy-efficient routing in multi-community dtn with social selfishness considerations, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2016, pp. 1–7.
[80] X. Li, J. Teng, B. Zhang, A.C. Champion, D. Xuan, Turfcast: a service for controlling information dissemination in wireless networks, IEEE Trans. Mobile Comput. 13 (2) (2014) 250–262.
[81] H. Dubois-Ferriere, M. Grossglauser, M. Vetterli, Efficient route discovery in mobile ad hoc networks using encounter ages, in: Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking & Computing, ACM, 2003, pp. 1–3.
[82] A. Lindgren, A. Doria, O. Schelen, Probabilistic Routing in Intermittently Connected Networks, Springer Service assurance with partial and intermittent resources, 2004, pp. 239–254.
[83] B.B. Bista, D.B. Rawat, Ea-prophet: an energy aware prophet-based routing protocol for delay tolerant networks, in: Proceedings of the 31st International Conference on Advanced Information Networking and Applications (AINA), IEEE, 2017, pp. 670–677.
[84] B.B. Bista, D.B. Rawat, Enhancement of prophet routing in delay tolerant networks from an energy prospective, in: Proceedings of the IEEE Region 10 Conference (TENCON), IEEE, 2016, pp. 1579–1582.
[85] H. Jiaxin, X. Chunxiu, W. Yuewei, Resource-efficient routing protocol based on historical encounter time interval in dtn, in: Proceedings of the 2nd IEEE International Conference on Computer and Communications (ICCC), IEEE, 2016, pp. 2026–2031.
[86] Q. Ayub, S. Rashid, Energy Efficient Inactive Node Detection Based Routing Protocol for Delay Tolerant Network, Springer Wireless Personal Communications, 2021, pp. 227–248.
[87] M.Y. Mir, C.-L. Hu, Exploiting mobile contact patterns for message forwarding in mobile opportunistic networks, in: Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), IEEE, 2020, pp. 1–7.
[88] J. Burgess, B. Gallagher, D. Jensen, B.N. Levine, et al., Maxprop: routing for vehicle-based disruption-tolerant networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2006, pp. 1–11.
[89] T. Spyropoulos, K. Psounis, C.S. Raghavendra, Efficient routing in intermittently connected mobile networks: the single-copy case, IEEE/ACM Trans. Netw. 16 (1) (2008) 63–76.
[90] F. Li, J. Wu, Localcom: a community-based epidemic forwarding scheme in disruption-tolerant networks, in: Proceedings of the 6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, IEEE, 2009, pp. 1–9.
[91] W. Gao, G. Cao, User-centric data dissemination in disruption tolerant networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2011, pp. 3119–3127.
[92] R. Zhao, L. Zhang, X. Wang, C. Ai, F. Hao, Y. Lin, L. Shi, A novel energy-efficient probabilistic routing method for mobile opportunistic networks, Springer J. Wirel. Commun. Netw. 2018 (1) (2018) 1–15.
[93] P. Hui, A. Chaintreau, J. Scott, R. Gass, J. Crowcroft, C. Diot, Pocket switched networks and human mobility in conference environments, in: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, ACM, 2005, pp. 244–251.
[94] N. Eagle, A.S. Pentland, Reality mining: sensing complex social systems, Springer Pers. ubiquitous comput. 10 (4) (2006) 255–268.
[95] M. Musolesi, C. Mascolo, Car: context-aware adaptive routing for delay-tolerant mobile networks, IEEE Trans. Mobile Comput. 8 (2) (2009) 246–260.
[96] W. Gao, G. Cao, T. La Porta, J. Han, On exploiting transient social contact patterns for data forwarding in delay-tolerant networks, IEEE Trans. Mobile Comput. 12 (1) (2013) 151–165.
[97] T. Abdelkader, K. Naik, A. Nayak, N. Goel, V. Srivastava, Sgbr, A routing protocol for delay tolerant networks using social grouping, IEEE Trans. Parallel Distr. Syst. 24 (12) (2013) 2472–2481.
[98] S.-H. Kim, Y. Jeong, S.-J. Han, Use of Contact Duration for Message Forwarding in Intermittently Connected Mobile Networks, vol. 64, Elsevier Computer Networks, 2014, pp. 38–54.
[99] N.N. Gondaliya, D. Kathiriya, M. Shah, Contact frequency and contact duration based relay selection approach inside the local community in social delay tolerant network, in: Proceedings of 3rd International Conference on Advanced Computing, Networking and Informatics, Springer, 2016, pp. 609–617.
[100] H. Zhang, L. Wan, Y. Chen, L.T. Yang, L. Peng, Adaptive message routing and replication in mobile opportunistic networks for connected communities, ACM Trans. Internet Technol. 18 (1) (2017) 2.
[101] B. Ravaei, M. Sabaei, H. Pedram, S. Valaee, Community-aware single-copy content forwarding in mobile social network, Springer Wirel. Netw. 24 (7) (2018) 2705–2721.
[102] D.K. Lobiyal, et al., Location based contact time energy efficient routing (lctee) approach for delay tolerant networks, Springer Wireless Pers. Commun. 108 (4) (2019) 2639–2662.
[103] T. Le, M. Gerla, Fragmented data routing based on exponentially distributed contacts and inter-contact times in dtns, Comput. Network. 164 (2019) 106917.
[104] A. Alhasanat, M. Alhasanat, S. Althunibat, K. Matrouk, A probabilistic home-based routing scheme for delay tolerant networks, Springer Wirel. Netw. 25 (7) (2019) 4037–4048.
[105] T. Spyropoulos, K. Psounis, C.S. Raghavendra, Efficient routing in intermittently connected mobile networks: the multiple-copy case, IEEE/ACM Trans. Netw. 16 (1) (2008) 77–90.
[106] G. Goudar, S. Batabyal, Optimizing bulk transfer size and scheduling for efficient buffer management in mobile opportunistic networks, IEEE Trans. Mobile Comput. (2021) 1–16.
[107] E.M. Daly, M. Haahr, Social network analysis for information flow in disconnected delay-tolerant manets, IEEE Trans. Mobile Comput. 8 (5) (2009) 606–621.
[108] A. Mtibaa, M. May, C. Diot, M. Ammar, Peoplerank: social opportunistic forwarding, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2010, pp. 1–5.
[109] S. Brin, L. Page, Reprint of: the anatomy of a large-scale hypertextual web search engine, Elsevier Comput. Netw. 56 (18) (2012) 3825–3833.
[110] P. Hui, J. Crowcroft, How small labels create big improvements, in: Proceedings of the Fifth Annual IEEE International Conference on Pervasive Computing and Communications Workshops, IEEE, 2007, pp. 65–70.
[111] P. Hui, J. Crowcroft, E. Yoneki, Bubble rap: social-based forwarding in delay-tolerant networks, IEEETrans. Mob. Comput. 10 (11) (2011) 1576–1589.
[112] R. Zhao, X. Wang, L. Zhang, Y. Lin, A social-aware probabilistic routing approach for mobile opportunistic social networks, Wiley Online Libr. Trans. Emerg. Telecommun. Technol. 28 (12) (2017) 1–19.
[113] P. Yuan, Z. Yang, Y. Li, Q. Zhang, An interest-driven routing algorithm in disruption-tolerant networking based social networks, in: Proceedings of the IEEE/CIC International Conference on Communications in China, IEEE, 2017, pp. 1–6.
[114] A.B. Paul, G. Akhil, S. Biswas, S. Nandi, N. Sett, Sas: seasonality aware social-based forwarder selection in delay tolerant networks, in: Proceedings of the International Conference on Innovations for Community Services, Springer, 2020, pp. 245–265.
[115] F. Xia, L. Liu, J. Li, A.M. Ahmed, L.T. Yang, J. Ma, Beeinfo: interest-based forwarding using artificial bee colony for socially aware networking, IEEE Trans. Veh. Technol. 64 (3) (2015) 1188–1200.
[116] K. Jahanbakhsh, G.C. Shoja, V. King, Social-greedy: a socially-based greedy routing algorithm for delay tolerant networks, in: Proceedings of the Second International Workshop on Mobile Opportunistic Networking, ACM, 2010, pp. 159–162.
[117] J. Wu, Y. Wang, Hypercube-based multipath social feature routing in human contact networks, IEEE Trans. Comput. 63 (2) (2014) 383–396.
[118] F. Xu, N. Xiao, M. Deng, Y. Xie, Z. Xiong, Q. Xu, Efficient Opportunistic Routing with Social Context Awareness for Distributed Mobile Social Networks, Wiley Online Library Concurrency and Computation: Practice and Experience, 2019, pp. 1–10.
[119] S. Yu, L. Zhang, P. Li, L. Li, B. Yan, Z. Cai, EFficient Interest-Aware Data Dissemination in Mobile Opportunistic Networks, Wiley Online Library Software: Practice and Experience.
[120] A. Mei, G. Morabito, P. Santi, J. Stefa, Social-aware stateless routingin pocket switched networks, IEEE Trans. Parallel Distr. Syst. 26 (1) (2015) 252–261.
[121] K. Jang, J. Lee, S.-K. Kim, J.-H. Yoon, S.-B. Yang, An adaptive routing algorithm considering position and social similarities in an opportunistic network, Springer Wirel. Netw. 22 (5) (2016) 1537–1551.
[122] G. Yu, Z. Chen, J. Wu, J. Wu, Predicted Encounter Probability Based on Dynamic Programming Proposed Probability Algorithm in Opportunistic Social Network, vol. 181, Elsevier Computer Networks, 2020, pp. 1–12.
[123] P. Yuan, H. Ma, H. Fu, Hotspot-entropy Based Data Forwarding in Opportunistic Social Networks, vol. 16, Elsevier Pervasive and Mobile Computing, 2015, pp. 136–154.
[124] J. Zhang, H. Huang, C. Yang, J. Liu, Y. Fan, G. Yang, Destination-aware Metric Based Social Routing for Mobile Opportunistic Networks, Springer Wireless Networks, 2019, pp. 1–12.
[125] I. Rhee, M. Shin, S. Hong, K. Lee, S.J. Kim, S. Chong, On the levy-walk nature of human mobility, IEEE/ACM Trans. Netw. 19 (3) (2011) 630–643.
[126] B. Burns, O. Brock, B.N. Levine, Mv routing and capacity building in disruption tolerant networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2005, pp. 398–408.
[127] J. Leguay, T. Friedman, V. Conan, Dtn routing in a mobility pattern space, in: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, ACM, 2005, pp. 276–283.
[128] H.-Y. Huang, P.-E. Luo, M. Li, D. Li, X. Li, W. Shu, M.-Y. Wu, Performance evaluation of suvnet with real-time traffic data, IEEE Trans. Veh. Technol. 56 (6) (2007) 3381–3396.

[129] X. Li, W. Shu, M. Li, H. Huang, M.-Y. Wu, Dtn routing in vehicular sensor networks, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2008, pp. 1–5.
[130] J. Zhu, J. Cao, M. Liu, Y. Zheng, H. Gong, G. Chen, A mobility prediction-based adaptive data gathering protocol for delay tolerant mobile sensor network, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2008, pp. 1–5.
[131] S.K. Dhurandher, D.K. Sharma, I. Woungang, A. Saini, Efficient routing based on past information to predict the future location for message passing in infrastructure-less opportunistic networks, Springer J. Supercomput. 71 (5) (2015) 1694–1711.
[132] P. Jaiswal, A. Sinha, Stable geographic forwarding with link lifetime prediction in mobile adhoc networks for battlefield environment, Springer Human-centric Comput. inform. Sci. 6 (1) (2016) 1–22.
[133] X. Wang, X. Wang, L. Zhang, Y. Lin, R. Zhao, A routing algorithm based on the prediction of node meeting location in opportunistic networks, in: Proceedings of the China Conference on Wireless Sensor Networks, Springer, 2017, pp. 285–295.
[134] P. Zou, M. Zhao, J. Wu, L. Wang, Routing algorithm based on trajectory prediction in opportunistic networks, MDPI Inform. 10 (2) (2019) 1–15.
[135] Q. Yuan, I. Cardei, J. Wu, Predict and relay: an efficient routing in disruption-tolerant networks, in: Proceedings of the Tenth ACM International Symposium on Mobile Ad Hoc Networking and Computing, ACM, 2009, pp. 95–104.
[136] A.B. Link, D. Schmitz, K. Wehrle, Geodtn: geographic routing in disruption tolerant networks, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2011, pp. 1–5.
[137] F. Ekman, A. Keränen, J. Karvo, J. Ott, Working day movement model, in: Proceedings of the 1st ACM SIGMOBILE Workshop on Mobility Models, ACM, 2008, pp. 33–40.
[138] S. Kaisar, J. Kamruzzaman, G. Karmakar, I. Gondal, Carry me if you can: a utility based forwarding scheme for content sharing in tourist destinations, in: Proceedings of the 22nd Asia-Pacific Conference on Communications (APCC), IEEE, 2016, pp. 261–267.
[139] Y. Xie, K. Pan, J. Shen, H. Yang, Cooperative willingness perception based routing algorithm in opportunistic network, in: Proceedings of the 5th International Conference on Advanced Materials and Computer Science, Atlantis Press, 2016, pp. 875–878.
[140] K.h. Chen, H. Shen, L. Yan, Dsearching, Using floating mobility information for distributed node searching in dtns, IEEE Trans. Mobile Comput. 15 (1) (2016) 121–136.
[141] N. Derakhshanfard, R. Soltani, Opportunistic Routing in Wireless Networks Using Bitmap-Based Weighted Tree, vol. 188, Elsevier Computer Networks, 2021 107892.
[142] Q. Zhang, Y. Song, B. Sun, Z. Dai, Design of routing protocol for opportunistic network based on adaptive motion, IEEE Access 8 (2020) 18228–18239.
[143] S. Lu, Y. Liu, Y. Liu, M. Kumar, Loop: a location based routing scheme for opportunistic networks, in: Proceedings of the 9th International Conference on Mobile Ad-Hoc and Sensor Systems, IEEE, 2012, pp. 118–126.
[144] H. Shen, L. Zhao, Alert: an anonymous location-based efficient routing protocol in manets, IEEE Trans. Mobile Comput. 12 (6) (2013) 1079–1093.
[145] D.K. Sharma, A. Sharma, J. Kumar, et al., Knnr: K-nearest neighbour classification based routing protocol for opportunistic networks, in: Proceedings of the IEEE Conference on Contemporary Computing, IEEE, 2017, pp. 1–6.
[146] D.K. Sharma, S.K. Dhurandher, I. Woungang, R.K. Srivastava, A. Mohananey, J.J. Rodrigues, A machine learning-based protocol for efficient routing in opportunistic networks, IEEE Syst. J. 12 (3) (2016) 2207–2213.
[147] V. Vashishth, A. Chhabra, D.K. Sharma, A machine learning approach using classifier cascades for optimal routing in opportunistic internet of things networks, in: Proceedings of the 16th Annual IEEE International Conference on Sensing, Communication, and Networking, IEEE, 2019, pp. 1–9.
[148] D.K. Sharma, J.J. Rodrigues, V. Vashishth, A. Khanna, A. Chhabra, Rlproph: a dynamic programming based reinforcement learning approach for optimal routing in opportunistic iot networks, Springer Wirel. Netw. 26 (6) (2020) 4319–4338.
[149] C. Souza, E. Mota, D. Soares, P. Manzoni, J.-C. Cano, C.T. Calafate, E. Hernández-Orallo, Fsf: applying machine learning techniques to data forwarding in socially selfish opportunistic networks, MDPI Sens. 19 (10) (2019) 1–26.
[150] N. Srinidhi, C. Sagar, J. Shreyas, D.K. Sm, et al., An Improved Prophet-Random Forest Based Optimized Multi-Copy Routing for Opportunistic Iot Networks, vol. 11, Elsevier Internet of Things, 2020, pp. 1–16.
[151] N. Kandhoul, S.K. Dhurandher, I. Woungang, Random forest classifier-based safe and reliable routing for opportunistic iot networks, Wiley Online Lib. Int. J. Commun. Syst. 34 (1) (2021) 1–18.
[152] V. Vashishth, A. Chhabra, D.K. Sharma, Gmmr: a Gaussian mixture model based unsupervised machine learning approach for optimal routing in opportunistic iot networks, Elsevier Comput. Commun. 134 (2019) 138–148.
[153] S.K. Dhurandher, J. Singh, M.S. Obaidat, I. Woungang, S. Srivastava, J.J. Rodrigues, Reinforcement learning-based routing protocol for opportunistic networks, in: Proceedings of the IEEE International Conference on Communications, IEEE, 2020, pp. 1–6.
[154] C. Borrego, E. Hernández-Orallo, P. Manzoni, A.M. Vegni, Lapse: a machine learning message forwarding approach based on node centrality estimation in sparse dynamic networks, in: Proceedings of the IEEE Wireless Days, IEEE, 2021, pp. 1–6.
[155] S.-B. Cho, Exploiting Machine Learning Techniques for Location Recognition and Prediction with Smartphone Logs, vol. 176, Elsevier Neurocomputing, 2016, pp. 98–106.
[156] C. Wang, L. Ma, R. Li, T.S. Durrani, H. Zhang, Exploring trajectory prediction through machine learning methods, IEEE Access 7 (2019) 101441–101452.
[157] Q. He, D. Wu, P. Khosla, A secure incentive architecture for ad hoc networks, Wiley Wirel. Commun. Mobile Comput. 6 (3) (2006) 333–346.
[158] M.Y.S. Uddin, B. Godfrey, T. Abdelzaher, Relics: in-network realization of incentives to combat selfishness in dtns, in: Proceedings of the 18th IEEE International Conference on Network Protocols, IEEE, 2010, pp. 203–212.
[159] N. Li, S.K. Das, Radon: reputation-assisted data forwarding in opportunistic networks, in: Proceedings of the Second International Workshop on Mobile Opportunistic Networking, ACM, 2010, pp. 8–14.
[160] G. Bigwood, T. Henderson, Ironman: using social networks to add incentives and reputation to opportunistic networks, in: Proceedings of the Third International Conference on Privacy, Security, Risk and Trust and 2011 IEEE Third International Conference on Social Computing, IEEE, 2011, pp. 65–72.
[161] L. Wei, H. Zhu, Z. Cao, X.S. Shen, Mobiid: a user-centric and social-aware reputation based incentive scheme for delay/disruption tolerant networks, in: Proceedings of the International Conference on Ad-Hoc Networks and Wireless, Springer, 2011, pp. 177–190.
[162] A. Mei, J. Stefa, Give2get: forwarding in social mobile wireless networks of selfish individuals, IEEE Trans. Dependable Secure Comput. 9 (4) (2012) 569–582.
[163] R.-I. Ciobanu, C. Dobre, M. Dascalu, S. Trausan-Matu, V. Cristea, Collaborative selfish node detection with an incentive mechanism for opportunistic networks, in: Proceedings of the IFIP/IEEE International Symposium on Integrated Network Management, IEEE, 2013, pp. 1161–1166.
[164] H. Zhu, X. Lin, R. Lu, Y. Fan, X. Shen, Smart: a secure multilayer credit-based incentive scheme for delay-tolerant networks, IEEE Trans. Veh. Technol. 58 (8) (2009) 4628–4639.
[165] R. Lu, X. Lin, H. Zhu, X. Shen, B. Preiss, Pi, A practical incentive protocol for delay tolerant networks, IEEE Wireless Commun. 9 (4) (2010) 1483–1493.
[166] H. Chen, W. Lou, Z. Wang, Q. Wang, A secure credit-based incentive mechanism for message forwarding in noncooperative dtns, IEEE Trans. Veh. Technol. 65 (8) (2016) 6377–6388.
[167] Y. Wang, M.-C. Chuah, Y. Chen, Incentive based data sharing in delay tolerant mobile networks, IEEE Wireless Commun. 13 (1) (2014) 370–381.
[168] T.H. Nguyen, O. Brun, B.J. Prabhu, Performance of a fixed reward incentive scheme for two-hop dtns with competing relays, ACM Trans. Model. Perform. Eval. Comput. Syst. (TOMPECS) 4 (2) (2019) 1–19.
[169] L. Kulkarni, J. Bakal, U. Shrawankar, Energy based incentive scheme for secure opportunistic routing in vehicular delay tolerant networks, Springer Comput. 102 (1) (2020) 201–219.
[170] Y. Wu, Y. Zhu, Z. Yang, Research of node incentive strategy in selfish opportunistic network, in: Proceedings of the 17th International Conference on Computer and Information Science, IEEE, 2018, pp. 525–530.
[171] S. Esfandiari, M.H. Rezvani, An Optimized Content Delivery Approach Based on Demand–Supply Theory in Disruption-Tolerant Networks, Springer Telecommunication Systems, 2020, pp. 1–25.
[172] Z. Ning, L. Liu, F. Xia, B. Jedari, I. Lee, W. Zhang, Cais: a copy adjustable incentive scheme in community-based socially aware networking, IEEE Trans. Veh. Technol. 66 (4) (2017) 3406–3419.
[173] U. Shevade, H.H. Song, L. Qiu, Y. Zhang, Incentive-aware routing in dtns, in: Proceedings of the IEEE International Conference on Network Protocols, IEEE, 2008, pp. 238–247.
[174] A. Krifa, C. Barakat, T. Spyropoulos, Mobitrade: trading content in disruption tolerant networks, in: Proceedings of the 6th ACM Workshop on Challenged Networks, ACM, 2011, pp. 31–36.
[175] A. Socievole, A. Caputo, F. De Rango, P. Fazio, Routing in mobile opportunistic social networks with selfish nodes, Hindawi Wirel. Commun. Mobile Comput. 2019 (2019) 1–15.
[176] Q. Li, W. Gao, S. Zhu, G. Cao, A routing protocol for socially selfish delay tolerant networks, Elsevier Ad Hoc Netw. 10 (8) (2012) 1619–1632.
[177] K. Wei, M. Dong, K. Ota, K. Xu, Camf: context-aware message forwarding in mobile social networks, IEEE Trans. Parallel Distr. Syst. 26 (8) (2015) 2178–2187.
[178] L. Yu, P. Liu, A service-based selfish routing for mobile social networks, SAGE Int. J. Distributed Sens. Netw. 11 (6) (2015) 1–8.
[179] R.-I. Ciobanu, R.-C. Marin, C. Dobre, V. Cristea, Onside-self: a selfish node detection and incentive mechanism for opportunistic dissemination, in: Internet of Things (IoT) in 5G Mobile Technologies, Springer, 2016, pp. 317–332.
[180] L. Liu, Q. Yang, X. Kong, H.B. Liaqat, A.M. Ahmed, N. Deonauth, F. Xia, Com-bis: a community-based barter incentive scheme in socially aware networking, SAGE Int. J. Distributed Sens. Netw. 11 (8) (2015) 1–14.
[181] Y. Xie, Y. Zhang, A secure, service priority-based incentive scheme for delay tolerant networks, Wiley Secur. Commun. Network. 9 (1) (2016) 5–18.
[182] T. Ning, Y. Liu, Z. Yang, H. Wu, Incentive mechanisms for data dissemination in autonomous mobile social networks, IEEE Trans. Mobile Comput. 16 (11) (2017) 3084–3099.
[183] O. Nazih, N. Benamar, M. Younis, An evolutionary bargaining-based approach for incentivized cooperation in opportunistic networks, Wiley Online Lib. Int. J. Commun. Syst. 33 (9) (2020) 1–17.
[184] E.K. Wang, C.-M. Chen, S.M. Yiu, M.M. Hassan, M. Alrubaian, G. Fortino, Incentive evolutionary game model for opportunistic social networks, Elsevier Future Generat. Comput. Syst. 102 (2020) 14–29.
[185] J.V. Neumann, O. Morgenstern, Theory of Games and Economic Behavior, Princeton University Press, 1944.
[186] X.-Y. Li, Y. Wu, P. Xu, G. Chen, M. Li, Hidden information and actions in multi-hop wireless ad hoc networks, in: Proceedings of the 9th ACM International

Symposium on Mobile Ad Hoc Networking and Computing, ACM, 2008, pp. 283–292.
[187] B.B. Chen, M.C. Chan, Mobicent: a credit-based incentive system for disruption tolerant network, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2010, pp. 1–9.
[188] X. Zhang, J. Kurose, B.N. Levine, D. Towsley, H. Zhang, Study of a bus-based disruption-tolerant network: mobility modeling and impact on routing, in: Proceedings of the 13th Annual ACM International Conference on Mobile Computing and Networking, ACM, 2007, pp. 195–206.
[189] A. Haq, Y. Faheem, A peer-to-peer communication based content distribution protocol for incentive-aware delay tolerant networks, Springer Wirel. Netw. 26 (1) (2020) 583–601.
[190] L. Wei, Z. Cao, H. Zhu, Mobigame: a user-centric reputation based incentive protocol for delay/disruption tolerant networks, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2011, pp. 1–5.
[191] L. Buttyán, L. Dóra, M. Félegyházi, I. Vajda, Barter trade improves message delivery in opportunistic networks, Elsevier Ad Hoc Netw. 8 (1) (2010) 1–14.
[192] T. Ning, Z. Yang, X. Xie, H. Wu, Incentive-aware data dissemination in delay-tolerant mobile networks, in: Proceedings of the 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, IEEE, 2011, pp. 539–547.
[193] T. Ning, Z. Yang, H. Wu, Z. Han, Self-interest-driven incentives for ad dissemination in autonomous mobile social networks, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2013, pp. 2310–2318.
[194] F. Xia, B. Jedari, L.T. Yang, J. Ma, R. Huang, A signaling game for uncertain data delivery in selfish mobile social networks, IEEE Trans. Comput. Soc. Syst. 3 (2) (2016) 100–112.
[195] B. Jedari, L. Liu, T. Qiu, A. Rahim, F. Xia, A game-theoretic incentive scheme for social-aware routing in selfish mobile social networks, Elsevier Future Generat. Comput. Syst. 70 (2017) 178–190.
[196] Z. Xu, Y. Jin, W. Shu, X. Liu, J. Luo, Sred: a secure reputation-based dynamic window scheme for disruption-tolerant networks, in: Proceedings of the IEEE Military Communications Conference, IEEE, 2009, pp. 1–7.
[197] N. Li, S.K. Das, A trust-based framework for data forwarding in opportunistic networks, Elsevier Ad Hoc Netw. 11 (4) (2013) 1497–1509.
[198] M. Salehi, A. Boukerche, A comprehensive reputation system to improve the security of opportunistic routing protocols in wireless networks, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2015, pp. 1–6.
[199] S. Yang, X. Wang, S. Zhang, B. Yi, M. Huang, Trust-based Security Routing Mechanism in Mobile Social Networks, Springer Neural Computing and Applications, 2019, pp. 1–12.
[200] A.M. Ahmed, X. Kong, L. Liu, F. Xia, S. Abolfazli, Z. Sanaei, A. Tolba, Bodmas: Bio-Inspired Selfishness Detection and Mitigation in Data Management for Ad-Hoc Social Networks, vol. 55, Elsevier Ad Hoc Networks, 2017, pp. 119–131.
[201] T. Ghosh, N. Pissinou, K. Makki, Towards designing a trusted routing solution in mobile ad hoc networks, Springer Mob. Netw. Appl. 10 (6) (2005) 985–995.
[202] R.-I. Ciobanu, C. Dobre, M. Dascălu, Ş. Trăuşan-Matu, V. Cristea, Sense, A collaborative selfish node detection and incentive mechanism for opportunistic networks, Elsevier J. Netw. Comput. Appl. 41 (2014) 240–249.
[203] H. Zhu, S. Du, Z. Gao, M. Dong, Z. Cao, A probabilistic misbehavior detection scheme toward efficient trust establishment in delay-tolerant networks, IEEE Trans. Parallel Distr. Syst. 25 (1) (2014) 22–32.
[204] K. Zhang, X. Liang, R. Lu, K. Yang, X.S. Shen, Exploiting mobile social behaviors for sybil detection, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2015, pp. 271–279.
[205] A.B. Waluyo, D. Taniar, W. Rahayu, B. Srinivasan, Trustworthy data delivery in mobile p2p network, Elsevier J. Comput. Syst. Sci. 86 (2017) 33–48.
[206] V. Lenders, M. May, G. Karlsson, C. Wacha, Wireless ad hoc podcasting, ACM SIGMOB - Mob. Comput. Commun. Rev. 12 (1) (2008) 65–67.
[207] Y. Ma, R. Kibria, A. Jamalipour, Cache-based content delivery in opportunistic mobile adhoc networks, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2008, pp. 1–5.
[208] Y. Ma, A. Jamalipour, A cooperative cache-based content delivery framework for intermittently connected mobile ad hoc networks, IEEE Wireless Commun. 9 (1) (2010) 366–373.
[209] K. Xuyuan, Z. Puning, W. Dapeng, W. Ruyan, et al., Cooperation willingness aware caching mechanism towards opportunistic network, in: Proceedings of the IEEE International Conference on Communication Systems, IEEE, 2018, pp. 473–477.
[210] W. Gao, G. Cao, A. Iyengar, M. Srivatsa, Supporting cooperative caching in disruption tolerant networks, in: Proceedings of the 31st International Conference on Distributed Computing Systems, IEEE, 2011, pp. 151–161.
[211] J. Zhao, X. Zhuo, Q. Li, W. Gao, G. Cao, Contact duration aware data replication in dtns with licensed and unlicensed spectrum, IEEE Trans. Mobile Comput. 15 (4) (2016) 803–816.
[212] G. Moualla, P.A. Frangoudis, Y. Hadjadj-Aoul, S. Ait-Chellouche, A bloom-filter-based socially aware scheme for content replication in mobile ad hoc networks, in: Proceedings of the 13th IEEE Annual Consumer Communications & Networking Conference, IEEE, 2016, pp. 359–365.
[213] T. Wang, P. Hui, S. Kulkarni, P. Cuff, Cooperative caching based on file popularity ranking in delay tolerant networks, in: Proceedings of the 4th Extreme Conference on Communication, ACM, 2012, pp. 11–16.
[214] Z. Wang, L. Sun, M. Zhang, H. Pang, E. Tian, W. Zhu, Propagation-and mobility-aware d2d social content replication, IEEE Trans. Mobile Comput. 16 (4) (2017) 1107–1120.
[215] S. Ioannidis, L. Massoulie, A. Chaintreau, Distributed caching over heterogeneous mobile networks, in: Proceedings of the ACM SIGMETRICS International Conference on Measurement and Modeling of Computer Systems, vol. 38, ACM, 2010, pp. 311–322.
[216] X. Zhuo, Q. Li, G. Cao, Y. Dai, B. Szymanski, T. La Porta, Social-based cooperative caching in dtns: a contact duration aware approach, in: IEEE MASS, 2011, pp. 92–101.
[217] K. Chen, H. Shen, Maximizing p2p file access availability in mobile ad hoc networks though replication for efficient file sharing, IEEE Trans. Comput. 64 (4) (2015) 1029–1042.
[218] S. Kaisar, J. Kamruzzaman, G. Karmakar, A dynamic content distribution scheme for decentralized sharing in tourist hotspots, J. Netw. Comput. Appl. 129 (2019) 9–24.
[219] L. Yan, H. Shen, K. Chen, G. Liu, Mobilecopy: improving data availability and file search efficiency in delay tolerant networks against correlated node failure, IEEE Trans. Mobile Comput. 20 (2019) 188–203.
[220] D. Wu, B. Liu, Q. Yang, R. Wang, Social-aware cooperative caching mechanism in mobile social networks, Elsevier J. Netw. Comput. Appl. 149 (2020) 1–12.
[221] Y. Li, H. Ma, L. Wang, S. Mao, G. Wang, Optimized Content Caching and User Association for Edge Computing in Densely Deployed Heterogeneous Networks, 21(6), IEEE Transactions on Mobile Computing, 2022, pp. 2130–2142.
[222] S. Xia, Z. Yao, Y. Li, S. Mao, Online distributed offloading and computing resource management with energy harvesting for heterogeneous mec-enabled iot, IEEE Trans. Wireless Commun. 20 (10) (2021) 6743–6757.
[223] R. Cabaniss, S. Madria, Content distribution in delay-tolerant networks using social context, in: Proceedings of the 7th IFIP Wireless and Mobile Networking Conference, IEEE, 2014, pp. 1–8.
[224] I.-W. Ting, Y.-K. Chang, Improved group-based cooperative caching scheme for mobile ad hoc networks, Elsevier Parallel Distribut. Comput. 73 (5) (2013) 595–607.
[225] A.I. Wang, T. Bjornsgard, K. Saxlund, Peer2me-rapid application framework for mobile peer-to-peer applications, in: Proceedings of the International Symposium on Collaborative Technologies and Systems, IEEE, 2007, pp. 379–388.
[226] V. Arnaboldi, M. Conti, F. Delmastro, Implementation of cameo: a context-aware middleware for opportunistic mobile social networks, in: Proceedings of the IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, IEEE, 2011, pp. 1–3.
[227] S. Trifunovic, B. Distl, D. Schatzmann, F. Legendre, Wifi-opp: ad-hoc-less opportunistic networking, in: Proceedings of the 6th ACM Workshop on Challenged Networks, ACM, 2011, pp. 37–42.
[228] A.C. Champion, Z. Yang, B. Zhang, J. Dai, D. Xuan, D. Li, E-smalltalker, A distributed mobile system for social networking in physical proximity, IEEE Trans. Parallel Distr. Syst. 24 (8) (2013) 1535–1545.
[229] A.A. Shahin, M. Younis, A framework for p2p networking of smart devices using wi-fi direct, in: Proceedings of the 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication, IEEE, 2014, pp. 2082–2087.
[230] Y. Wang, L. Wei, Q. Jin, J. Ma, Alljoyn based direct proximity service development: overview and prototype, in: Proceedings of the 17th International Conference on Computational Science and Engineering, IEEE, 2014, pp. 634–641.
[231] J.-E. Park, J. Park, M.-J. Lee, Directspace, A collaborative framework for supporting group workspaces over wi-fi direct, in: Proceedings of the Mobile, Ubiquitous, and Intelligent Computing, Springer, 2014, pp. 55–61.
[232] E. Nordström, C. Rohner, P. Gunningberg, Haggle: opportunistic mobile content sharing using search, Elsevier Comput. Commun. 48 (2014) 121–132.
[233] I.M. Lombera, L.E. Moser, P.M. Melliar-Smith, Y.-T. Chuang, Peer-to-peer Publication, Search and Retrieval Using the Android Mobile Platform, vol. 65, Elsevier Computer networks, 2014, pp. 56–72.
[234] O. Turkes, H. Scholten, P.J. Havinga, Friend-to-friend short message service with opportunistic wi-fi beacons, in: Proceedings of the IEEE International Conference on Pervasive Computing and Communication Workshops, IEEE, 2016, pp. 1–6.
[235] M. Kadadha, H. Al-Ali, M. Al Mufti, A. Al-Aamri, R. Mizouni, Opportunistic mobile social networks: challenges survey and application in smart campus, in: Proceedings of the 12th International Conference on Wireless and Mobile Computing, Networking and Communications, IEEE, 2016, pp. 1–8.
[236] Z. Lu, G. Cao, T. La Porta, Teamphone: networking smartphones for disaster recovery, IEEE Trans. Mobile Comput. 16 (12) (2017) 3554–3567.
[237] C. Casetti, C.F. Chiasserini, Y. Duan, P. Giaccone, A.P. Manriquez, Data connectivity and smart group formation in wi-fi direct multi-group networks, IEEE trans. netw. serv. manag. 15 (1) (2017) 245–259.
[238] A. Ippisch, P. Brühn, K. Graffi, Field experiment on the performance of an android-based opportunistic network, in: Proceedings of the European Conference on Parallel Processing, Springer, 2018, pp. 547–558.
[239] F. Bonvin, G. Manzo, C. Esposito, T. Braun, G. Rizzo, Floater: post-disaster communications via floating content, in: Proceedings of the International Conference on Ad-Hoc Networks and Wireless, Springer, 2019, pp. 619–626.
[240] P.S. Paul, N. Mehta, A.K. Das, S. Agarwal, S. Saha, S. Nandi, Surakshit: a smartphone-based application for'localized'gis data aggregation in absence of internet, in: Proceedings of the 20th International Conference on Distributed Computing and Networking, ACM, 2019, pp. 393–396.
[241] S. Kaisar, J. Kamruzzaman, G. Karmakar, I. Gondal, Dynamic content distribution for decentralized sharing in tourist spots using demand and supply, in: Proceedings of the 13th International Wireless Communications and Mobile Computing Conference (IWCMC), IEEE, 2016, pp. 2121–2126.
[242] J. Li, L. Liu, F. Xia, Beeinfo: data forwarding based on interest and swarm intelligence for socially-aware networking, in: Proceedings of the 19th Annual

International Conference on Mobile Computing & Networking, ACM, 2013, pp. 175–178.
[243] K. Thilakarathna, H. Petander, J. Mestre, A. Seneviratne, Mobitribe: cost efficient distributed user generated content sharing on smartphones, IEEE Trans. Mobile Comput. 13 (9) (2013) 1–14.
[244] B.K. Saha, S. Misra, S. Pal, Seer: simulated annealing-based routing in opportunistic mobile networks, IEEE Trans. Mobile Comput. 16 (10) (2017) 2876–2888.
[245] Y. Cai, Y. Fan, D. Wen, An incentive-compatible routing protocol for two-hop delay-tolerant networks, IEEE Trans. Veh. Technol. 65 (1) (2015) 266–277.
[246] B. Xing, K. Seada, N. Venkatasubramanian, An experimental study on wi-fi ad-hoc mode for mobile device-to-device video delivery, in: Proceedings of the IEEE Conference on Computer Communications (INFOCOM), IEEE, 2009, pp. 1–6.
[247] H. Yoon, J. Kim, Collaborative streaming-based media content sharing in wifi-enabled home networks, IEEE Trans. Consum. Electron. 56 (4) (2010) 2193–2200.
[248] J. Morgenroth, T. Pögel, L. Wolf, Live-streaming in delay tolerant networks, in: Proceedings of the 6th ACM Workshop on Challenged Networks, ACM, 2011, pp. 67–68.
[249] E. Lochin, J. Lacan, P.U. Tournoux, J. Leguay, Reliable data streaming over delay-tolerant networks (dtns), in: Elsevier Advances in Delay-Tolerant Networks, DTNs), 2015, pp. 173–185.
[250] S.M. Badhusha, B. Geetha, P. Prabhu, R. Vasanthi, Improved video streaming using msvc and nonoverlapping zone routing multipath propagation over manet s, Wiley Online Lib. Int. J. Commun. Syst. 31 (10) (2018) 1–23.
[251] A. Thakur, A. Dhamija, T. Reddy, Vectors—video Communication through Opportunistic Relays and Scalable Video Coding, vol. 9, Elsevier SoftwareX, 2019, pp. 55–60.
[252] A. Thakur, V. Balloli, A. Dhamija, Video streaming using scalable video coding over opportunistic networks, in: Proceedings of the International Conference on Wireless Communications Signal Processing and Networking, IEEE, 2019, pp. 112–116.
[253] X. Jiang, F.R. Yu, T. Song, V.C. Leung, Resource Allocation of Video Streaming over Vehicular Networks: A Survey, Some Research Issues and Challenges, IEEE Transactions on Intelligent Transportation Systems 23(7), 2022, pp. 5955–5975.
[254] I. Bekmezci, O.K. Sahingoz, Ş. Temel, Flying ad-hoc networks (fanets): a survey, Elsevier Ad Hoc Netw. 11 (3) (2013) 1254–1270.
[255] D.S. Lakew, U. Sa'ad, N.-N. Dao, W. Na, S. Cho, Routing in flying ad hoc networks: a comprehensive survey, IEEE Commun. Surv. Tutorials. 22 (2) (2020) 1071–1120.
[256] S. Rosati, K. Krużelecki, L. Traynard, B.R. Mobile, Speed-aware routing for uav ad-hoc networks, in: Proceedings of the IEEE Global Communications Conference (GLOBECOM), IEEE, 2013, pp. 1367–1373.
[257] C. Pu, Link-quality and traffic-load aware routing for uav ad hoc networks, in: Proceedings of the 4th International Conference on Collaboration and Internet Computing, IEEE, 2018, pp. 71–79.
[258] P. Xie, An enhanced olsr routing protocol based on node link expiration time and residual energy in ocean fanets, in: Proceedings of the 24th Asia-Pacific Conference on Communications, IEEE, 2018, pp. 598–603.
[259] S.Y. Dong, Optimization of olsr routing protocol in uav ad hoc network, in: Proceedings of the 13th International Computer Conference on Wavelet Active Media Technology and Information Processing, IEEE, 2016, pp. 90–94.
[260] G. Gankhuyag, A.P. Shrestha, S.-J. Yoo, Robust and reliable predictive routing strategy for flying ad-hoc networks, IEEE Access 5 (2017) 643–654.
[261] Q. Usman, O. Chughtai, N. Nawaz, Z. Kaleem, K.A. Khaliq, L.D. Nguyen, Lifetime improvement through suitable next hop nodes using forwarding angle in fanet, in: Proceedings of the 4th International Conference on Recent Advances in Signal Processing, Telecommunications & Computing, IEEE, 2020, pp. 50–55.
[262] X. Li, J. Yan, Lepr, Link stability estimation-based preemptive routing protocol for flying ad hoc networks, in: Proceedings of the IEEE Symposium on Computers and Communications, IEEE, 2017, pp. 1079–1084.
[263] O.S. Oubbati, M. Mozaffari, N. Chaib, P. Lorenz, M. Atiquzzaman, A. Jamalipour, Ecad: energy-efficient routing in flying ad hoc networks, Wiley Online Lib. Int. J. Commun. Syst. 32 (18) (2019) e4156.
[264] S. Kumar, R.S. Raw, A. Bansal, M.A. Mohammed, P. Khuwuthyakorn, O. Thinnukool, 3d location oriented routing in flying ad-hoc networks for information dissemination, IEEE Access 9 (2021) 137083–137098.
[265] S.-W. Lee, S. Ali, M.S. Yousefpoor, E. Yousefpoor, P. Lalbakhsh, D. Javaheri, A.M. Rahmani, M. Hosseinzadeh, An energy-aware and predictive fuzzy logic-based routing scheme in flying ad hoc networks (fanets), IEEE Access 9 (2021) 129977–130005.
[266] C. Pu, L. Carpenter, To route or to ferry: a hybrid packet forwarding algorithm in flying ad hoc networks, in: Proceedings of the 18th International Symposium on Network Computing and Applications, IEEE, 2019, pp. 1–8.
[267] C. Pu, Stochastic packet forwarding algorithm in flying ad hoc networks, in: Proceedings of the IEEE Military Communications Conference, IEEE, 2019, pp. 490–495.
[268] C. Pu, I. Ahmed, E. Allen, K.-K.R. Choo, A stochastic packet forwarding algorithm in flying ad hoc networks: design, analysis, and evaluation, IEEE Access 9 (2021) 162614–162632.
[269] C. Pu, L. Carpenter, Psched, A priority-based service scheduling scheme for the internet of drones, IEEE Syst. J. 15 (3) (2020) 4230–4239.
[270] F. De Rango, M. Tropea, P. Fazio, Bio-inspired routing over fanet in emergency situations to support multimedia traffic, in: Proceedings of the ACM MobiHoc Workshop on Innovative Aerial Communication Solutions for FIrst REsponders Network in Emergency Scenarios, ACM, 2019, pp. 12–17.
[271] I.U. Khan, I.M. Qureshi, M.A. Aziz, T.A. Cheema, S.B.H. Shah, Smart iot control-based nature inspired energy efficient routing protocol for flying ad hoc network (fanet), IEEE Access 8 (2020) 56371–56378.
[272] V. Bhardwaj, N. Kaur, S. Vashisht, S. Jain, Secrip: secure and reliable intercluster routing protocol for efficient data transmission in flying ad hoc networks, Wiley Online Libr. Trans. Emerg. Telecommun. Technol. 32 (6) (2021) e4068.
[273] J. Liu, Q. Wang, C. He, K. Jaffrès-Runser, Y. Xu, Z. Li, Y. Xu, Qmr: Q-learning based multi-objective optimization routing protocol for flying ad hoc networks, Elsevier Comput. Commun. 150 (2020) 304–316.
[274] L.A.L. da Costa, R. Kunst, E.P. de Freitas, Q.- fanet, Improved Q-Learning Based Routing Protocol for Fanets, vol. 198, Elsevier Computer Networks, 2021 108379.
[275] Y. Liu, W. Wu, B. Wang, T. He, S. Yi, Y. Xia, Measurement-based channel management in wlans, in: Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC), IEEE, 2010, pp. 1–6.
[276] J. Giti, A. Sakzad, B. Srinivasan, J. Kamruzzaman, R. Gaire, Secrecy capacity against adaptive eavesdroppers in a random wireless network using friendly jammers and protected zone, Elsevier J. Netw. Comput. Appl. 165 (2020) 1–11.
[277] Z. Jia, X. Lin, S.-H. Tan, L. Li, Y. Yang, Public key distribution scheme for delay tolerant networks based on two-channel cryptography, Elsevier Netw. Comput. Appl. 35 (3) (2012) 905–913.
[278] J.-H. Cho, R. Chen, K.S. Chan, Trust Threshold Based Public Key Management in Mobile Ad Hoc Networks, vol. 44, Elsevier Ad Hoc Networks, 2016, pp. 58–75.
[279] S. Bakiras, E. Troja, X. Xu, J.F. Naves, Secure and anonymous communications over delay tolerant networks, IEEE Access 8 (2020) 88158–88169.
[280] S. Rashidibajgan, T. Hupperich, R. Doss, A. Förster, Secure and Privacy-Preserving Structure in Opportunistic Networks, vol. 104, Elsevier Computers & Security, 2021, pp. 1–15.
[281] G.C. Karmakar, R. Das, J. Kamruzzaman, Iot sensor numerical data trust model using temporal correlation, IEEE Internet Things J. 7 (4) (2020) 2573–2581.
[282] M.M. Islam, G. Karmakar, J. Kamruzzaman, M. Murshed, Measuring trustworthiness of iot image sensor data using other sensors' complementary multimodal data, in: Proceedings of the 18th IEEE International Conference on Trust, Security and Privacy in Computing and Communications, IEEE, 2019, pp. 775–780.
[283] B. Shayesteh, V. Hakami, S. Mostafavi, A. Akbari Azirani, A novel trust computation scheme for internet of things applications, Tabriz J. Electr. Eng. 50 (2) (2020) 743–755.
[284] V.B. Reddy, S. Venkataraman, A. Negi, Communication and data trust for wireless sensor networks using d–s theory, IEEE Sensor. J. 17 (12) (2017) 3921–3929.
[285] X. You, C.-X. Wang, J. Huang, X. Gao, Z. Zhang, M. Wang, Y. Huang, C. Zhang, Y. Jiang, J. Wang, et al., Towards 6g wireless communication networks: vision, enabling technologies, and new paradigm shifts, Springer Sci. China Inf. Sci. 64 (1) (2021) 1–74.
[286] G. Pau, F. Arena, Y.E. Gebremariam, I. You, Bluetooth 5.1: an analysis of direction finding capability for high-precision location services, MDPI Sens. 21 (11) (2021) 3589.