SCIENCE CHINA
Information Sciences

• **RESEARCH PAPER** •
Special Focus on Machine-Type Communications

October 2017, Vol. 60 100306:1–100306:15
doi: 10.1007/s11432-017-9186-6

A trust framework based smart aggregation for machine type communication

Tabinda SALAM[1], Waheed ur REHMAN[1,2], Xiaofeng TAO[1]*, Yu CHEN[1] & Ping ZHANG[1]

[1] *National Engineering Laboratory for Mobile Network Technologies, Beijing University of Posts and Telecommunication, Beijing* 100876*, China;*
[2] *Department of Computer Science, University of Peshawar, Peshawar* 25000*, Pakistan*

Received April 21, 2017; accepted July 11, 2017; published online September 6, 2017

Abstract Machine type communication (MTC) is one of the significant communication paradigms in the fifth generation networks. The existing cellular networks are not designed for massive access of the MTC devices. Therefore, data aggregation and relaying are advocated to reduce the massive MTC access besides other physical layer solutions. In this paper, we propose a secured multiple mobile relay selection algorithm that smartly aggregates data from adjacent MTC devices through multiple user equipments and transmits it to the base station (BS). The paper also presents a framework for the selection of trusted relays to cooperatively aggregate MTC data and render two-hop connectivity to the BS. Our proposed algorithm is compared with existing algorithms on the basis of energy efficiency, system capacity, communication delay and outage probability. Our proposed algorithm outperforms the other schemes by improving outage probability and communication delay by 33% and 25%, respectively.

Keywords D2D communication, data aggregation, machine type communication (MTC), mobile relay, MTC offloading

Citation Salam T, Rehman W, Tao X F, et al. A trust framework based smart aggregation for machine type communication. Sci China Inf Sci, 2017, 60(10): 100306, doi: 10.1007/s11432-017-9186-6

1 Introduction

The fifth generation (5G) networks have given rise to many new technologies and communication paradigms to accomplish different useful services. Machine type communication (MTC) is one of such technologies to plow the requirements of 5G networks [1]. It allows direct communication among machine type objects with/without human intervention [2]. The amount of data per MTC device is not much but collectively the MTC devices pose huge challenge [3] to the network providers through their massive access to the network. MTC enables a large number of applications in a wide plethora of domains such as smart grid, health monitoring, intelligent transport system and smart metering [4]. MTC networks are characterized by massive number of concurrent active, low-powered devices, low-payload data transmission and vastly diverse quality of service (QoS) requirements [5]. The number of MTC devices is

* Corresponding author (email: taoxf@bupt.edu.cn)

expected to reach 50 billion by 2020 [6]. Due to ubiquitous connectivity, reliable communication and high level security: cellular networks are the perfect candidates to accommodate MTC traffic [7,8]. Albeit the suitability of cellular networks to handle the MTC traffic, these networks are already heavily overloaded with mobile traffic and it is predicted that there would be ten fold increase in mobile data traffic till the end of this decade [9].

The existing cellular networks are not designed to support plentitude of MTC devices [8]. Despite the fact that the data demands of MTC devices are very low, still they pose serious challenges for the network stability due to massive signalling and overhead. Furthermore, the proliferation of MTC devices helps achieve the idea of Internet of Things (IoT) [4]. In this vein, MTC will be used in every object around us, which poses serious challenges regarding trust and security issues. In addition, the constraints on the limited battery power of MTC devices seriously limit the communication options especially the case of direct communication to the base station (BS).

The nuisance of massive access and limited battery power of MTC devices can be catered by employing data aggregation. The authors in [2, 8] define data aggregation as a promising solution to collect and process data from MTC devices to solve the congestion caused by massive access from these devices. It relaxes the need to send data from MTC devices directly to the base station, that improves the channel access rate. It also improves the efficiency of data transmission particularly from MTC devices with poor communication links [10] and is also beneficial in terms of power consumption of MTC devices, due to short communication link between the MTC device and the aggregating device [2].

MTC devices can employ device to device (D2D) communication to send their data to the aggregator device. D2D communication employs direct transmission between D2D pairs with/without the involvement of the BS [11]. It results in high energy efficiency, low delay, reuse gain, spectral efficiency and increased throughput [12–14] by offloading data from the BS. The D2D communication can play a significant role in managing the problems related to MTC devices' massive access, by offloading MTC traffic on D2D links using relays. It results in efficient management of radio resources, spectrum access and extension in MTC devices' battery life due to short-range D2D links [15]. In order to harvest these benefits, this paper proposes a relay algorithm that employs multiple user equipments to aggregate data.

The structure of this paper is as following. Section 2 begins with a brief rundown of the state of art solutions employing UE as relay for MTC's massive access problem. This section also highlights the significance and contributions of this paper. Section 3 deals with the system model. Our proposed algorithm to cater the unavailability of relay UE requires formation of group of trusted relays; therefore Section 4 presents the proposed scheme along with the explanation of trust framework. The assignment of MTC devices to the relay group is also explained in the same section. The outage probability of the proposed scheme is analyzed in Section 5. The results of simulation and analysis are discussed in Section 6. Finally, Section 7 concludes the paper.

2 Literature review

The continued growth of wireless communication has brought an upper limit of Shannon's Information theory of a single user channel. This gave birth to the notion of cooperative communication [16]. It deals with the transmission of data from sender to receiver through intermediate nodes known as relays. The relay channel, being a three terminal network, was first introduced by [17]. Since then, cooperative communication has been extensively used to enhance the capacity of wireless channels. In this vein, relay design and selection have gained much attention from research community [14,16–28]. Relays offer several benefits to wireless networks like increased system capacity, improved coverage reliability in shadowed areas and/or BS's range extension, and cost reduction [23, 28].

The use of user equipment (UE) as relay has been advocated in the literature generally for data offloading, cooperative communication and cooperative caching [11,13,14,18,29–36]. However, the use of UE as relay in MTC is just beginning to take notice [10,15,37–40]. Since, UEs have limited battery power, relaying MTC data put additional strains. In order to address this limitation of UEs, the authors in [15] propose to employ radio frequency (RF) energy harvesting to enable D2D users to harvest ambient RF energy. The paper also shows how to efficiently employ underlay D2D communication not only to achieve a higher D2D transmission probability but also to have a higher MTC and D2D spectral efficiency in dense cellular networks. The authors in [37] describe how to employ low power underlay D2D communication to deliver MTC data to the BS through UE using Successive Interference Cancellation. According to [10], D2D communication paradigm has inspired the idea to employ UE as machine type relay by relaying the MTC data through D2D communication. The paper also devises a protocol to aggregate the MTC data at a relay UE, which is then transmitted to the BS in addition to UE's own data in cellular uplink communication.

The security issues, in addition to UE relaying, are addressed in [38]. The paper proposes a protocol for multi-hop D2D communication by aggregating data from neighboring MTC devices. A connection is established between D2D pairs only if they share at minimum one security key. After the establishment of secure connection, the MTC data is relayed to BS by multi-hoping among D2D pairs.

The concept of employing UE as a relay for MTC traffic is also favored by the authors in [39, 40] especially for healthcare applications. As the UEs are equipped with capabilities like sensing (content and environment) and multiple communication networks (NFC, Bluetooth, Wi-Fi Direct and cellular communication), it is feasible to use them as mobile relays for MTC data: particularly in healthcare applications [39]. The authors in [40] also second the idea of using mobile relay for remote patient monitoring and healthcare applications. The patient's on-body sensors send the sensed data to the patient's UE, which then aggregates MTC data and forwards it to the BS. The authors also suggest including UE as a tier in the network hierarchy, by formulating P2P nanocells.

All the above mentioned research works advocate the use of UE as MTC relay to forward data to the BS. However, none of research work addresses the scenario when the relay UE becomes unavailable. By allowing a UE to aggregate data from various MTC devices put additional responsibilities on UE to reliably send the data to BS. The failure of reliable data transmission may severely damage the purpose and objective of MTC networks. The reasons of failure and unavailability of UE include UE's mobility, battery power depletion, a temporary failure/reboot and the like. Furthermore, the security in MTC networks is also very important. MTC devices cannot just send their data to any UE. The UEs should be trusted by the MTC devices. There should be a mechanism so that a group of trusted UEs are made available to the MTC devices to reliably relay their data to the BS.

In order to increase the reliability, battery life and security in MTC networks, we propose the use of multiple UEs following the strict trust criteria. Our proposed scheme diffuses the nuisance of single point of failure in MTC networks by utilizing cooperative data aggregation with the help of multiple trusted UEs. Furthermore, in our proposed scheme, the relay UEs may exchange the MTC data with one another to further increase the reliability at the cost of more delay tolerance. That is why we termed the data aggregation in our proposed scheme as cooperative aggregation. We have used the term cooperative aggregation and smart aggregation interchangeably throughout the text due to the use of smart UEs as relays. The trust graphs and the concept of trust transitivity are used to define a trust framework to widen and strengthen the scope of trusted relays' availability.

The main contributions of this paper include: 1) proposing a multiple mobile relay selection algorithm based on the use of multiple cooperative UEs, 2) designing the framework to support trusted UEs to facilitate smart data aggregation, 3) providing outage probability analysis of the proposed scheme, 4) the comparison of the proposed scheme with single and multiple fixed (stationary) relays along with a single mobile relay schemes in MTC networks. It should be noted here that by fixed we mean the stationary relays, which do not change their positions. The simulation results show that the proposed multiple mobile relay scheme outperforms single/multiple fixed and single mobile relay schemes.

3 Typical MTC system model

We are considering a typical MTC scenario having UEs and MTC devices in an area, as shown in Figure 1. It is quite common nowadays that UEs are part of certain groups [18], demonstrated by dotted line circle

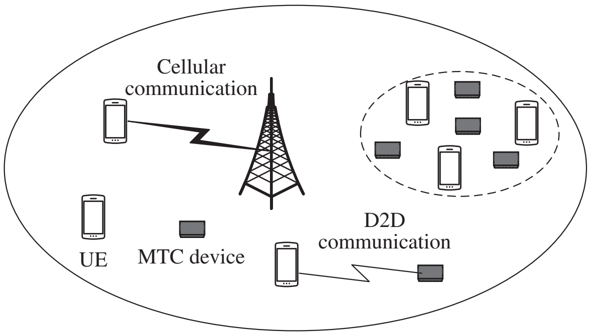

Figure 1 Typical MTC system model.

in Figure 1. The rationale for this grouping is the attainment of their required popular contents from other UEs through either D2D communications or NFC, Bluetooth, Wi-Fi Direct or other short range communication technologies. Such UEs have trust relationship among one another and can be utilized to relay data from surrounding MTC devices in a cooperative manner.

Our system model considered various MTC devices randomly distributed in an area as shown in Figure 1. Due to the rationale behind UEs grouping, multiple UEs may be available in areas such as homes, buildings, and shopping malls, to work in conjunction to relay the MTC data to the BS. We assume that there are N UEs and M MTC devices in the area. Each UE $n \in N$ may relay the data of $|M_n|$ devices, where $M_n \subseteq M$ and UE n serves all $|M_n|$ devices. The MTC devices choose a particular UE on the basis of mutual trust and distance (explain in detail in latter section). A UE $n \in N$ may become unavailable for reasons such as mobility, battery depletion or temporary shutdown. This may cause a halt to the data transmission in MTC network. In such case, we propose to exploit the social trust of UE $n \in N$, either directly or transitively, in order to choose another appropriate relay (explain in latter section), to continue transmitting the MTC data.

The typical two-hop MTC communication scenario is considered in which all MTC devices are assigned to UEs to relay their data. MTC devices first transmit their data to the UEs and get a reply with an ACK. The rationale of two hop relaying strategy lies in the fact that multi-hoping results in increased delay in data transmission of MTC devices. Moreover, since our relay scheme strongly emphasise on the use of trusted relays, in case of multi-hoping, establishment of trust relationship among all the relay nodes would not be possible all the times. Lastly, multi-hoping involves several complexities regarding trusted relay selection, shortest path selection, and the like,which will further increase data transmission delay.

The packets generated by MTC devices are assumed to be according to Poisson process with an average of λ packets arrival per second. The relay UEs aggregate the data from different MTC devices and transmit it to the BS at the expiry of the predefined threshold time $\mathcal{T}$.

The MTC devices send their data through D2D communication to the UE. By employing regular cellular communications, the UEs relay MTC data to the BS in their uplink communications. In our proposed two-hop relay scheme, interference is possible in the first hop; however we are assuming no interference in the second hop since it is a cellular uplink communication. The interference in the first hop may result as multiple MTC devices try to transmit their data to their respective UEs. This is depicted in Figure 2 where the transmitter device is designated as A, the UE that relays the data is called R, the interfering device is called C and the BS is named B for simplicity.

If P_t^A be the transmit power of transmitter A and P_t^I be the average transmit power of the interfering signal, the received signal to interference and noise ratio (SINR) can be calculated as

$$\gamma_{\rm AR} = \frac{P_r\left(y\right)}{P_r\left(y_I\right) + N_0} = \frac{P_t^A K_{\rm AR} (d_0/d1)^n \varepsilon_{\rm AR} |h_{\rm AR}|^2}{P_t^I K_I (d_0/dI)^n \varepsilon_I |h_I|^2 + N_0}, \tag{1}$$

where $P_r\left(y\right)$ is the received desired signal power and $P_r\left(y_I\right)$ is the interference power at relay R. Furthermore, $K_{\rm AR}$ is free space path loss at d_0 that is a reference distance (1 m), $d1$ is the distance from MTC

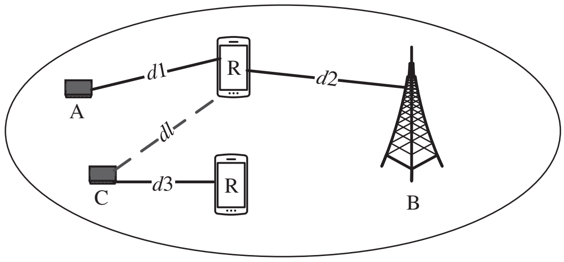

Figure 2 Communication scenario of MTC network.

device to UE, n is path loss exponent, $\varepsilon_{\mathrm{AR}} = 10^{-\frac{0\ \mathrm{dB}}{10}}$ denotes the shadow fading, 0 is zero mean Gaussian random variable, h_{AR} is channel coefficient of the desired link and N_0 is the average background white Gaussian noise power.

If P_t^R be the transmit power of relay R, the SNR at BS B can be expressed as

$$\gamma_{\mathrm{RB}} = \frac{P_t^R K_{\mathrm{RB}}(d_0/d2)^n \varepsilon_{\mathrm{RB}} |h_{\mathrm{RB}}|^2}{N_0}. \tag{2}$$

4 Trust framework using graph formation

This section elucidates the formation of trust framework for the selection of trusted relays. As discussed earlier, the cellular networks are not designed to cater millions of MTC devices in a cell thus paving the path to use data aggregation at UEs. In order to avoid single point of failure, we propose the use of multiple smart relays. We assume that the trust group of MTC devices contains at least one UE which acts as a primary relay. This primary relay can have trust relationship with the nearby nodes. In this paper, graph theory is employed to represent the relationship among nodes. The cooperative D2D communications based on social trust and trust transitivity is also considered in this paper. This can also be exploited to designate secondary relay(s) if the primary or any secondary relays get(s) unavailable.

4.1 Formation of graphs

In this subsection, the graph formation is discussed that is used to define the relationship among the relay UEs. This relationship can be exploited to ensure the selection of secured multiple relays to successfully transmit the MTC data to the BS.

Let all UEs in an area are represented by set $\mathcal{N} = \{1, 2, \ldots, N\}$, where N is the total number of UEs in that area. We are assuming that the set $\mathcal{N}$ contains UEs which are willing to relay MTC data. The MTC devices are represented by the set $\mathcal{M} = \{1, 2, \ldots, M\}$, where M is the total number of MTC devices in the vicinity of relay UEs. We are assuming one UE $n \in N$, which is designated as primary relay. All the secondary relays will be selected on the basis of trust relationship among n to the rest of the set $\mathcal{N}$ i.e., $n \to \{1, 2, \ldots N, \} - \{n\}$.

We define the trust group of a primary UE as all the UEs that have social trust towards the primary UE. These relations can be developed in the form of friendships, colleagues, neighbors and kinships. The trust group graph G_T can be represented as

$$G_T = \left\{\mathcal{N},\ \varepsilon^T\right\}. \tag{3}$$

The edge set ε^T is given as

$$\varepsilon^T = \left\{(n, m) :\ e_{nm}^T = 1,\ \forall n, m \in \mathcal{N}\right\}, \tag{4}$$

where $e_{nm}^T = 1,$ iff $n, m \in\ \mathcal{N}$, i.e., n and m are two UEs in $\mathcal{N}$, that have mutual trust in the form of ε^T, as shown in Figure 3(a).

Since, only mutual trust is not enough for UEs to relay the MTC data, they should be in the D2D communication range of each other. It can be seen as a relationship in the geographic domain and we

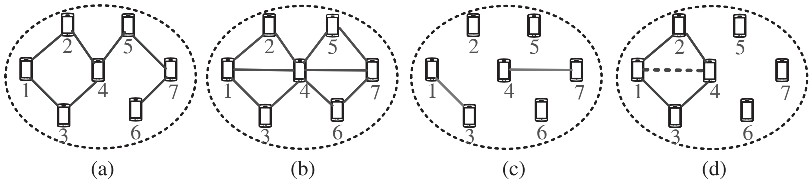

Figure 3 Formation of graphs. (a) Social graph; (b) geo-graph; (c) recent file sharing history based graph; (d) trust transitivity based graph.

termed it as geo-graph, as shown in Figure 3(b). The geo-graph G_G for the defined scenario is given as

$$G_G = \left\{\mathcal{N},\ \varepsilon^G\right\}. \tag{5}$$

The edge set ε^G is given as

$$\varepsilon^G = \left\{(n,m):\ e^G_{nm} = 1,\ \forall n,m \in \mathcal{N}\right\}, \tag{6}$$

where $e^G_{nm} = 1,$ iff n, m are in close proximity of one another. In other words, n and m are two UEs in $\mathcal{N}$, that are in the transmission range of each other. As it is clear from Figure 3(b), UE 1 and 4 do not have trust relationship but are in close proximity of one another.

We are also considering a scenario in which there might not be any active trust relationship among UEs; however, they may have past history of communication in some form such as file sharing. We make a graph containing all the nodes with which UE has a recent history of communication. The resultant graph is shown in Figure 3(c) and can be expressed as

$$G_H = \left\{\mathcal{N},\ \varepsilon^H\right\}. \tag{7}$$

The edge set is

$$\varepsilon^H = \left\{(n,m):\ e^H_{nm} = 1,\ \forall n,m \in \mathcal{N}\right\}, \tag{8}$$

where $e^H_{nm} = 1,$ iff n, m have some mutual communication history. In other words, n and m are UEs in $\mathcal{N}$ such that they have some history of mutual file exchange like through Bluetooth pairing, despite not having any active trust relationship.

4.2 Relay group formation (without trust transitivity)

Once the graphs are constructed, the next step is to form a set of feasible relays. For the constructed graphs, we need to define sets of nodes which can serve as relays for the primary node $n \in \mathcal{N}$. These sets are expressed as

$$\mathcal{N}^T_n = \{p \in \mathcal{N} : e^T_{np} = 1\},$$
$$\mathcal{N}^G_n = \{q \in \mathcal{N} : e^G_{nq} = 1\},$$
$$\mathcal{N}^H_n = \{r \in \mathcal{N} : e^H_{nr} = 1\},$$

where $\mathcal{N}^T_n$ represents the set of nodes with which node n has trust relationship, $\mathcal{N}^G_n$ is the geo-graph based node set and $\mathcal{N}^H_n$ contains the nodes with which node n recently has Bluetooth pairing or shared files. Now the relay group is given as

$$\mathcal{R}_n = \{(\mathcal{N}^T_n \cup \mathcal{N}^H_n) \cap \mathcal{N}^G_n\}, \tag{9}$$

where $\mathcal{R}_n$ is a set of UEs which are the potential secondary relays for UE n. Figure 4 represents set of UE relays with respect to $n = 1$, i.e., $\mathcal{R}_1 = \{1, 2, 3\}$. Although UE 4 is in geo-graph of 1 but it is not taken as a relay because neither UE 1 has trust relationship with UE 4 nor possesses a communication history through Bluetooth pairing and the like; only UE 2 and 3 can serve as secondary relays for UE 1.

The set $\mathcal{R}_n$ contains the list of all UEs for $n \in \mathcal{N}$ that can act as relays to transmit the MTC data to the BS. This list can be used either to designate the secondary relay(s) in the absence of primary relay n (under sparse MTC deployment) or it can be used to designate multiple relays in a network, all working

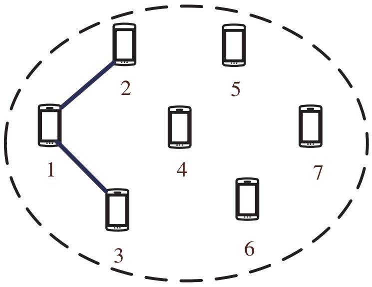

Figure 4 Relay graph for (9) with $n = 1$.

simultaneously in addition to primary relay n (under dense MTC deployment). It is pertinent to note that the UEs in (9) have direct mutual trust with respect to the primary relay n. We may call the set $\mathcal{R}_n$ as friends of n. However, it is possible that the set $\mathcal{R}_n$ gets empty due to reasons such as battery depletion and mobility, in that case we propose to employ trust transitivity to search for feasible relays.

4.3 Framework for trust transitivity

Trust transitivity means to trust friends of friends [41] i.e., If A trusts B and B trusts C, then A can transitively trust C. It is possible that the UEs which can act as secondary relays are not capable or not ready to relay MTC data. In this scenario, their trust relationships may be exploited to find feasible relays. Simply stated, friends of a friend are considered as friends. In order to further enhance security, we propose that a common friend of two or more secondary devices of the primary relay n can be taken as a trusted friend. i.e.,

$$\mathcal{A} \to \mathcal{B},\ \mathcal{A} \to \mathcal{D},\ \mathcal{B} \to \mathcal{C},\ \mathcal{D} \to \mathcal{C}\ \Longrightarrow \mathcal{A} \to \mathcal{C}.$$

Let $F_n =\ \mathcal{R}_n - \{n\}$ if

$$F_n = \begin{cases} 0, & \text{no friends,} \\ h, & h \text{ cannot relay.} \end{cases} \tag{10}$$

Then friends of h, F_h should be exploited as $F_h = Q$ where $Q \in \mathcal{N}$ represents friends of friends list for n. Similarly, friends of $q \in Q$ can be represented as

$$F_{q \in Q} = R_q,$$
$$F_Q = \uplus_{q \in Q} R_q,$$

where F_Q is a multiset representing all UEs which are friends of UE h, while $\uplus$ is the multiset union.

In order to go a step further towards building stronger trust, we consider using common friends of a friend as a relay. Since F_Q is a multiset, the common friend will be the UE with maximum number of occurrences in the set F_Q. $\mathrm{CF}_n = \max(F_Q)$, where max() represents the maximum number of occurrences in ascending order in F_Q. Alternatively, Let F_n be a set of nodes containing friends of $n(n\ \varepsilon \mathcal{N})$ and is given by [42] as $F_n = \left\{m \in \mathcal{N} : n, m \in \epsilon^T\right\}$. Let CF_n is a set of nodes which are common friends of friends of $n(n\ \varepsilon \mathcal{N})$ i.e.,

$$\mathrm{CF}_n = \left\{ \begin{array}{c} k \in \mathcal{N} : K \in ((F_i \cap F_j) : \forall i, j \in F_n) \\ \text{iff} \left((k \neq i, j, n) \wedge (k, n \in\ \varepsilon^G)\right) \end{array} \right\}. \tag{11}$$

k is a common friend of friends of n and it is also present in close proximity of n, i.e., $(k, n \in \varepsilon^G)$. The graph representation of common friends of primary node n as a result of trust transitivity among the UEs is shown in Figure 3(d) and can be expressed as

$$G_{\mathrm{CF}} =\ \left\{\mathcal{N},\ \varepsilon^{\mathrm{CF}}\right\}.$$

The edge set is

$$\varepsilon^{\mathrm{CF}} = \left\{(n, m) :\ e_{nm}^{\mathrm{CF}} = 1,\ \forall n, m \in \mathcal{N}\right\}, \tag{12}$$

where $e_{nm}^{\mathrm{CF}} = 1$ iff $n, m \in \mathrm{CF}_n$.

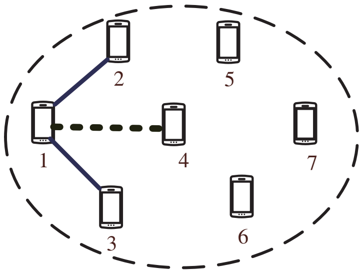

Figure 5 Relay graph for (13) with $n = 1$.

4.4 Relay group formation (with trust transitivity)

With the addition of trust transitivity, (9) can now be modified as following

$$\mathcal{R}_n = \{(\mathcal{N}_n^T \cup \mathcal{N}_n^H \cup \mathcal{N}_n^{\mathrm{CF}}) \cap \mathcal{N}_n^G\}, \tag{13}$$

where $\mathcal{N}_n^T$, $\mathcal{N}_n^H$, $\mathcal{N}_n^{\mathrm{CF}}$ and $\mathcal{N}_n^G$ respectively represent trust group, communication history domain, set of common friends and geographic domain of primary relay $n \ \varepsilon \mathcal{N}$. Figure 5 shows the graph corresponding to (13) with $n = 1$. The UEs 2 and 3 have trust relationship with UE 1. Also, UE 4 is a common friend of both the UEs 2 and 3, as shown in Figure 3 (a) and (c); it is also in communication range of UE 1. Through trust transitivity, UE 4 is added in the relay group of UE 1 through (13).

The UEs yield by (13) comprises a comprehensive list of all the secondary relays, which can be well trusted and feasible to aggregate and forward MTC data. Different parameters such as current load and remaining battery power can be used to arrange the UEs in $\mathcal{R}_n$ in order to select the optimal candidate(s) to relay MTC data.

5 Proposed relay selection scheme

In this section, the proposed relay scheme is explained in detail along with the procedure of assigning MTC devices to the relays.

5.1 Multiple mobile relay scheme

In this subsection, we will discuss our proposed algorithm. All the prerequisites for the formation of graphs are already discussed in previous section. Our proposed multiple mobile relay scheme is outlined in Algorithm 1. Our algorithm begins with the selection of primary relay $n \ \varepsilon \mathcal{N}$ (Algorithm 1, line 1). This selection is based on mutual trusts among MTC devices and UEs. In case of non-availability of trusted UEs, the BS will assist the MTC devices to find a reliable UE willing to relay MTC data. This situation may arise in scenarios like stadiums, shopping malls, exhibition centers and the like.

Once a primary relay UE is selected, it will then make a relay group $\mathcal{R}_n$ (Algorithm 1, lines 2 and 3). The formation of $\mathcal{R}_n$ is mandatory to cater the issues like UE's mobility, traffic load, or temporary failure. After obtaining $\mathcal{R}_n$ by employing (13), the primary UE will then arrange $\mathcal{R}_n$ nodes on the basis of current load and remaining battery power (Algorithm 1, lines 4 and 5). The MTC devices associated with primary relay will send their data to it (Algorithm 1, line 6). In case of non-availability of this primary relay, the MTC devices will make use of the information present in $\mathcal{R}_n$. i.e., they will choose a relay from $\mathcal{R}_n$ to send their data. There is a possibility that the serving relay becomes unavailable. In that case, MTC devices have to scan $\mathcal{R}_n$ to check the availability of other relays in the group (Algorithm 1, line 7). The relay UE after receiving MTC data will wait for a threshold time $\mathcal{T}$. When this time expires, the relay UE will append its own data with MTC data and transmit it to the BS in uplink communication (Algorithm 1, line 8).

Algorithm 1 Multiple mobile relays algorithm

1: Selection of primary relay $n \, \varepsilon \mathcal{N}$
2: Graphs formation i.e., $\mathcal{N}_n^T$, $\mathcal{N}_n^H$, $\mathcal{N}_n^{\rm CF}$, $\mathcal{N}_n^G$
3: Formation of potential relays using (13)
4: Arrange $\mathcal{R}_n$ on the basis of current load and battery life.
5: Selection of relays from $\mathcal{R}_n$ until all $\mathcal{M}$ MTC devices are served. The set of relays are called $\mathcal{R}_n^{\rm current}$, where $\mathcal{R}_n^{\rm current} \subseteq \mathcal{R}_n$ and

$$\mathcal{M} = \bigcup_{n=1}^{N} M_n.$$

6: Data transmission from MTC devices to respective relays i.e., $\mathcal{R}_n^{\rm current}$.
7: If certain relay is unavailable, goto step 5.
8: Transmission of aggregated MTC data to the BS at the end of time $\mathcal{T}$.

5.2 MTC devices assignment

In this subsection, we discuss the assignment of MTC devices to the primary and secondary relays (UEs). All the MTC devices send their data to the UEs through D2D communication. However, the communication of UEs with the BS is through cellular standards. We are considering network assisted D2D communication [11], where the BS is responsible for controlling uplink/downlink communications. It calculates the permissible transmission power level for every UE $n \in \mathcal{R}_n$. Furthermore, the BS also assists the primary relay $n \, \varepsilon \mathcal{N}$ to discover its neighboring UEs, which can be candidates of its potential set of relays. Let the list of all currently employed relays is represented as $\mathcal{R}_n^{\rm current}$, where $\mathcal{R}_n^{\rm current} \subseteq \mathcal{R}_n$.

Our proposed scheme employs time division multiple access (TDMA) mechanism, where the transmission time is slotted in frames. Each UE $n \in \mathcal{R}_n^{\rm current}$ is responsible for collecting data of $|M_n|$ MTC devices in its vicinity, sent to it through D2D communication. M_n for $n \in \mathcal{R}_n^{\rm current}$ are the disjoint sets such that $\mathcal{M} = \bigcup_{n=1}^{N} M_n$ where $\mathcal{M}$ is the set of all MTC devices. The relay UE aggregates the data from $|M_n|$ devices, appends its own data with the aggregated data and sends it to the BS in uplink communication in its allotted time slot.

To send the data of $|M_n|$ devices to the relay UE, it is proposed in [10] that the time slot should be further divided into reservation mini-slots. All $|M_n|$ devices first require reserving mini-slots to alert their respective relays about their upcoming data packets. In case if any $|M_n|$ device fails to reserve a mini-slot with its relay, its data packet will be dropped. This will result in an outage for MTC devices data. In order to address this problem, we propose that all $|M_n|$ MTC devices should broadcast to $|\mathcal{R}_n^{\rm current}|$ UEs in order to reserve the mini-slot. MTC devices will be segregated on the basis of proximity with a set of optimal relays for each segregation. In this way, single point of failure will be avoided in addition to improving the outage probability. Moreover, since the communication distance between MTC devices and UEs is reduced, therefore, it results in an improved battery power of MTC devices.

6 Outage probability analysis

In order to evaluate the proposed scheme, outage probability (OP) is utilized as a metric. OP is an important performance indicator in wireless systems. It can be defined as the probability that the end-to-end SNR falls below a predefined threshold $\gamma_{\rm th}$. The type of threshold $\gamma_{\rm th}$ varies according to different quality of service requirements. For example, the value may be based on minimum error rate or a minimum data rate. Since MTC devices deals with the reliability of data, therefore minimum error rate is selected as a threshold,

$$\gamma_{\rm th} = \min {\rm BER}.$$

In two-hop relay assisted transmission scenario, the outage is decided by either of the weaker hops. Thus, OP can be expressed as

$$P_{\rm out} = P_r(\min(\gamma_{\rm AR}, \gamma_{\rm RB})).$$

That is

$$P_{\rm out}(d1,d2,dI,\gamma_{\rm th}) = P_r\left(\min\left(\gamma_{\rm AR}\left(d1,dI\right),\gamma_{\rm RB}\left(d2\right)\right)\right) < \gamma_{\rm th}$$
$$= 1 - \left(1 - F_{\rm AR}\left(d1,dI,\gamma_{\rm th}\right)\right)\left(1 - F_{\rm RB}(d2,\gamma_{\rm th})\right)$$
$$= F_{\rm AR}\left(d1,dI,\gamma_{\rm th}\right) + F_{\rm RB}\left(d2,\gamma_{\rm th}\right) - F_{\rm AR}\left(d1,dI,\gamma_{\rm th}\right)F_{\rm RB}\left(d2,\gamma_{\rm th}\right), \quad (14)$$

where $F_{\rm AR}\left(d1,dI,\gamma_{\rm th}\right)$ and $F_{\rm RB}\left(d2,\gamma_{\rm th}\right)$ are cumulative distribution functions of the received SINR and SNR of both the hops i.e., A-R and R-B, respectively.

We consider Rayleigh distribution to model non-line of sight (NLOS) scenario. Hence, the instantaneous received power of the desired signal follows an exponent distribution with probability distribution function (pdf) expressed as

$$P_{\gamma_{\rm AR}}\left(x\right) = \frac{1}{\overline{\overline{P_r}}}\exp\left(-\frac{x}{\overline{\overline{P_r}}}\right).$$

For the OP of A-R, the desired signal (y) and interfering channel (y_I) coefficients are considered to be independent and not identically distributed (INID). Both follow Rayleigh distribution. Thus, the OP of A-R hop can be approximated as

$$F_{\rm AR} = P_r\left(x < \gamma_{\rm th}\left(y+N_0\right)\right) = 1 - P_r\left(x > \gamma_{\rm th}\left(y+N_0\right)\right)$$
$$= 1 - \int_0^\infty f\left(y\right)\int_{\gamma_{\rm th}(y+N_0)}^\infty f\left(x\right){\rm d}x{\rm d}y$$
$$= 1 - \int_0^\infty \frac{1}{P_{r_I({\rm AR})}}\exp\left(-\frac{y}{P_{R_I(AR)}}\right)\int_{\gamma_{\rm th}(y+N_0)}^\infty \frac{1}{P_{r({\rm AR})}}\exp\left(-\frac{x}{P_{r({\rm AR})}}\right){\rm d}x{\rm d}y$$
$$= 1 - \frac{P_{r({\rm AR})}}{P_{r({\rm AR})}+P_{r_I({\rm AR})}}\exp\left(-\frac{\gamma_{\rm th}N_0}{P_{r({\rm AR})}}\right), \quad (15)$$

the OP of R-B hop can be calculated as

$$F_{\rm RB} = P_r\left(x < \gamma_{\rm th}N_0\right) = 1 - P_r\left(x > \gamma_{\rm th}N_0\right), \quad 1 - \int_{\gamma_{th N_0}}^\infty \frac{1}{\overline{\overline{P_r}}}\exp\left(\frac{x}{\overline{\overline{P_r}}}\right){\rm d}x = 1 - \exp\left(-\frac{\gamma_{\rm th}N_0}{\overline{\overline{P_r}}}\right), \quad (16)$$

where $\overline{P_r}\left(x\right) = P_R^t K_{CR}(d_0/d2)^n \varepsilon_{\rm RB}$. The OP at the given device position can be obtained by inserting (15) and (16) in (14).

$$P_{\rm out}\left(d1,\ d2,dI,\gamma_{\rm th}\right) = 1 - \frac{P_{r({\rm AR})}}{P_{r({\rm AR})}+P_{r_I({\rm AR})}}\exp\left(-\frac{\gamma_{\rm th}N_0}{P_{r({\rm AR})}}\right) + 1 - \exp\left(-\frac{\gamma_{\rm th}N_0}{P_r}\right)$$
$$-\left(1 - \frac{P_{r({\rm AR})}}{P_{r({\rm AR})}+P_{r_I({\rm AR})}}\exp\left(-\frac{\gamma_{\rm th}N_0}{P_{r({\rm AR})}}\right)\right)\left(1 - \exp\left(-\frac{\gamma_{\rm th}N_0}{P_r}\right)\right). \quad (17)$$

7 Performance and simulation analysis

This section presents the numerical and simulation results for our proposed relay selection scheme. The simulation parameters are shown in Table 1. Maximum 100 MTC devices are considered in an area with variable packet arrival rate. We are comparing the performance of our proposed scheme with fixed (i.e., stationary) relay, single mobile relay (i.e., existing MTC offloading schemes) and multiple fixed relays. The stationary relays are randomly distributed in the simulation area. Throughout the text, we are interchangeably using the terms fixed and stationary for all those relays which have fixed deployment at a particular area. The MTC network is divided into geographic areas with fixed and mobile relays. We also consider multiple fixed relay selection scheme with the maximum of 4 relays.

Our proposed multiple mobile relay scheme is based on two hop relaying and the relay selection is based on trust relationship between nodes. Most of the recent research work considered dual-hop relaying schemes like in [10,15,37,43,44] mainly for a fact that MTC services are mostly delay intolerant.

Table 1 Simulation parameters

Parameter	Value
Time slot (T)	1 ms
Channel bandwidth	180 kHz
Packet size	64 kb
Reference distance d_0	1 m
Energy consumption/packet	50 J/d_0
Number of stationary relays randomly distributed	4
Speed of UE	1–3 m/s
Maximum MTC device-UE distance ($d1$)	50 m
Maximum UE-BS distance ($d2$)	200 m
MTC device transmit power (A-R)	18 dBm
MTC device transmit power (A-B)	25 dBm
Time interval to send aggregated data ($\mathcal{T}$)	5 s

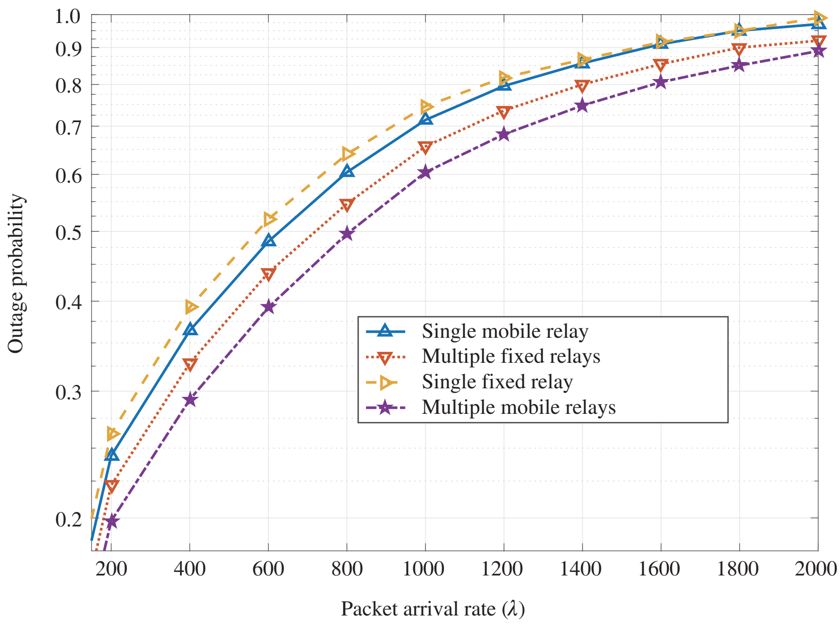

Figure 6 (Color online) Outage probability for different packet arrival rates.

Refs. [43, 44] consider clustered based approach and introduces the cluster head which acts as a data aggregator while [10, 15, 37] considered mobile data aggregators. Following the same footsteps, we also proposed a two-hop scheme and compared our scheme with these existing mechanisms.

The outage probability is analyzed in Figure 6. Our proposed multiple mobile relay scheme is compared with single fixed, multiple fixed and single mobile relay selection schemes. The evaluation is performed on the basis of varying packet arrival rate λ. Figure 6 shows that the outage probability increases with the increase in packet arrival rate. The single fixed relay selection scheme suffers more as compared to other schemes because there are not enough radio resources available to cater the high number of packets. Similarly, the performance of single mobile relay is slightly better than single fixed relay but also suffers due to the same reason. However, multiple fixed relays perform better as compared to single relays because of the availability of more radio resources. Our proposed multiple mobile relay selection scheme outperforms other schemes by significantly reducing the outage probability. At $\lambda = 400$, our proposed scheme improves the outage by 33% as compared to fixed relay selection scheme. The multiple mobile relays not only provide more radio resources to support plenitude of MTC devices but also reduce the

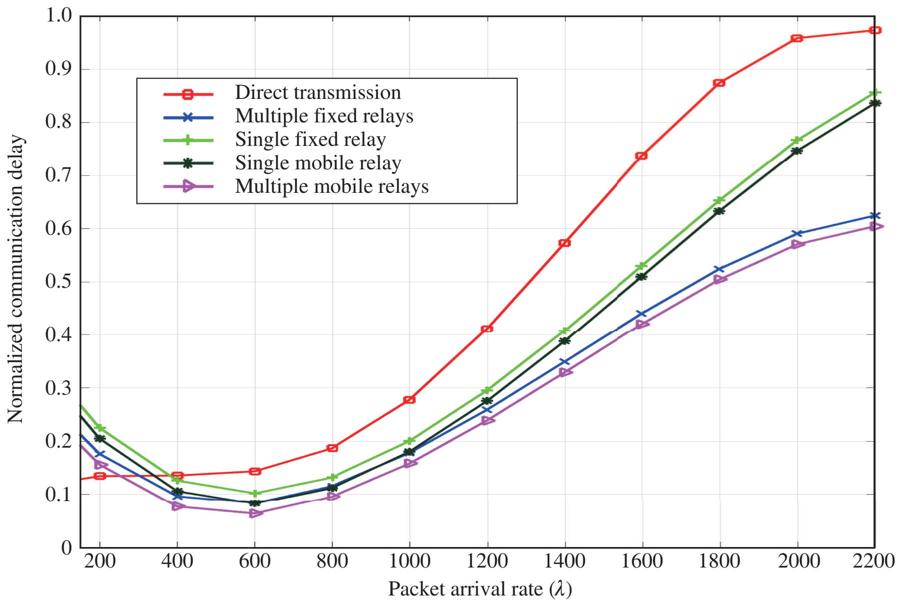

Figure 7 (Color online) Communication delay with different packet arrival rates.

communication distance due to their nature of mobility.

The normalized communication delay is considered in Figure 7. The communication delay is defined as the amount of time from the transmitter MTC device to the BS. Although, it is not feasible for multitude of MTC devices, however we have also considered direct communication of MTC devices to the BS along with single fixed/mobile relay selection schemes. The results in Figure 7 shows the minimum delay for lower packet arrival rate (λ) for direct transmission. However, with increased packet arrival rate, the delay increases exponentially. The performance of the direct transmission is better for the low packet arrival rate because it does not involve the delay induced by the relay selection and dual hop communication. In other words, for the lower packet arrival rate, direct data transmission is delay efficient, however it is not energy efficient for obvious reasons. Similarly, the performance of single fixed and mobile relay is not significantly different. However, the use of multiple relays significantly improves the communication delay with respect to increasing packet arrival rate. The increased packet arrival rate results in increasing the queuing delay for single mobile/fixed relay schemes. For $\lambda = 1800$, our proposed relay selection scheme improves the communication delay by 25% as compared to single fixed relay. The improvement is due to the availability of multiple relays and reduced queuing delay.

Energy efficiency is another performance metric used to evaluate the given relay selections schemes. We consider 50 J per packet per reference-distance as baseline energy consumption. The energy efficiency performance is shown in Figure 8. Two scenarios are considered: namely delay tolerant and delay intolerant. In delay tolerant scenario, MTC devices can wait longer before they transmit their data to their respective relays. The longer wait time allows different relay devices to come in close proximity of MTC devices. We can see in Figure 8, that the performance of single-fixed and -mobile relay (delay intolerant) is comparable with increasing number of MTC devices. However, in case of delay tolerance the single mobile relay improves significantly as compared to its other counterpart. Similarly, our proposed multiple mobile relay scheme improves the energy efficiency in both scenarios as compared to multiple fixed relays. For number of MTC devices = 50, our proposed multiple mobile relay scheme improves the energy efficiency upto 70% as compared to single relay scheme in delay intolerant scenario.

As a final point, system capacity is considered for evaluation as shown in Figure 9. The system capacity is calculated as the sum of all the MTC devices' capacities. With the increase in packet arrival rate λ, the system capacity improves for all the relay selection schemes. However, the increase in the proposed multiple mobile relay scheme is significant as compared to others. Our proposed scheme, due to its multiplicity nature, better manages the higher packet arrival rate by reducing the packet drop rate. Our

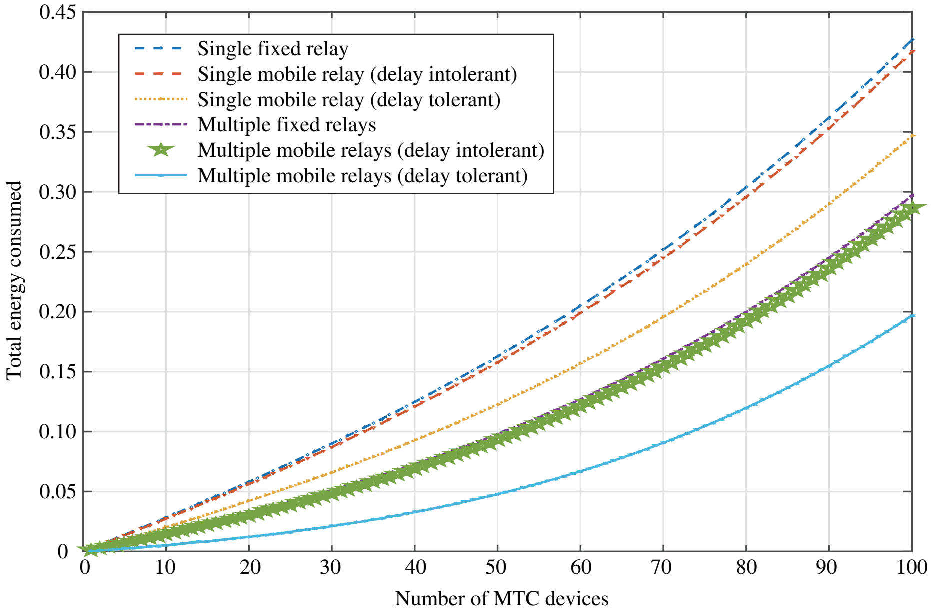

Figure 8 (Color online) Energy consumption for increasing number of MTC devices.

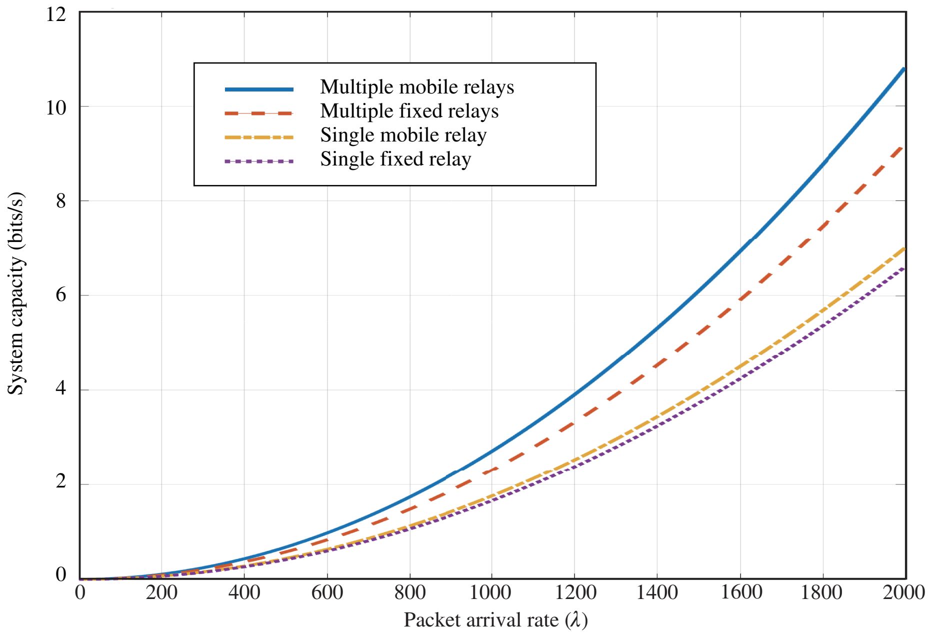

Figure 9 (Color online) System capacity for increasing packet arrival rate.

proposed multiple mobile relay scheme improves the system capacity by 15% at $\lambda = 1200$ as compared to multiple fixed relay scheme.

Overall, our proposed multiple mobile relay scheme outperforms single fixed relay, single mobile relay and multiple fixed relays on the basis of outage, energy efficiency, system capacity and communication delay.

8 Conclusion

Our proposed scheme employs relay multiplicity and a framework to support a set of trusted relays to smartly aggregate MTC data and to provide two-hop access to the BS. MTC devices suffer from massive access and battery depletion, which ultimately results in outage and increased end to end delay. This paper discusses the framework to enhance the security in MTC network by considering trust relationship between UEs. It also proposes the multiple mobile relay scheme to provide two-hop access to the MTC devices to transmit their aggregated data to the BS. The proposed scheme employs cooperative aggregation of multiple UEs, resulting in reduced load on relay devices. The outage probability analysis shows that our proposed multiple mobile relay scheme outperforms single fixed and mobile relay selection schemes, in addition to multiple fixed relays algorithm. Furthermore, the performance of multiple mobile relay is further evaluated using communication delay, system capacity and energy efficiency. The simulations results confirm that our proposed scheme performs better by significantly improving the results as compared to other relay selection schemes.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 61325006, 61461136002) and 111 Project of China (Grant No. B16006).

Conflict of interest The authors declare that they have no conflict of interest.

References

1 Hossain E, Hasan M. 5G cellular: key enabling technologies and research challenges. IEEE Instrum Meas Mag, 2015, 18: 11–21

2 Guo J, Durrani S, Zhou X Y, et al. Massive machine type communication with data aggregation and resource scheduling. IEEE Trans Commun, 2017, in press

3 Ali A, Shah G A, Farooq M O, et al. Technologies and challenges in developing machine to machine applications: a survey. J Netw Comput Appl, 2017, 83: 124–139

4 Chen S Y, Ma R F, Chen H H, et al. Machine-to-machine communications in ultra-dense networks—a survey. IEEE Commun Surv Tutor, 2017, 19: 1478–1503

5 Ghavimi F, Chen H H. M2M communications in 3GPP LTE/LTE-A networks: architectures, service requirements, challenges, and applications. IEEE Commun Surv Tutor, 2015, 17: 525–549

6 Ericsson. More than 50 billion connected devices. Technical Report, 2011

7 Lien S Y, Chen K C, Lin Y. Toward ubiquitous massive accesses in 3GPP machine-to-machine communications. IEEE Commun Mag, 2011, 49: 66–74

8 Dawy Z, Saad W, Ghosh A, et al. Toward massive machine type cellular communications. IEEE Wirel Commun, 2017, 24: 120–128

9 Ge X H, Chen J Q, Wang C X, et al. 5G green cellular networks considering power allocation schemes. Sci China Inf Sci, 2016, 59: 022308

10 Rigazzi G, Pratas N K, Popovski P, et al. Aggregation and trunking of M2M traffic via D2D connections. In: Proceedings of IEEE International Conference on Communications, London, 2015. 2973–2978

11 Asadi A, Wang Q, Mancuso V. A survey on device-to-device communication in cellular networks. IEEE Commun Surv Tutor, 2014, 16: 1801–1819

12 Belleschi M, Fodor G, Abrardo A. Performance analysis of a distributed resource allocation scheme for D2D communications. In: Proceedings of IEEE GLOBECOM Workshops (GC Wkshps), Houston, 2011. 358–362

13 Zhang G P, Yang K, Liu P, et al. Using full duplex relaying in device-to-device (D2D) based wireless multicast services: a two-user case. Sci China Inf Sci, 2015, 58: 082301

14 Zhang G P, Liu P, Yang K, et al. Orthogonal resource sharing scheme for device-to-device communication overlaying cellular networks: a cooperative relay based approach. Sci China Inf Sci, 2015, 58: 102301

15 Atat R, Liu L, Mastronarde N, et al. Energy harvesting-based D2D-assisted machine-type communications. IEEE Trans Commun, 2017, 65: 1289–1302

16 Nosratinia A, Hunter T E, Hedayat A. Cooperative communication in wireless networks. IEEE Commun Mag, 2004, 42: 74–80

17 van-der Meulen E C. Three-terminal communication channels. Adv Appl Prob, 1971, 3: 120–154

18 Ur Rehman W, Salam T, Xu J, et al. Capacity enhancement in 60 GHz based D2D networks by relay selection and scheduling. Int J Antenn Propag, 2015, 2015: 205163

19 Song C, Lee K J, Lee I. Designs of MIMO amplify-and-forward wireless relaying networks: practical challenges and solutions based on MSE decomposition. IEEE Access, 2017, 5: 9223–9234

20 Ur Rehman W, Salam T, Tao X F. Relay selection schemes in millimeter-wave WPANs. In: Proceedings of International Symposium on Wireless Personal Multimedia Communications (WPMC), Sydney, 2014. 192–197

21 Xing C W, Ma S D, Zhou Y Q. Matrix-monotonic optimization for MIMO systems. IEEE Trans Signal Process, 2015, 63: 334–348

22 Ur Rehman W, Salam T, Tao X F. Vertex multi-coloring scheduling algorithm for concurrent transmission in 60-GHz networks. In: Proceedings of IEEE Global Communications Conference (GLOBECOM), Austin, 2014. 4751–4757

23 Genc V, Murphy S, Yu Y, et al. IEEE 802.16J relay-based wireless access networks: an overview. IEEE Wirel Commun, 2008, 15: 56–63
24 Xing C W, Ma Y, Zhou Y Q, et al. Transceiver optimization for multi-hop communications with per-antenna power constraints. IEEE Trans Signal Process, 2016, 64: 1519–1534
25 Mohammed A H, Dai B, Huang B X, et al. A survey and tutorial of wireless relay network protocols based on network coding. J Netw Comput Appl, 2013, 36: 593–610
26 Saghezchi F B, Radwan A, Rodriguez J. Energy-aware relay selection in cooperative wireless networks: an assignment game approach. Ad Hoc Netw, 2017, 56: 96–108
27 Xing C W, Gao F F, Zhou Y Q. A framework for transceiver designs for multi-hop communications with covariance shaping constraints. IEEE Trans Signal Process, 2015, 63: 3930–3945
28 Satish Kumar D, Nagarajan N. Relay technologies and technical issues in IEEE 802.16j Mobile Multi-hop Relay (MMR) networks. J Netw Comput Appl, 2013, 36: 91–102
29 Wang Y, Tao X F, Zhang X F, et al. Cooperative caching placement in cache-enabled D2D underlaid cellular network. IEEE Commun Lett, 2017, 21: 1151–1154
30 Rebecchi F, de Amorim M D, Conan V, et al. Data offloading techniques in cellular networks: a survey. IEEE Commun Surv Tutor, 2015, 17: 580–603
31 Nishiyama H, Ito M, Kato N. Relay-by-smartphone: realizing multihop device-to-device communications. IEEE Commun Mag, 2014, 2–11
32 Andreev S, Pyattaev A, Johnsson K, et al. Cellular traffic offloading onto network-assisted device-to-device connections. IEEE Commun Mag, 2014, 52: 20–31
33 Zhang S, Wu J, Qian Z Z, et al. MobiCache: cellular traffic offloading leveraging cooperative caching in mobile social networks. Comput Netw, 2015, 83: 184–198
34 Meng Y, Jiang C X, Chen H H, et al. Cooperative device-to-device communications: social networking perspectives. IEEE Netw, 2017, 31: 12–18
35 Alim M A, Pan T, Thai M T, et al. Leveraging social communities for optimizing cellular device-to-device communications. IEEE Trans Wirel Commun, 2017, 16: 551–564
36 Ma Z, Zhang Z Q, Ding Z G, et al. Key techniques for 5G wireless communications: network architecture physical layer and MAC layer perspectives. Sci China Inf Sci, 2015, 58: 041301
37 Pratas N K, Popovski P. Underlay of low-rate machine-type D2D links on downlink cellular links. In: Proceedings of IEEE International Conference on Communications Workshops (ICC), Sydney, 2014. 423–428
38 Steri G, Baldini G, Fovino I N, et al. A novel multi-hop secure LTE-D2D communication protocol for IoT scenarios. In: Proceedings of 23rd International Conference on Telecommunications (ICT), Thessaloniki, 2016. 1–6
39 Pereira C, Aguiar A. Towards efficient mobile M2M communications: survey and open challenges . Sensors, 2014, 14: 19582–19608
40 Wu G, Talwar S, Johnsson K, et al. M2M: from mobile to embedded Internet. IEEE Commun Mag, 2011, 49: 36–43
41 Ometov A, Orsino A, Militano L, et al. Toward trusted, social-aware D2D connectivity: bridging across the technology and sociality realms. IEEE Wirel Commun, 2016, 23: 103–111
42 Nitti M, Girau R, Atzori L. Trustworthiness management in the Social Internet of Things. IEEE Trans Knowl Data Eng, 2014, 26: 1253–1266
43 Zhao Z W, Szyszkowicz S, Beitelmal T, et al. Spatial clustering in slotted ALOHA two-hop random access for machine type communication. In: Proceedings of IEEE Global Communications Conference (GLOBECOM), Washington DC, 2016. 1–6
44 Ho C Y, Huang C Y. Energy-saving massive access control and resource allocation schemes for M2M communications in OFDMA cellular networks. IEEE Wirel Commun Lett, 2012, 1: 209–212