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Community-based Random Access Scheme for M2M Communications in LTE Networks

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***Abstract*—Supporting Machine-to-Machine (M2M) communications has been an essential requirement for the Long Term Evolution (LTE) networks. To cope with the massive access requests with stringent delay requirements, in this paper, a community-based random access scheme is proposed by exploiting the spatial correlation of Machine-Type Devices (MTDs). Specifically, a community detection algorithm is first proposed to form the community structure of the network, based on which one MTD is selected in each community to establish a connection with the base station upon each emergency event. Simulation results corroborate that by reducing the number of access requests, the proposed scheme can significantly improve the delay performance especially in the massive access scenarios with a limited number of preambles.**

***Index Terms*—Machine-to-Machine (M2M) communications, random access, LTE, community structure, delay.**

I. Introduction

Machine-to-Machine (M2M) communications refers to a novel category of communication paradigms, in which the Machine-Type Devices (MTD) can communicate with each other or remote servers automatically without human intervention. Different from the traditional human-type devices, which are greedy in terms of data rate, MTDs that sporadically report data triggered by the reporting period or certain external events could have a strict requirement on latency, especially for the alarm reporting M2M services such as tsunami warning [1].

To facilitate M2M communications, the cellular system, i.e., the Long Term Evolution (LTE) network, has been widely regarded as a suitable solution owing to its ubiquitous coverage [2]. However, supporting the stringent delay requirement of M2M services is not a trivial issue especially in the massive access scenarios [3]. Specifically, when many MTDs attempt to initiate connection with the Base Station (BS), such a large amount of access requests will cause severe congestion, frequent access transmission failures and poor delay performance. For alarm reporting M2M applications, for instance, thousands of devices may try to send the alert simultaneously upon the detection of an emergency event [1]. It is therefore of great practical importance to improve their access performance in LTE networks.

Substantial endeavors have been made in the existing literature to improve the access efficiency of M2M communications in LTE network, where a major focus has been put on the tuning of key system parameters including backoff parameters and the number of preambles. For instance, various algorithms were proposed to dynamically adjust the Access Class Barring (ACB) factor or the Uniform Backoff (UB) window size of each MTD or system resources for random access based on the periodical estimation of the channel traffic load [4]–[8]. In our recent work [9], the optimal tuning of ACB factor and UB window size was proposed for maximizing the throughput based on statistical information such as the traffic input rate of each MTD. To improve the delay performance, cooperative access control schemes were proposed in [10] to adjust the transmission probability of each MTD in neighboring cells. Fixed or adaptive resource allocation schemes were also introduced in [11], [12] to allocate different amounts of random access resources to M2M applications with distinct delay requirements.

Note that a key assumption in the above studies is that the information each MTD delivers is spatially uncorrelated, so that the BS has to establish the connection with every MTD to receive their packets. This assumption, however, may not be in line with many alarm reporting M2M applications. A showcase example is the smart metering in which MTDs are placed over transmission lines to measure the grid state, and a power outage event may trigger lots of neighboring MTDs to report the same blackout alert [1]. In this scenario, it is inefficient and unnecessary for the BS to establish connections with every single MTD. To reduce the number of connections, clustering schemes were introduced [13]–[15], in which the cluster head would first aggregate the packets from other MTDs and then access the BS to relay those packets. In those studies, however, the main focus is placed on optimizing the data aggregation process, which may not be applied to alarm reporting scenarios where the primary concern is to minimize the access delay of alarming messages.

In this paper, a community-based random access scheme for M2M communications in LTE networks is proposed to support the alarm reporting M2M services. Specifically, a community detection algorithm is proposed to form the community structure of the network, where a community refers to a fully connected subnetwork in which each MTD can communicate with another MTD. For MTDs that are closely located, the spatial correlation is exploited in the four-step random access process. That is, upon the detection of an emergency event, all affected MTDs in a community transmit the same preamble immediately while only one MTD finally establishes the connection with the BS. Thanks to the orthogonality of preambles, no control information exchange is required for the cooperation in the random access process, implying that no additional signaling overhead and time expense is introduced. Simulation results

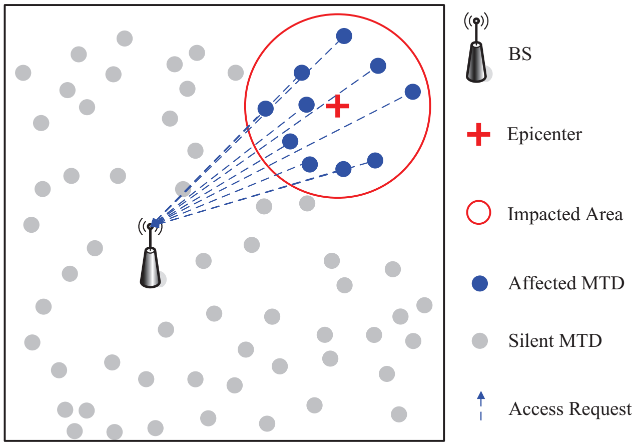

Fig. 1. A graphical illustration of the network scenario.

corroborate that with the proposed community-based random access scheme, significant gains in delay performance can be achieved, especially in the massive access scenarios, e.g., the total number of MTDs is large or the emergency event has a large-scale geographic impact area.

The rest of the paper is organized as follow. Section II introduces the system model. Section III illustrates the random access procedure in standard. The proposed community-based random access scheme is presented in Section IV and simulation results are provided in Section V. Finally, the concluding remarks are given in Section VI.

II. System Model

Consider a single-cell LTE system with a set of MTDs $\mathbf{V} = \{1, 2, \ldots, n\}$. Without loss of generality, we assume that each MTD has a fixed transmission range d by properly setting its transmission power. For any two MTDs, they are neighbors if they are within the transmission range of each other.

We assume that all MTDs run the alarm reporting service [1], such as tsunami warning service. Specifically, an MTD remains silent unless the emergency event is detected, upon which the MTD will access the BS and send the alarming message. If the alarming message is successfully sent, then the MTD returns to the silent mode until the next emergency event is detected. Note that, in general, the emergency event has its specific impact area and thus may not trigger all MTDs in the network. In this paper, we consider that each emergency event has a circular-shaped impact area with radius d_r, and regard the location of the emergency event as the *epicenter*. Once an alarm event occurs, all MTDs in the impact area can be aware of it immediately. A graphical illustration of the network scenario is presented in Fig. 1.

Note that a connection-based random access scheme is adopted in LTE networks, that is, each device with data packets to transmit first sends a connection request to the BS, and if a device's request is successfully received, then the BS will allocate resource blocks for the device to transmit its data packets, i.e., the alarming message. In the next section, we present the random access procedure of the LTE networks to explain how an MTD establishes a connection with the BS.

III. Conventional Random Access Procedure in LTE Networks

According to the current LTE standard [16], the random access procedure of an MTD contains four steps:

1) The MTD randomly chooses one out of M orthogonal preambles and sends the selected preamble to the BS.
2) For each detected preamble, the BS replies a random access response, in which the BS indicates a reserved uplink resource unit.
3) The MTD uses the indicated uplink resource unit to transmit *RRCConnectionSetup* message to inform the BS that it has an uplink data transmission demand.
4) If the *RRCConnectionRequest* message is successfully decoded, then the BS responses with *RRCConnectionSetup* message to confirm that the connection is established. Otherwise, the access request fails and the MTD has to perform the Uniform Backoff (UB) scheme, in which it randomly selects a value from $\{0, \ldots, W\}$, where W is the UB window size, and counts down in each time unit until it reaches zero. The MTD then starts from Step 1 again.

Upon the successful connection establishment, the BS allocates uplink radio resource for the MTD to transmit its alarming message.

As the number of preambles M is limited, i.e., much smaller than the number of MTDs, it is likely that multiple MTDs would choose the same preamble in Step 1. The BS, however, cannot distinguish if a particular preamble is sent from a single MTD or multiple MTDs. Therefore, it would assign them a common uplink resource unit, through which multiple *RRCConnectionRequest* messages are sent in Step 3, and none of them can be decoded by the BS. An MTD's access request can be successful if and only if none of other MTDs chooses the same preamble.

It can be expected that massive concurrent access attempts to the BS cause frequent failures and thus intolerably low access efficiency. Intuitively, the BS can choose a larger UB window size W such that the number of access requests in each time unit is reduced and the probability of successful transmission of access requests can be improved. In this case, however, larger delay may be caused for successfully delivering an alarming message. In the next section, we will propose a community-based random access scheme for M2M communications in LTE networks. It will be demonstrated that with the proposed scheme, significant gains in delay performance can be achieved, especially in the massive access scenarios.

IV. Community-based Random Access Scheme

The main idea of the proposed community-based random access scheme is to reduce the number of MTDs that transmit *RRCConnectionRequest* messages in Step 3 of the random access procedure by leveraging cooperation among the MTDs that are neighbors to each other.

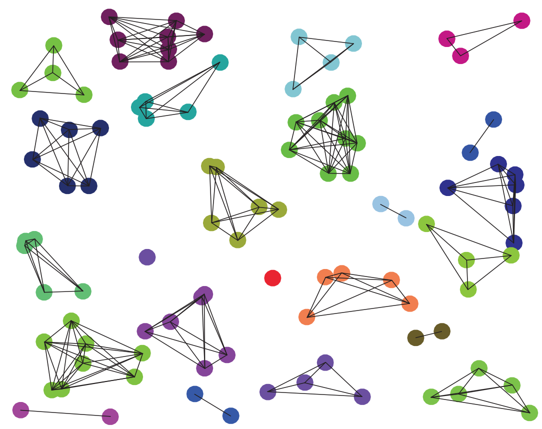

Fig. 2. Consider a square-shaped network, where the side length of 1 and the transmission range of each MTD $d = 0.2$. $n = 100$. Each dot denotes an MTD and the dots with the same color indicate a community.

Specifically, based on connections among neighboring MTDs, a distributed community formulation algorithm will be used to find all communities in the network. The community structure that we are interested in is a clique, i.e., a fully-connected subnetwork, where all MTDs in the same community can communicate with each other directly. Upon the occurrence of an emergency event, the MTDs in the same community will use the same preamble to access the BS, and thus get the same uplink resource unit from the BS for *RRCConnectionRequest* transmission in Step 3. Different from the conventional random access procedure in which each of those MTDs independently transmits their own *RRCConnectionRequest* through the same resource unit, which leads to a failure, with the proposed community-based random access scheme, only one delegated MTD in the affected community performs the *RRCConnectionRequest* transmission. Therefore, the number of contending MTDs can be efficiently reduced.

In the following, we elaborate on the proposed community-based random access scheme in more details:

1) Initialization: In the initialization stage, the community structures of the network are formed. Specifically, upon the deployment of the network, each MTD discovers its neighbors in a distributed fashion, where $\mathbf{N}_v$ denotes the set of neighbors of MTD v and $v \in \mathbf{V}$, and then delivers $\mathbf{N}_v$ to the BS. Based on $\mathbf{N}_v$ of each MTD, the BS can formulate an undirected graph $\mathbf{G} = \{\mathbf{V}, \mathbf{E}\}$, where $\mathbf{E}$ denotes the set of edges, i.e., links among MTDs, and then perform clique detection.

Note that the clique detection in an undirected graph is an NP-hard problem and various heuristic algorithms have been proposed [17]–[19]. In this section, we will develop a clique detection algorithm, i.e., Algorithm 1, based on the classic Bron-Kerbosch algorithm [19], which is denoted by the function *Bron-Kerbosch*$(\mathbf{G})$. For an undirected graph $\mathbf{G}$, *Bron-Kerbosch*$(\mathbf{G})$ returns a clique set, denoted by $\mathbf{C}_{BK}$, which contains all maximal cliques in graph $\mathbf{G}$, where a maximal clique is a clique that is not a subset of a larger clique.

Details of the proposed Algorithm 1 are presented at the top of this page.

Algorithm 1 Clique Detection Algorithm

```
Input the undirected graph G and initialize the clique set C = ∅.
repeat
    C_BK ← Bron-Kerbosch(G)
    C_max ← {C_j ∈ C_BK : |C_j| ≥ |C_j'|, ∀C_j' ∈ C_BK}
    C ← C ⋃ C_max
    V ← V \ C_r, E ← E \ E_{v∈C_r}
until V = ∅
Output the clique set C.
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Specifically, it takes a graph $\mathbf{G}$ as input and outputs a clique set $\mathbf{C}$ that comprises of non-overlap cliques where each MTD belongs to one single clique. For the inner-loop, the maximal clique set $\mathbf{C}_{BK}$ can be obtained based on *Bron-Kerbosch*$(\mathbf{G})$. Note that the cliques in $\mathbf{C}_{BK}$ may overlap with each other, indicating that an MTD could be contained by multiple cliques. In this regard, only one single clique with the largest size in $\mathbf{C}_{BK}$, denoted by $\mathbf{C}_{\max}$, is chosen and added into $\mathbf{C}$. The graph $\mathbf{G} = \{\mathbf{V}, \mathbf{E}\}$ is then updated by subtracting vertexes in $\mathbf{C}_{\max}$ from $\mathbf{V}$ and edges $\mathbf{E}_{v\in\mathbf{C}_{\max}}$ that connect to any $v \in \mathbf{C}_{\max}$ from $\mathbf{E}$. The above operation repeats until $\mathbf{V} = \emptyset$.

Let $L_1, L_2, \ldots, L_u$ denote the communities in $\mathbf{C}$ and $u = |\mathbf{C}|$. For each community $L_j, j = 1, 2, \ldots, u$, the BS further generates a transmission pair $\{X^{L_j}, R^{L_j}\}$, where X^{L_j} is a preamble randomly selected from $\{1, 2, \ldots, M\}$ and R^{L_j} is the delegated MTD randomly selected from L_j. Finally, the BS broadcasts $\mathbf{C}$ and $\{X^{L_j}, R^{L_j}\}, j = 1, 2, \ldots, u$, to all MTDs.

It is worth mentioning that the community formulation process is both time- and energy-consuming, since it requires a neighbor discovering process and the information exchange between MTDs and the BS. However, for many M2M applications, the locations of MTDs are usually fixed [2]. Therefore, the community formulation only needs to be performed once, i.e., upon the deployment of the network. The time and energy cost of the community formulation is negligible for the long run.

2) Community-based Random Access: In the random access stage, the MTDs in a community can cooperate with each other in the random access procedure. More details of the community-based random access will be elaborated based on the example shown in Fig. 3:

1) Upon the occurrence of the emergency event, the affected MTDs follow Step 1 of the conventional random access procedure to transmit the preamble, as shown in Section III. Different from the conventional random access procedure where each MTD transmits a randomly selected preamble, in the proposed scheme, the affected MTDs in community L_j transmit the assigned preamble, i.e., preamble X^{L_j}. Note that as the delegated MTD R^{L_j} are neighbors to all other MTDs in the community L_j, it can hear transmissions of the preamble X^{L_j}.
2) After receiving the preamble X^{L_j}, the BS follows Step 2 of the conventional random access procedure by replying

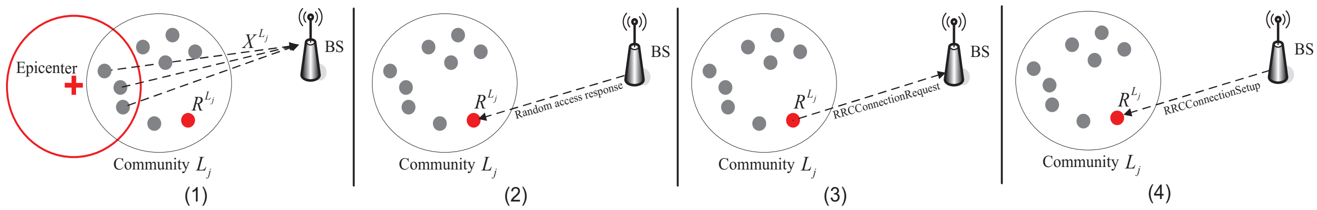

Fig. 3. A graphic illustration of the community-based random access scheme.

a random access response, in which a reserved uplink resource unit is indicated.

3) Only the delegated MTD R^{L_j} in community L_j uses the indicated uplink resource unit to transmit *RRCConnection-Request* message by following Step 3 of the conventional random access procedure, even though the delegated MTD could be out of the impact area of the emergency event, as shown in Fig. 3.
4) If the *RRCConnectionRequest* message is successfully decoded, then the BS follows Step 4 of the random access procedure by replying *RRCConnectionSetup* message to confirm that the connection is established. Otherwise, the access request fails, in which case the delegated MTD R^{L_j} performs the UB scheme and then retransmits the access request by following the conventional random access procedure.

Upon the successful connection establishment, the delegated MTD R^{L_j} can obtain uplink radio resource from the BS for alarming message transmission.

It can be seen that in an alarm event reporting, no matter how many MTDs in a community are affected, only the delegated MTD replies the *RRCConnectionRequest* message. By reducing the number of requests, the probability of success and the delay performance can be greatly improved. Moreover, we can also see that no coordination or control information exchange is required among the affected MTDs and the delegated MTD in the random access process, thanks to the orthogonality among preambles. It indicates that compared to the conventional random access procedure, the proposed community-based random access procedure does not introduce any additional signaling overhead and time expense.

V. Simulation Results

In this section, we present simulation results to evaluate the performance of the proposed community-based random access scheme. In simulations, we consider a square-shape cellular scenario, as illustrated in Fig. 1. Without loss of generality, the side length is normalized as 1.

The simulation is on time-slot base and the length of each time slot is long enough such that the four-step random access procedure can be completed within one time slot. The UB window size W is fixed, as the standard does [20], and is preselected as 4 time slots. Each simulation run starts with a random deployment of MTDs and the epicenter, based on which the communities are formed according to Algorithm 1,

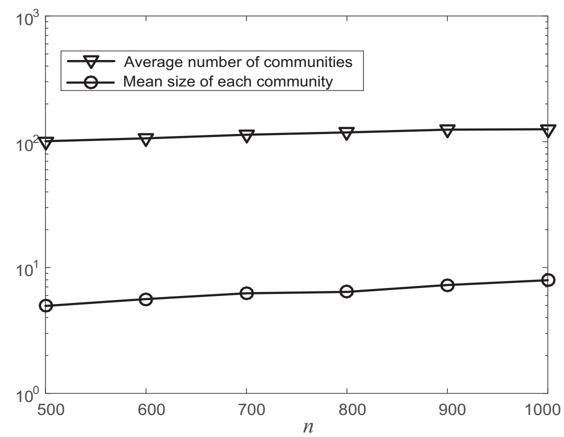

Fig. 4. Average number of communities and mean size of each community versus the number of MTDs n. $d = 0.1$.

and the transmission pairs $\{X^{L_j}, R^{L_j}\}, j = 1, 2, \ldots, |\mathbf{C}|$, are generated. The emergency event occurs at slot $t = 1$, and then all affected MTDs start the alarm reporting by following the proposed community-based random access scheme. A simulation run ends when all alarming messages are successfully received.

In this paper, we are interested in the access delay performance of MTDs, where the access delay of an MTD is defined as the time spent from the detection of the emergency event, i.e., slot $t = 1$, until its access request is successfully received. It is worth mentioning that for many alarm reporting M2M applications, such as the earthquake warning system, how fast the first alarming message is successfully received is of great practical interest and importance. Accordingly, in this paper, we evaluate the delay performance based on the mean access delay of the first successful access request, which is denoted by D_f. Specifically, in each simulation run, we count the access delay of the first successful access request from affected communities. The simulation runs are repeated for 10^3 times. The mean access delay of the first successful access request is then obtained by calculating the ratio of the sum of access delay of the first successful access request in each simulation run to 10^3.

Note that the delay performance of the proposed community-based random access scheme closely depends on the community structure of the network. Accordingly, let us start by analyzing the community structure that is formed according to Algorithm 1 based on two metrics: the average number

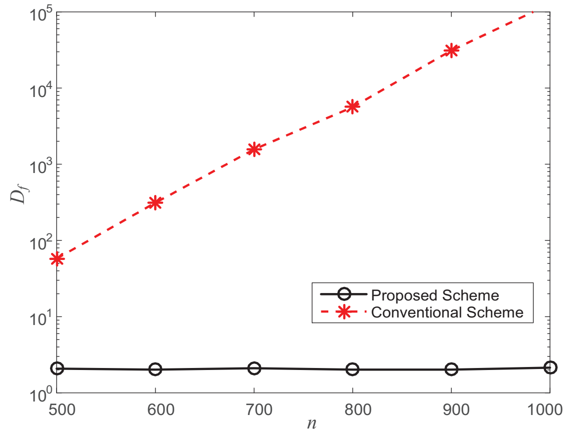

Fig. 5. Mean access delay of the first successful access request D_f (in unit of time slots) versus the number of MTDs n. $M = 10$. $W = 4$. $d = 0.1$. $d_r = 0.7$.

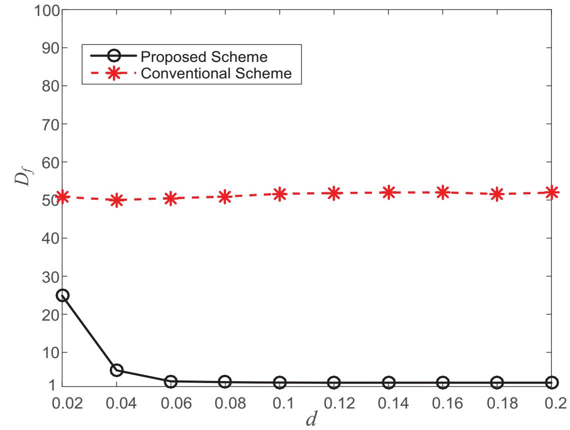

Fig. 7. Mean access delay of the first successful access request D_f (in unit of time slots) versus the transmission range of each MTD d. $n = 500$. $M = 10$. $W = 4$. $d_r = 0.7$.

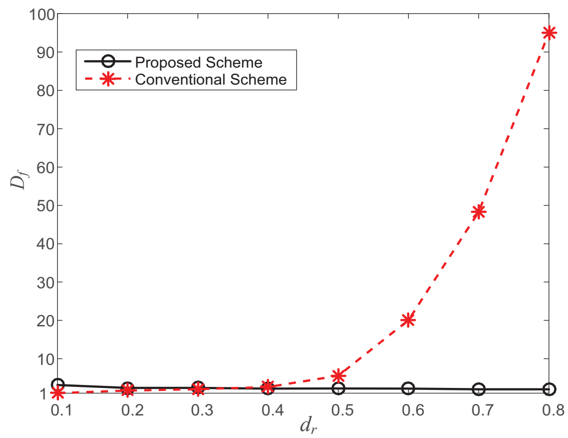

Fig. 6. Mean access delay of the first successful access request D_f (in unit of time slots) versus the radius of the emergency event impact area d_r. $n = 500$. $M = 10$. $W = 4$. $d = 0.1$.

of communities and the mean size of each community. As Fig. 4 shows, when the number of MTDs n increases, each community includes more MTDs. Yet, the average number of communities is insensitive to n. Recall that with the proposed community-based random access scheme, no matter how many MTDs are affected in a community, only the delegated MTD transmits the access request. The number of access requests is then determined by the number of affected communities, which is significantly smaller than the total number of MTDs, and almost keeps constant as n increases.

Intuitively, by substantially reducing the number of access requests, the access delay performance can be greatly improved. Fig. 5 demonstrates how the mean access delay of the first successful access request D_f varies with the number of MTDs n, where the number of preambles $M = 10$, the transmission range of each MTD $d = 0.1$ and the radius of the emergency event impact area $d_r = 0.7$. It can be clearly seen from Fig. 5 that in contrast to the conventional random access scheme, where D_f quickly increases with the number of MTDs n, with the proposed scheme, the delay performance is insensitive to the variation of n. Significant gains can be achieved especially when the number of MTDs n is large.

Note that for given number of MTDs n, if the radius of the emergency event impact area d_r increases, the number of affected MTDs would also increase, leading to more access requests if the conventional random access scheme is adopted. As we can see from Fig. 6, the mean access delay of the first successful access request D_f with the conventional scheme drastically increases with the radius of the emergency event impact area d_r when d_r exceeds 0.5. In contrast, with the proposed community-based random access scheme, D_f remains at a low level regardless of the increase of d_r, which is highly attractive when the emergency event has a large-scale geographic impact area, such as tsunami and earthquake. We can also see from Fig. 5 and Fig. 6 that the improvement brought by the proposed scheme in delay performance is significant especially in the massive access scenario.

Fig. 7 further demonstrates how the mean access delay of the first successful access request D_f varies with the transmission range of each MTD d. Note that with a larger d, each MTD connects to more neighbors, leading to fewer communities and fewer access requests. Therefore, we can see from Fig. 7 that the delay performance of the proposed scheme can further be improved as the transmission range of each MTD d increases.

Note that the delay performance can also be improved by using more orthogonal preambles. The improvement, nevertheless, may become marginal when the number of access requests is small. To see the effect of the number of preambles M on the delay performance, Fig. 8 further illustrates the mean access delay of the first successful access request D_f when M varies from 6 to 20. It can be seen from Fig. 8 that the performance gain over the conventional random access scheme is significant only when M is small. Nevertheless, for given delay requirement, much fewer preambles are needed with the proposed community-based random access scheme.

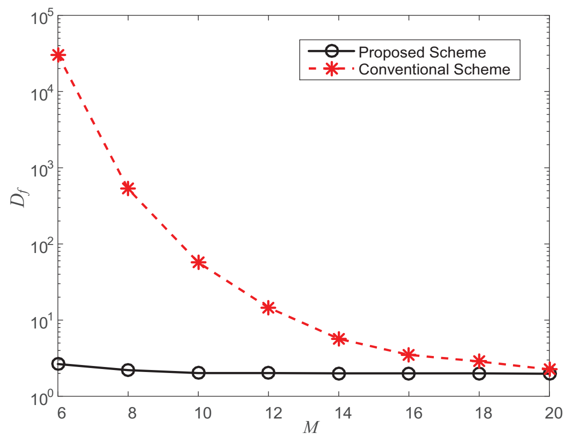

Fig. 8. Mean access delay of the first successful access request D_f (in unit of time slots) versus the number of preambles M. $n = 500$. $W = 4$. $d = 0.1$. $d_r = 0.7$.

VI. Conclusion

In this paper, we propose a community-based random access scheme for alarm reporting M2M communications in LTE networks. A community detection algorithm is first proposed to detect the community structure among the MTDs. In each community, by leveraging cooperation among the MTDs and the orthogonality of preambles, only the delegated MTD establishes a connection with the BS no matter how many MTDs are triggered by the emergency event. The simulation results demonstrate that in contrast to the conventional random access scheme where the delay performance drastically deteriorates as the total number of MTDs or the size of the emergency event impact area increases, with the proposed community-based random access scheme, the mean access delay of the first successful access request remains at a low level regardless of the variation of the number of affected MTDs. The gain is especially significant in the massive access scenarios, indicating that the proposed scheme is promising for being used in a wide spectrum of alarm reporting services with stringent delay requirements.

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