Spatial Clustering in Slotted ALOHA Two-Hop Random Access for Machine Type Communication

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***Abstract*—The LTE random access procedures proposed in 3GPP for Machine Type Communication in current cellular systems may become overwhelmed when too many machine devices attempt to upload their data. In this paper, we propose a two-hop cluster random access based on slotted ALOHA communication. In each cluster, a cluster head (CH) is selected according to the channel gains. The CH aggregates data from cluster members and then initiates the LTE random access procedure to the base station. Due to the offloading from the random access channel to the slotted ALOHA, the number of contending devices is reduced, which alleviates the collision problem and results in better performance. The simplification of access procedure can also significantly decrease the energy consumption. We define a clustering metric for machine locations and we examine the impact of the metric on the performance. The simulation results show that as machine locations become more clustered, the overall performance improves.**

I. Introduction

An unprecedented market growth of machine devices is expected in the near future. Many machines will connect to the Internet, forming the Internet of Things (IOT), which empowers a full automatic communication system between machines without necessary human intervention [1], [2]. Machine-to-machine (M2M) communication has a wide range of applications, such as smart metering, tracking and tracing, automatic payment, eHealth, surveillance, and security [3].

The realization of M2M communication could rely on current LTE cellular networks, because of the easier infrastructure installation, and also the support of reliable long distance M2M communications, especially with mobility [4]. However, traditional cellular networks designed for human-centric device communications may not support M2M communications effectively, which have distinctive features such as: a large number of terminals, small data transmissions, low mobility, time tolerance, and group-based features [3]. A major challenge for M2M communication is to handle the massive simultaneous access requests. A medium access control (MAC) procedure for M2M is proposed in [5]. Machines send connection requests through physical random access channels (PRACHs). If two requests use the same channels concurrently, there will be a collision. The overload access signalling in random access channel (RACH) can lead to large delay, packet loss, and even service unavailability. Thus, a tailored solution is needed to adapt cellular networks to M2M characteristics and accommodate a large number of machines.

To efficiently adapt to the characteristics of M2M traffic, several studies proposed random access methods based on the clustering [6]–[10]. An improved random access method is proposed in [6] in response to group paging, where the paging intervals are separated into three periods for data aggregation and random access. Thus it decreases the number of machines that perform direct access attempts and alleviate the RACH congestion. In [7], a cluster head (CH) performs the random access procedure on behalf of all the machines in a group, and cluster members (CMs) take turns to transmit data on the channels allocated for the CH. In [8], [9], a CH is elected in each cluster to process the access attempts from the CMs. The network spatially reuses the random access resources to support more machines. The inter-cluster interference is also analyzed with the conclusion that it does not affect the results and full reuse of the random access resources in each cluster is feasible. In [10], cognitive radio technology is used for CH gathering the traffic from multiple machines to avoid interference with the primary link between users and the base station (BS). The cluster-based methods mentioned above either use the LTE random access procedure or the time division multiple access (TDMA) method to implement the communication within a cluster. However, the former method puts high requirements on the function of the CH, and the TDMA method is inconsistent with the nature of bursty MTC traffic and may waste channel resources.

In this paper, we propose a slotted ALOHA-based two-hop cluster random access method. In this method, the CH aggregates data from CMs through slotted ALOHA and then initiates the LTE random access procedure to the BS. Due to the offloading from the RACH to the slotted ALOHA, the number of contending machines in the RACH is reduced resulting in fewer collisions and better performance. The access procedure is also simplified, which decreases the power consumption. We also introduce a clustering geometry model for M2M locations. This model is more suitable for the current LTE networks with the feature of random and cluster, such as body networks, personal residences, and commercial buildings. We examine the impact of location clustering on the performance. Simulation results show that as the machine locations are more clustered, the overall performance improves.

The remainder of the paper is organized as follows: In Section II, we introduce the LTE random access procedure and the general two-hop clustering communication method.

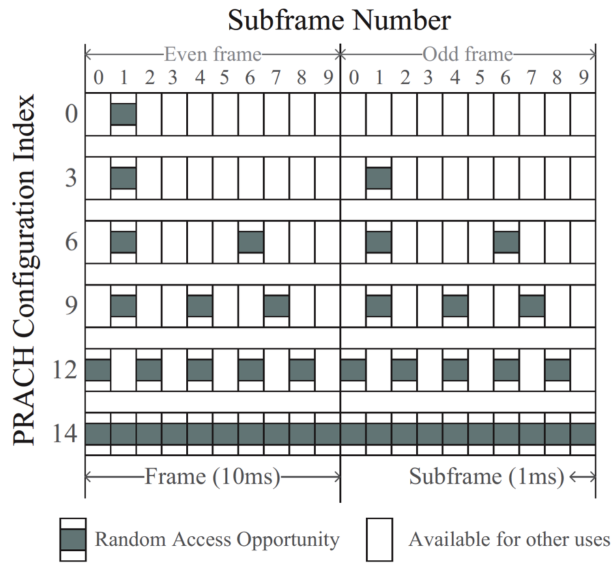

Fig. 1. PRACH configuration. Source: [11].

In Section III, we explain the system model, introduce the hierarchical clustering algorithm, and examine the CoV-based clustering metrics. Simulation results are summarized in Section IV. Finally, we conclude our work in Section V.

II. Related Work

A. LTE One-Hop Random Access Procedure

In an LTE network, a machine device triggers a random access procedure whenever it needs to set up connection with the eNodeB. In this random access procedure, all machines directly connect to the eNodeB in one hop. They send access requests to the eNodeB through the RACH. The RACH consists of a number of subframes for random access opportunities (RAOs), which are released every few subframes according to the specific configuration, as depicted in Fig. 1. The handshake consists of a four message signalling exchange, the details of which are depicted in Fig. 4 (a) [5], [11].

Msg1 is the preamble transmission. The device waits for the next random access slot and randomly selects a preamble to transmit. If two or more devices choose the same preamble simultaneously, a collision occurs. After the device transmits Msg1, it waits for the Random Access Response (RAR) until a time window (RAR_{window}) expires. Msg2 is the response to the preambles transmitted in Msg1. The detection of the preamble collision in Msg1 depends on the arrival time at the eNodeB. If a collision is detected, the devices will perform a random back-off before retrying another access. Msg3 is the connection request message, after which the device waits for the acknowledgement until the contention resolution timer (CR_{timer}) expires. Msg4 is an acknowledgement message to Msg3. After a machine successfully receives Msg4, its random access procedure is regarded as complete.

We build a simulator of the LTE one-hop random access procedure based on the parameters from 3GPP [12], [13].

TABLE I
Simulation parameter setup

Symbol	Parameter	Value
B	Cell bandwidth	5 MHz
-	PRACH configuration index	6
$N_{preamble}$	Total number of preambles	54
$Max_{preamble}$	Maximum number of preamble transmissions	10
RAR_{window}	Ra-Response WindowSize	5 ms
CR_{timer}	Mac-contentionResolutionTimer	48 ms
BI	BackoffTimer	20 ms
-	Probability of successful delivery for both Msg3 & Msg4 (non-adaptive HARQ)	90%
$Msg3_{max}$	Maximum number of Msg3 transmissions	5
-	Number of MTC devices	5k, 10k, 30k
-	Number of available subframes over the distribution period	10k, 60k
T_{Msg1}	Msg1 transmission time	1 ms
T_{Msg2}	Preamble detection at eNodeB & Msg2 trans. time	3 ms
T_{Msg3}	Device processing time before sending Msg3	5 ms
$T_{TransMsg3}$	Msg3 transmission time	1 ms
T_{Msg4}	Time of processing Msg3 & sending Msg4	5 ms
T_{Tx}	Time of packet transmission in slotted ALOHA	1 ms
T_{RESP}	Response window size in slotted ALOHA	5 ms
T_{Rx}	Time of packet processing & acknowledgement transmission time	3 ms
P_{idle}	Power consumption in idle state	0.025 mW [14]
P_{Rx1}	Power consumption of processing and Rx in RACH	50 mW [14]
P_{Tx1}	Power consumption during Tx in RACH	50 mW [14]
P_{Rx2}	Power consumption of processing and Rx in slotted Aloha	25 mW [15]
P_{Tx2}	Power consumption during Tx in slotted Aloha	25 mW [15]

TABLE II
Validation of LTE random access simulator with 3GPP results

Performance Measures	Number of MTC devices			
	5k	10k	30k	Result Origin
Collision Probability (%)	0.01	0.03	0.22	3GPP [12]
	0.01	0.03	0.23	Simulation
Access Success Probability (%)	100	100	100	3GPP [12]
	100	100	100	Simulation
Average Access Delay (ms)	25.6	26.0	27.3	3GPP [12]
	28.2	28.5	29.6	Simulation
Average Preamble Trans (%)	1.43	.145	1.50	3GPP [12]
	1.43	1.45	1.50	Simulation

The parameters are presented in Table I. In our simulator, the random access procedure is run subframe by subframe. Fig. 2 shows the flowchart of our simulator in each subframe. Table II shows a match between our simulation and 3GPP [12].

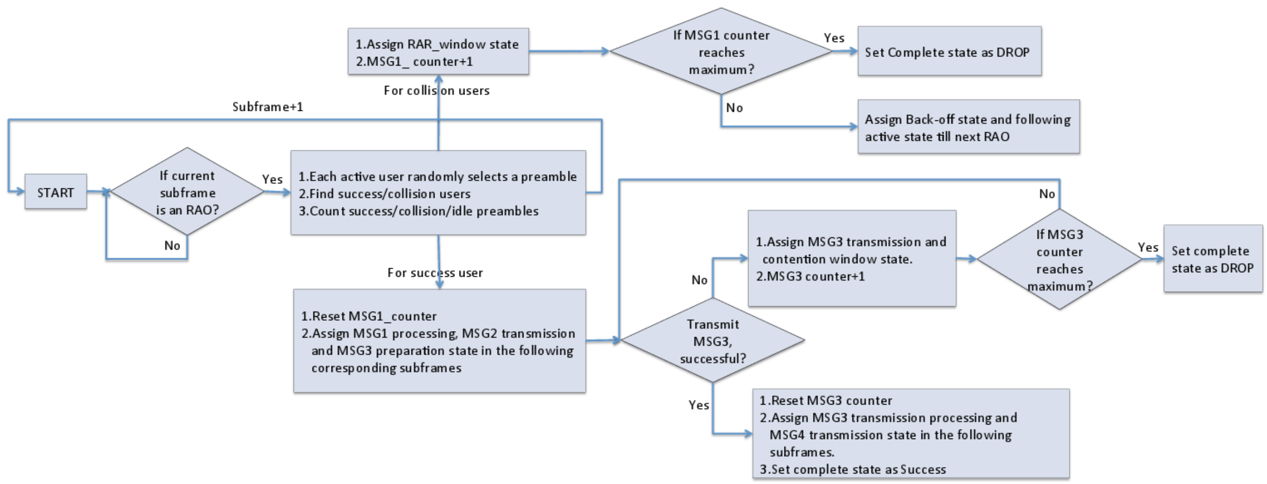

Fig. 2. Flowchart of LTE random access procedure in one subframe.

B. Two-Hop Cluster-Based Random Access

To efficiently adapt to the characteristics of a network like LTE, cluster-based random access is proposed for MTC. Machines gather into logical clusters and a CH is selected within each cluster as a relay to aggregate data from CMs and forward it to the eNodeB. This method is particularly suitable for, e.g., smart metering applications, where nodes are static or of low-mobility. Thus the structure of a cluster can be maintained for a long time without frequent re-organization. Most of the data from sensors is delay-tolerant. Hence, the data can wait for the accumulation in the CH buffer, and be forwarded to the eNodeB in one package. In this method, the traffic can be shaped into a small number of bulky loads, which is more appropriate for cellular networks.

Cluster-based schemes have many benefits for MTC communication. Most machines upload data to the CH and only the CHs contend in the RACH. Hence, the access load can be dramatically decreased in the RACH, which can significantly alleviate the collision problems. Additionally, a crowd of neighbor sensors associated with the same event may upload similar information, and the CH can perform data compression to reduce the redundancy. The link between CM and CH is usually short-distance and line-of-sight (LOS), which has a better channel gain than the long-distance and non-line-of-sight (NLOS) link between machines and eNodeB. Due to the better channel gains and fewer retransmissions, the energy of machines can be conserved.

III. System Model

A. Slotted ALOHA-Based Cluster Random Access

We first introduce a clustering location generator. Algorithm 1 demonstrates our procedures of generating clustering locations for machines, where M is the number of clusters, N is the number of points, R is the radius of clusters, and $P_{isolated}$ is the probability of a point being isolated from any clusters. Fig. 3 shows an example of our clustering location model. In our model, there are two types of machines. A machine is either a member of a cluster or is an independent node isolated from any clusters.

Algorithm 1: Algorithm for clustering location generator

1 Generate M cluster centroids $\{C_i\}$, $i = 1, \ldots, M$ through a Poisson Point Process.
2 Generate N points:
- For each point, uniformly selects a random variable $X \sim \mathcal{U}(0, 1)$.
- If $0 < X \leq P_{isolated}$, randomly choose a location for the point.
- If $P_{isolated} < X \leq 1$,
  - randomly select a centroid $C_k, k \in [1, M]$.
  - randomly locate the point within a circle with radius R and center C_k.

After obtaining the machine locations, we use a hierarchical clustering algorithm to cluster the machines and select a CH in each cluster based on the channels between the machines and the BS. In the time domain, we assume that each machine has one packet to transmit and the arrival time is randomly distributed over the whole random access period (10s). There are two hops of communication in our model. In the first hop, CMs upload packets to their CH through slotted ALOHA communication, and in the second hop, once the buffer of the CH reaches a certain level, the CH performs a random access procedure to set up the connection with the BS. Fig. 4 shows the details of random access procedure between machine and BS, and the slotted ALOHA procedure between CM and CH. We assume all packet transmissions can be finished within one subframe. The BS sends back an acknowledgement in response to the reception of a packet. If a transmission fails, the device backs off for a random period after the expiration of the response window, and retransmits the packet. It is

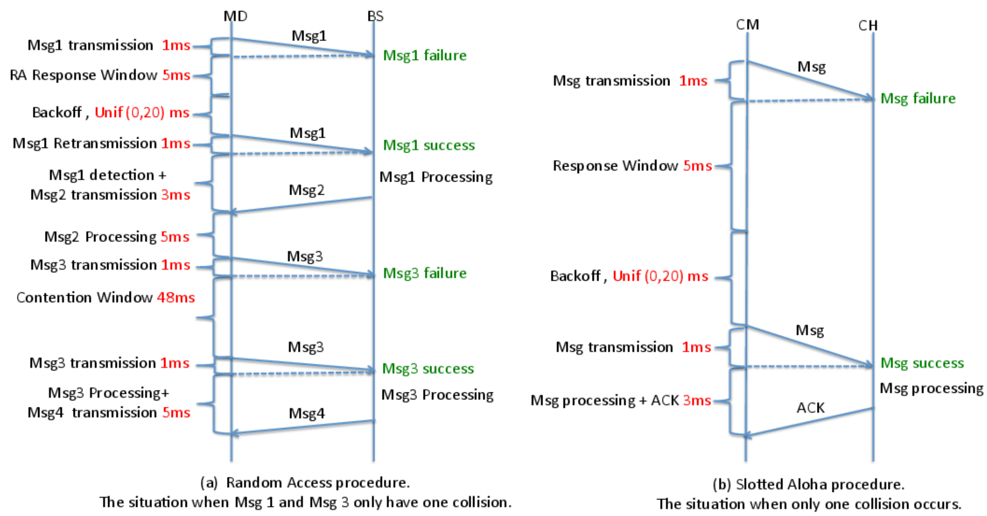

Fig. 4. (a) Random access procedure details assuming Msg1 and Msg3 both have one collision (b) slotted ALOHA procedure details assuming only one collision occurs.

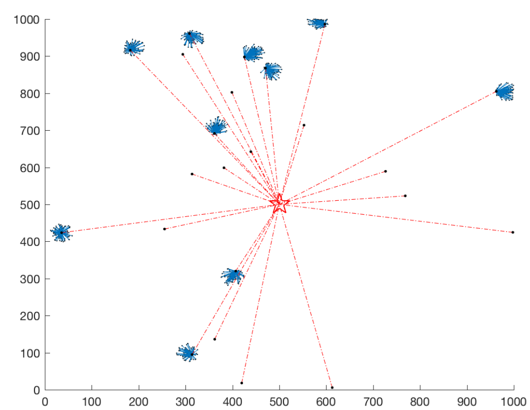

Fig. 3. An example of clustering location model and the output of hierarchical clustering. The blue links are the slotted ALOHA communication between the CM and the CH, and the red links are the LTE random access procedure between CH and BS. The inputs of our location generator are $N = 1000$, $M = 10$, $R = 25$, and $P_{isolated} = 0.01$.

also assumed that the buffer in the CH has no limit, so that the uploaded packets cannot be dropped by the CH due to insufficient storage. The resources (slots) for slotted ALOHA are migrated from the original RACH resources in order to keep a fair comparison with the reference method. From the original resources, we allocate one subframe for the RACH every 100 RAOs. All the clusters fully reuse the resources for slotted ALOHA communication. Hence, interference exists, and it can arise from both inside and outside the cluster. We assume a packet can be successfully decoded by the CH only if the SINR is greater than 20dB. The SINR is calculated on the basis of the M2M channel model in [15]. The path loss is $48.9 + 40\ \log(D)$, where D is the distance between two machines in meters. The shadowing standard deviation and noise figure is 8dB and 9dB, respectively. The maximum transmission power is 14 dBm. It is worth noting that the channel model between the machine and the BS is not needed in this work, because collisions in the RACH only depend on the selection of random access channels.

B. Hierarchical Clustering

In this paper, we use the hierarchical clustering algorithm [16] to cluster the points. Fig. 3 shows the results using this algorithm. Lines are used to indicate cluster grouping. A group of nodes linking to a same point constitute a cluster, and that point is the CH. In the results, we can also observe that an individual node can become a cluster itself when it is far away from all the other machines and becomes isolated. From the figure, it can be seen that the hierarchical clustering algorithm works well for the clustered points.

C. CoV-Based Clustering Metrics and Location Generator

1) CoV of Voronoi cell areas : In [17], it is proposed to use a scaled coefficient of variation (CoV) of the Voronoi cell areas to measure the traffic clustering. The Voronoi tessellation is defined as follows:

Given a point set $P = \{p_1, p_2, ..., p_n\}$, the Voronoi tessellation $T = \{C_{p1}, C_{p2}, ..., C_{pn}\}$ is the set of cells such that every location, y $\in C_{pi}$, is nearer to p_i than any other point in P. This can be expressed formally as

$$C_{pi} = \{y \in \mathbb{R}^d : \|y - p_i\| \leqslant \|y - p_j\| \text{ for } i, j \in 1, ..., n\}. \quad (1)$$

Fig. 5 shows the Voronoi tessellation of a clustered point pattern. The CoV of a random value is defined as the ratio of its standard deviation to its mean. The CoV-based metric of Voronoi cell areas is defined as:

$$C_V = \frac{1}{k} \cdot \frac{\sigma}{\mu}, \qquad k \approx 0.529, \quad (2)$$

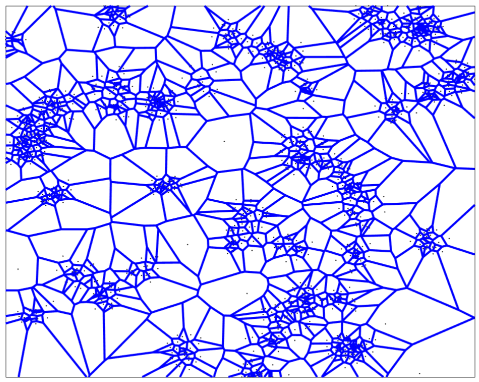

Fig. 5. Voronoi tessellation of geographical clusters of nodes.

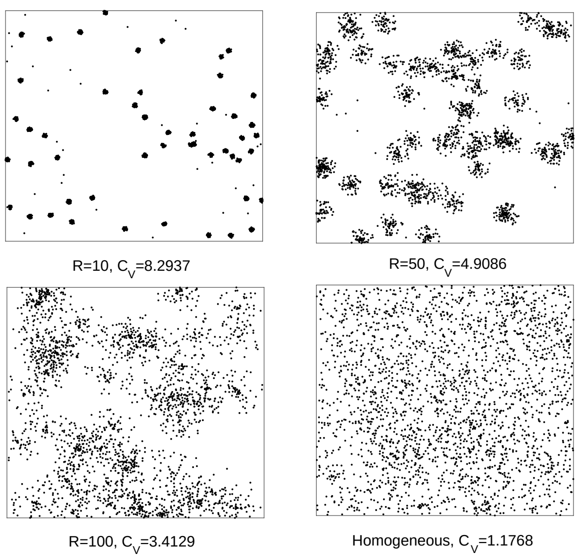

Fig. 6. Clustering machine locations with different R and C_V, with N=2500, $P_{isolated}$=0.01 and M=50.

where μ is the mean and σ is the standard deviation of the Voronoi cell areas, and k is factor to normalize C_V to 1 when the points are taken from a Poisson point process (PPP). Fig. 6 shows different points patterns and their C_V. The first three subfigures show clustered points, with a cluster radius of 10, 50, and 100 meters, respectively. The last subfigure shows PPP points. As is seen from Fig. 6, as the machine locations become more clustered, the value of C_V increases.

2) C_V and the inputs of the location generator: In this part, we examine the relationship between the location generator and C_V, so that we can control C_V by tuning the inputs of our location generator. Fig. 7 shows the behavior of C_V versus the inputs N, M, R, and $P_{isolated}$. As can be seen in Fig. 7(a), varying the number of clusters M can only provide a C_V of over approximately 5. In Fig. 7(b) the number of devices is not fixed, which cannot satisfy our needs either. In Fig. 7(c)

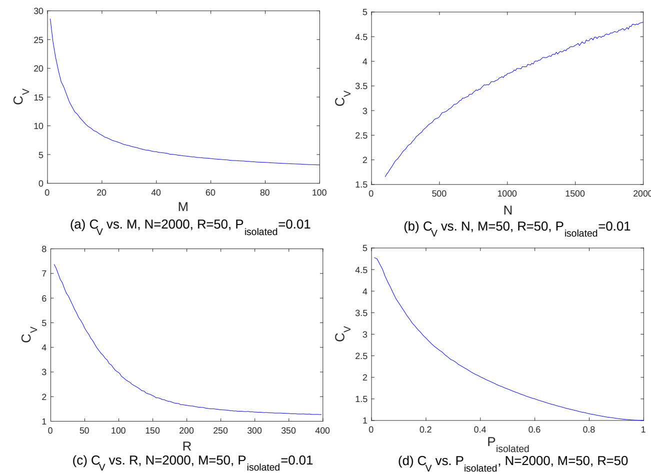

Fig. 7. Relationship between C_V and the inputs of location generator.

and Fig. 7(d), varying the cluster radius and the probability of isolated node can offer a proper range of C_V starting from 1. From Fig. 7(c) it can be observed that when the cluster radius is small, the geometry is highly clustered, with a larger C_V. As the cluster radius increases, different clusters will overlap with each other, and will merge together and lose their distinct boundaries. The locations will become homogeneous and the value of C_V will drop to 1 (as in the PPP). Similarly with $P_{isolated}$, it can also provide a proper range of C_V. In this work, we choose R as the tuning parameter for C_V.

IV. Simulation Results

Based on our one-hop random access simulator, we integrate the clustering location generator, hierarchical clustering algorithm, and the two-hop slotted ALOHA communication. The simulator is run subframe by subframe until all machines complete their access procedure.

We examine the impact of spatial clustering metric on a group of performance metrics: total transmission times, average access delay, collision/success probability, and energy consumption. We compare the reference one-hop method (Sec. II-A) with the proposed two-hop method (Sec. III-A). Fig. 8 shows the results.

It can be observed that, as C_V increases, the overall performance remains the same for the reference method, while it improves for the proposed method. This is because in the reference method it is the number of machines rather than the geometry of their locations that is relevant to the performance. Whereas, in the proposed method, when C_V is higher, the geometry of the machines is more clustered and different clusters are farther away from each other, which results in less interference in the slotted ALOHA communication, and therefore the overall performance is improved. It can also be observed that when C_V is greater than about 3, our proposed method outperforms the reference method.

In Fig. 8(d), the energy consumed by the machines in the proposed method is only 20% of that in the reference one.

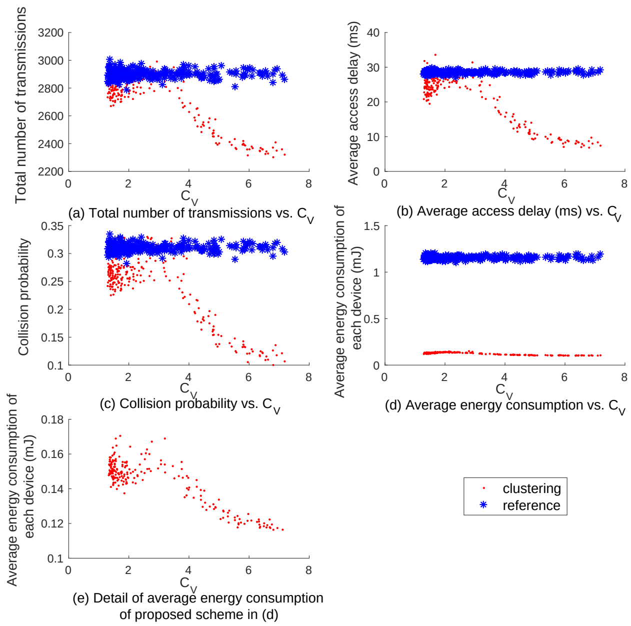

Fig. 8. Performance vs. C_V. C_V is varied by tuning the cluster radius R. The other inputs of location generator are: the number of clusters $M = 50$, the number of devices $N = 2000$, and the probability of isolated node $P_{isolated} = 0.01$.

Here the energy consumption in the proposed scheme only considers the CM devices, because CH could be assigned as a special device with sufficient battery power, the energy of which is not a critical issue. This difference mainly results from the different access procedures in the two methods. In the reference method, a machine device experiences a four-message exchange, while in the proposed method, most of the devices go through the slotted ALOHA procedure. According to Fig. 4, it can be seen that the slotted ALOHA procedure only consists of the repetitions of transmission, a response waiting window, and a backoff period, which are less complicated than the random access procedures. Therefore, the energy consumption can be dramatically decreased.

V. Conclusion

In this paper, we proposed a slotted ALOHA-based two-hop cluster random access method to improve the performance of MTC. In this method, the CH aggregates data from CMs through slotted ALOHA and then initiates the LTE random access procedure to the BS. Due to the offloading from RACH to slotted ALOHA communication, the number of contending devices is greatly reduced in the RACH. The utilization of the slotted ALOHA method also simplifies the access procedure, which can decrease the energy consumption of machines. We also introduce a clustering geometry model for M2M locations, and define a clustering metric. Our results show that as the machine locations become more clustered, the overall performance metrics improve. In particular, the energy consumption is dramatically decreased, which is the main contribution of our proposed method.

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