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Clustering-Enabled Prioritized Access Control for Massive Machine-Type Communications in Smart Grid

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***Abstract*—In this paper, we propose a massive access control scheme in machine-type communications (MTC) aided smart grid, which prioritizes and clusters the devices based on the latency requirement and the distance between devices. The considered use case features a single cell in the massive connectivity smart grid and a large number of devices with different priority types. For the delay-sensitive devices, a dynamic random access channel (RACH) resource allocation scheme is proposed, where a back-off mechanism is used to defer the access requests of delay-tolerance devices. In addition, we propose a cluster-based congestion control algorithm, which clusters the devices to establish local collaboration. Simulation results show the proposed scheme reduces the average blocking probability, while significantly reducing access delay for delay-sensitive devices compared with state-of-the-art access control methods.**

***Index Terms*—massive access, channel access control, priority, clustering**

I. INTRODUCTION

Smart grid (SG) has enhanced the conventional way of power supply and consumption, which can effectively detect the power usage and dispatch the power supply accordingly [1]. There are mainly three types of MTC devices in smart grid with different delay requirements, which are metering automation, distributed energy, and emergency command. The main function of metering automation devices is to upload the electricity information. Distributed energy devices can achieve the power grid balance and increase the power grid's reliability. And the emergency command devices requires emergency access when they are triggered. With the development of distributed energy, the device connectivity will reach ten million level. Note that, the delay requirement for the emergency command device is millisecond level [2]. Hence, highly efficient coordination mechanisms for massive access are essential for information delivery in smart grid.

Due to limited radio resources, the congestion problem is the most urgent issue. The connection establishment usually adopts the random access (RA) mechanism because it can be executed without central regulation [3]. However, conventional access technologies can be difficult to meet the access requirements for massive access. Existing studies propose several solutions, for example, 3GPP has identified candidate overload solutions, including the separation or dynamic allocation of random access channel (RACH) to MTC devices, back-off scheme, and access class barring scheme [4]. The authors in [5] propose an adaptive ACB (DACB) algorithm that dynamically adjusts the ACB factor. A new protocol structure is proposed in [6], where each contention time slot is concatenated by a data transmission slot. However, the performance improvement is still limited due to massive access [7]. As a result, the accumulated access delay and packet loss can make the quality-of-service (QoS) guarantee challenging.

Some works prioritize device transmission opportunities by using distributed binary sequences. A random access method is proposed in [9], which designs the access probabilities for each group with different delay requirement. More comprehensive channel access coordination is needed for delay guarantee with massive access. In this paper, we propose a clustering-enabled prioritized channel access control mechanism in machine-type communications (MTC) aided smart grid, which prioritizes and clusters the devices. The main contributions of this paper are three-folded:

- To guarantee the access delay requirement, we propose a prioritized channel access control (PCAC) scheme, which includes dynamic allocation of RACH resources with back-off. Dedicated RACH resources are dynamically allocated to the delay-sensitive devices. And we optimize the number of it according to the number of activated devices. Moreover, the back-off mechanism is used to defer access requests from delay-tolerant devices.
- To further reduce the access blocking rate, a clustering-based congestion mitigation algorithm is proposed. We cluster the devices, and devices in the same cluster will select idle resources when accessing by direct communication, which can effectively reduce collisions.
- The performance of the proposed algorithm is compared with the DACB algorithm and the machine-to-machine-OSA (M2M-OSA) algorithm. Simulation results show that the proposed scheme reduces the average blocking probability, while significantly reducing access delay for delay-sensitive devices.

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II. System Model

In this section, we present the network model, the traffic model, and the allocation of time and frequency resources.

A. Network Model

Consider a single cell access network with one base station (BS) located in the center of the cell. An illustration of the considered access network is given in Fig. 1.

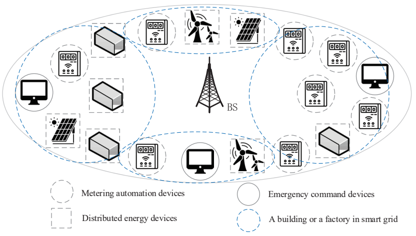

Fig. 1. An illustration of the access network in smart grid scenarios.

MTC devices in the smart grid have different delay requirements, and we divide the priority of the devices according to the delay requirements in actual engineering. The delay requirements of metering automation devices are about 3s, and the delay requirements of distributed energy devices such as distributed photovoltaics and wind power are less than 1s. The ideal delay of the emergency command devices such as relay protection and video surveillance should be less than 200ms.

We denote delay-tolerant devices for metering automation as low-priority devices, while delay-sensitive devices for emergency commands are denoted as high-priority devices. We also denote distributed energy devices as medium-priority devices. We divide the N MTC devices into N_h high-priority devices, N_m medium-priority devices, and N_l low-priority devices, where $N = N_h + N_m + N_l$.

B. Traffic Model

As for the traffic model, we consider the burst machine-to-machine (M2M) traffic model. This paper considers a scenario where a base station serves N MTC devices. It is assumed that these devices access the network in a synchronous manner. In this model, massive devices activate with a certain probability within a short period of time T_A. According to the 3GPP standard and previous research [5][6], the beta distribution with parameters α and β is used to simulate the burst arrivals of M2M traffic. Based on this, each device is activated with probability $beta(t)$ within time $t \in [0, T_A]$ as follows:

$$\mathrm{beta}(t) = \frac{t^{\alpha-1}\,(T_A - t)^{\beta-1}}{T_A^{\alpha+\beta-1}\mathcal{B}(\alpha,\beta)}, \quad 0 \le t \le T_A, \tag{1}$$

where $\mathcal{B}(\alpha,\beta)$ denotes the beta function $(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}dt$. According to [6], we set $\alpha = 3$ and $\beta = 4$.

We divide the activation time T_A into I_A slots. Slot i starts at time t_i and ends at time t_{i+1}. And we defined i_m as the m mini-slot in slot i. To simplify the model, we assume that a newly activated device in the slot i will only attempt to access for the first time at the beginning of the next slot.

C. Allocation of Time/Frequency Resources

For the allocation of time resources, we adopt the model proposed in [7]. We divide a time slot into s mini-slots. A time slot is divided into two distinct periods: the contention period and the data transmission period. The base station broadcasts a maximum retransmission limit, O_m. Whenever a device fails to compete in a time slot, the number of retransmissions O_n increases by one. When $O_n > O_m$, the device will no longer contend for the resources.

As for the frequency resources, we refer to each uplink frequency resource as RB. It is assumed that among the available M RBs, M_h RBs are allocated to high-priority devices, and the remaining $M_t = M - M_h$ RBs are allocated to medium-priority and low-priority devices. Fig. 2 illustrates the time/frequency resources structure in our proposed scheme.

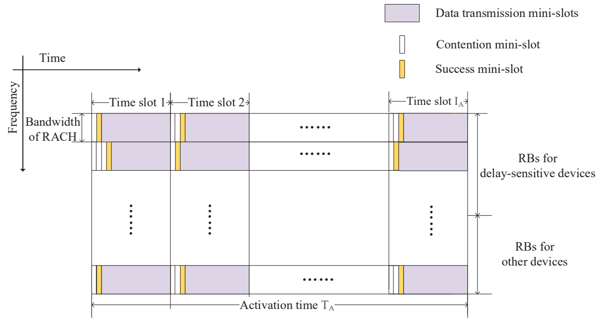

Fig. 2. Structure of the time/frequency resources in our proposed scheme.

III. Clustering-Enabled Prioritized Channel Access Control

In this section, we propose a clustering-enabled prioritized channel access control (CEP-CAC) scheme. We design our scheme in three steps, which are priority-based dynamic access control algorithm, fuzzy c-means (FCM) based clustering algorithm, and clustering-based congestion control algorithm.

A. Priority-Based Dynamic Access Control Algorithm

In this subsection, we propose a priority-based dynamic access control algorithm, which combines the dynamic allocation of RACH and the back-off scheme.

In slot i, we define N_i as the number of devices that attempt to access. We assume that N_i is fully known to the base station based on existing research [5], which can be estimated by drift analysis method [10]. We define $N_{h,i}$, $N_{m,i}$, and $N_{l,i}$ as the number of high-priority, medium -priority, and low-priority devices. According to the actual number of devices in the smart grid, we have $N_{m,i} > N_{l,i} > N_{h,i}$.

To guarantee the delay requirements of devices for emergency commands, we give the highest priority to these devices by allocating $M_{h,i}$ RBs to them. There is a trade-off between resource utilization and the delay of delay-sensitive devices in choosing a proper value of $M_{h,i}$. To obtain a balance between resource utilization and the delay of the high-priority devices, we try to maximize the probability that only one device chooses each RB. We denote the number of devices that select RB m in slot i by $\lambda_{m,i}$. For each allocated RB number $M_{h,i}$, we assume that when $N_{h,i} = r$, then the above probability can be expressed as:

$$\begin{aligned}\mathbb{P}\left(\lambda = 1 \mid N_{h,i} = r\right) &= \sum_{m=1}^{M_{h,i}} \mathrm{P}\left(\lambda_{m,i} = 1 \mid N_{h,i} = r\right) \\ &= r\left(1 - \frac{1}{M_{h,i}}\right)^{(r-1)}.\end{aligned} \tag{2}$$

For each allocated RB numbers $M_{h,i}$, we can obtain the optimal r by taking derivate with respect to r,

$$\begin{aligned}&\frac{d}{dr}\mathbb{P}\left(\lambda = 1 \mid N_{h,i} = r\right) = \\ &\left(1 - \frac{1}{M_{h,i}}\right)^{r-1}\left[1 + r\ln\left(1 - \frac{1}{M_{h,i}}\right)\right].\end{aligned} \tag{3}$$

Let $\frac{d}{dr}\mathbb{P}\left(\lambda = 1 \mid N_{h,i} = r\right) = 0$, we get the corresponding expression of r and $M_{h,i}$,

$$r = \left(\ln\frac{M_{h,i}}{M_{h,i} - 1}\right)^{-1}. \tag{4}$$

If $M_{h,i} > M$, all RBs are allocated to high-priority devices. We can calculate the number of RBs allocated to high-priority devices in each time slot as follows:

$$M_{h,i} = \begin{cases} \left\lceil \dfrac{e^{\frac{1}{N_{h,i}}}}{e^{\frac{1}{N_{h,i}}} - 1} \right\rceil, \left\lceil \dfrac{e^{\frac{1}{N_{h,i}}}}{e^{\frac{1}{N_{h,i}}} - 1} \right\rceil < M \\ M, \left\lceil \dfrac{e^{\frac{1}{N_{h,i}}}}{e^{\frac{1}{N_{h,i}}} - 1} \right\rceil \geq M \end{cases} \tag{5}$$

The back-off scheme is applied when medium-priority devices conflicts with the low-priority devices by setting a back-off indicator (BI). All low-priority devices must wait for T_b mini-slot before resending the access request when a collision occurs. T_b is randomly generated by the devices in the range of 0 to BI, which can be given as $T_b = U(0, BI)$, where $U(.)$ stands for uniform distribution.

The device attempts to access after reaching the back-off time and repeats the above process until a device successfully transmits on the RB. We denote the mini-slots that the device has backed off since the last competition failure as b. Algorithm 1 is the pseudo-code of the proposed algorithm.

B. FCM-Based Clustering Algorithm

In order to obtain more flexible clustering results, the smart grid devices are clustered by the FCM algorithm.

Assume the number of clusters as C, we denote the coordinate vector of device i and the center of cluster j as x_i, c_j. First, we initialize the initial partition matrix $U^{(k)} = [u_{ij}]$, where k is the number of algorithm iterations. u_{ij} tells the degree to which device d_i belongs to cluster j, and value of u_{ij} is assigned a random number in the range of $(0, 1)$.

Then, the weighing average is made with u_{ij} as the weight, and c_j of each cluster is obtained,

$$c_j = \frac{\sum_{i=1}^{N} u_{ij}^2 \cdot x_i}{\sum_{i=1}^{N} u_{ij}^2} \tag{6}$$

Algorithm 1 Priority-Based Dynamic Access Control Algorithm.

```
Input $N_{h,i}$, $s$, $T_b$
calculate $r$ according to (5)
$i = 1$
while devices not yet access successfully do
    if $N_{h,i} > r$ then
        $M_{h,i} = M$, $M_{t,i} = 0$
    else
        $M_{h,i} = \left\lceil \frac{e^{1/N_{h,i}}}{e^{1/N_{h,i}}-1} \right\rceil$, $M_{t,i} = M - M_{h,i}$
    end if
    $i_m = 1$
    while $i_m \leq s$ do
        if delay-tolerant devices then
            if $b > T_b$ then
                transmit access request, $i_m = i_m + 1$
            end if
        end if
    end while
    $i = i + 1$
end while
```

Subsequently, the degree u_{ij} of the devices can be updated according to c_j and matrix $U^{(k)}$. The calculation method of updating u_{ij} is:

$$u_{ij} = \frac{1}{\sum_{k=1}^{C}\left(\frac{\|x_i - c_j\|}{\|x_i - c_k\|}\right)^2}, \tag{7}$$

where the $\|\cdot\|$ is the Euclidean Distance.

Each parameter u_{ij} in $U^{(k)}$ can be updated, and the new partition matrix $U^{(k+1)}$ after the iteration of $K + 1$ is obtained. This process is repeated until the current conditions meet the pre-set iteration stop threshold ε, and generally takes $\varepsilon = 10^{-3}$. The iterative stop conditions are $\max_{ij}\left\{\left|u_{ij}^{k+1} - u_{ij}^{k}\right|\right\} < \varepsilon$. Finally, the algorithm finally stops and the device is classified by comparing the degree value of each u_{ij} of the same device.

At the beginning of each slot, d activate devices are selected from C groups. Only the selected fixed number of devices in each group will attempt to access in this time slot. Device to Device (D2D) communication allows direct communication between closely located devices in the same group. These devices try to select different RBs for access.

C. Clustering-Enabled Congestion Control Algorithm

In this subsection, we introduced the proposed congestion control algorithm based on the clustering results.

After clustering, each chosen MTC device generates a random number from the standard uniform distribution (i.e., $\mathrm{U}[0, 1]$) in each slot, and uses this number as its competing metric, T_n. We set two thresholds T_h and T_l for each RB, and if the contention metric T_n satisfies the condition that $T_h < T_n < T_l$, then the corresponding device is allowed to access. The above procedure will be repeated after the thresholds are changed. Each device receives feedback from the BS, which are denote by f. f is either 0, 1, or e, representing idle, successful transmission, or collision, respectively. If $f = 0$, the RB should adjust the threshold. If $f = 1$, the access is successful. If $f = e$, the RB should narrow the threshold range. Each RB continuously adjusts the threshold until either successful access occurs or the time slot ends.

To adjust the thresholds, we denote the number of devices competing for the same RB as λ. And we define two functions, split and lower functions which are calculated as follows:

$$\operatorname{split}\left(T_l, T_{\mathrm{h}}\right)=\left(\frac{T_l+T_{\mathrm{h}}}{2}\right). \tag{8}$$

$$\operatorname{lower}\left(T_{\mathrm{h}}, \lambda\right)=\begin{cases}T_{\mathrm{h}}+\frac{1}{\lambda} & \text{if } T_{\mathrm{h}}<1 \\ 1 & \text{otherwise}\end{cases}. \tag{9}$$

To limit the upper bound of the splitting algorithm to 1, another threshold T_{hh} is designed. Algorithm 2 is the pseudo-code of the proposed algorithm.

IV. SIMULATION RESULTS

This section provides a detailed discussion to validate our algorithm's performance effectively.

A. Simulation Setup:

The parameters employed in our simulations are listed in Table I. Especially, the total number of MTC devices N is increased from 1,000 to 10,000. In the experiment, two state-of-the-art schemes are chosen for quantitative and qualitative comparisons, namely DACB [7] and M2M-OSA [8].

- DACB scheme [7]: In the simulation, the base station dynamically broadcasts the optimal $P = min(1, M/N_i)$. The value of P depends on the number of activated devices that have not been successfully accessed. Only devices with a random draw less than P will transmit the access request.
- M2M-OSA scheme [8]: It allows devices to draw random numbers and use them in contention if these numbers meet certain criteria based on prespecified thresholds.

TABLE I
SYSTEM MODEL PARAMETERS

Parameter	Value
Number of uplink resources(RBs) M	15
Number of slots per activation time period I_A	100
Number of mini-slots per time slot s	40
Number of attempted access devices per group per time slot d	15
Number of slots per backoff indicator BI	3
Proportion of high, medium and low priority devices $N_h : N_m : N_l$	1:7:2

Algorithm 2 Clustering-Enabled Congestion Control Algorithm Done by Device n.

```
Input $m$, $s$, $\lambda$;
if $O_n \le O_m$ then
    Randomly select a RB that has not been selected by other devices in the same group
    Draw a random number $T_n = \mathrm{U}[0, 1]$
    Initialize $i_m = 1$, $T_l = 0$, $T_h = \frac{1}{\lambda}$, $T_{hh} = 1$
    while ($i_m \le s$ and f $\neq 1$) do
        if $T_h < T_n < T_l$ then
            Transmit access request
        end if
        Receive $f \in \{0, 1, e\}$
        if $f = e$ then
            $T_{hh} = T_h$, $T_h = \mathrm{split}(T_l, T_h)$
        else if $f = 0$ then
            $T_l = T_h$
            if $T_{hh} \neq 1$ then
                $T_h = \mathrm{split}(T_l, T_{hh})$
            else
                $T_h = \mathrm{lower}(T_h, \lambda)$
            end if
        end if
        $i_m = i_m + 1$
    end while
    if f=1 then
        Data Transmission
    else
        $O_n = O_n + 1$
    end if
else
    Device access defeated
end if
```

B. Performance Metrics:

Three commonly used performance metrics are used to evaluate our simulation results.

Blocking probability: This metric is defined as the ratio between the number of defeated devices exceeding the maximum retransmission limit O_m, to the total number of devices N.

Access delay: This metric is defined as the number of time slots elapsed from activated until gaining successful access.

Resource utilization rate: This metric is defined as the average ratio of the number of successfully accessed RBs to the number of all available RBs.

C. Performance Evaluation:

Fig. 3 shows the average blocking probability and average access delay with different numbers of clusters and O_m set to 20. The figure shows the effect of increasing C in decreasing the blocking probability and increasing the access delay.

We examine the average blocking probability with N increasing to 10000 in Fig. 4 with the number of clusters set to 15. The results show the effect of increasing M in decreasing the average blocking probability.

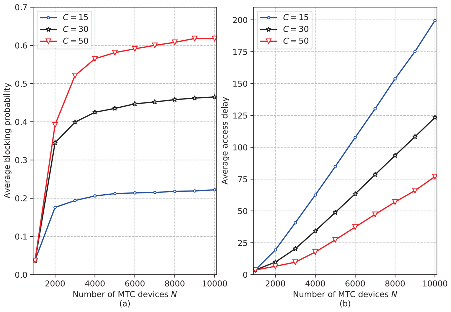

Fig. 3. Performance while changing clustered numbers C. (a)Average blocking probability. (b) Average access Delay.

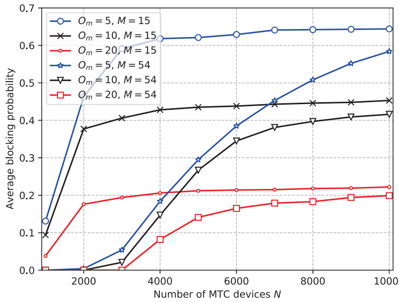

Fig. 4. Average blocking probability versus the total number of devices while changing max retransimition limit O_m and number of RBs M.

Fig. 5 (a) shows the results of average blocking probability with the total number of MTC devices N increasing from 1000 to 10000 with the number of clusters set to 50 and O_m set to 20. Meanwhile, Fig. 5 (b) shows the results of the resource utilization rate. We can conclude that base on the clustering algorithm, our algorithm decreases the average blocking probability and improves resource utilization.

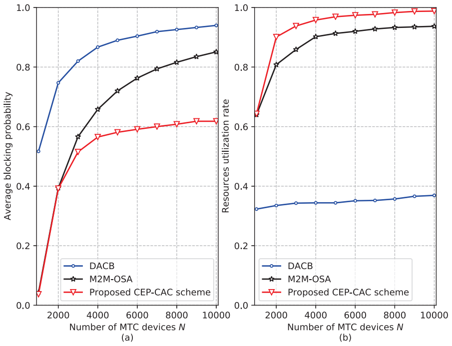

Fig. 5. Comparison between CEP-CAC and state-of-art schemes. (a) Average blocking probability. (b) Resource utilization rate.

Fig. 6 shows the results of average access delay for high-priority devices, average blocking probability, and resource utilization rate with the number of clusters set to 15 and O_m set to 50. It can be seen from Fig. 6 (a) that our algorithm significantly decreases the average access delay of delay-sensitive devices. Fig. 6 (b) shows our algorithm decreases the average blocking probability of all categories of devices. Fig. 6 (c) shows our algorithm improves the resource utilization.

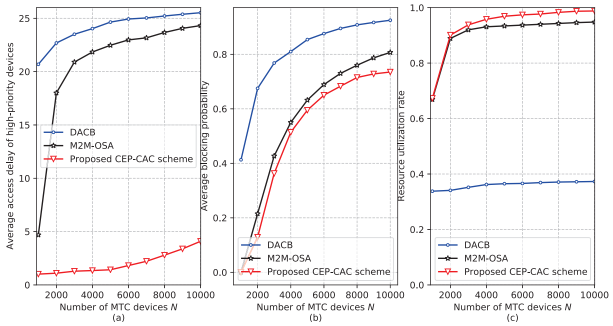

Fig. 6. Comparison between CEP-CAC and state-of-art schemes. (a) Average access delay for high-priority devices. (b) Average blocking probability. (c) Resource utilization rate.

V. CONCLUSION

In this paper, we propose a clustering-enabled prioritized channel access control scheme, which can effectively solve the congestion problem and reduce the access latency of the delay-sensitive devices in the smart grid. To guarantee the access delay requirement in the smart grid, we propose a prioritized channel access control scheme, which includes dynamic allocation of RACH resources with back-off. A clustering-based congestion mitigation algorithm is designed to improve the channel access performance further. Simulation results show that the proposed channel access scheme reduces the average blocking probability, while significantly reducing access delay for delay-sensitive devices.

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