For Massive Access With Sporadic Traffic in M2M Communication: Collision Avoidance or Collision Resolution

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This work was supported by the National Natural Science Foundation of China under Grant 91638205 and Grant 61871257.

ABSTRACT To meet the increased requirement of machine-to-machine (M2M) communication, the potential to support massive access with sporadic traffic in uplink of two typical methods, one is the collision avoidance (CA) method at the user side, and the other is the collision resolution (CR) method at the base station (BS) side, is explored under grant-free protocol in this paper. A comprehensive study from MAC layer is conducted under the proposed distributed queue model, which describes the queue behavior of each device and the interaction between devices under grant-free protocol. The upper bounds of the throughput and the success probability of CA method are derived and the closed forms of the throughput and the success probability of a typical CR method, known as power domain multiple access (PDMA), are derived. The performance is further analyzed besides delay and stability. Through simulations, we validate that there is a hopeful upper bound for CA method, and the performance of PDMA can be flexibly improved with variable power level, which has a similar effect with channel extension. On the other hand, we note that grant-free protocol is suitable for access when the input traffic is below a critical threshold, otherwise packets would be blocked at the queue and the delay would increase infinitely.

INDEX TERMS Collision avoidance, collision resolution, grant-free protocol, machine-to-machine (M2M) communication, massive access.

I. INTRODUCTION

Machine-to-machine (M2M), also known as machine-type communications (MTC), is one of the important technologies of Internet-of-Things (IoT) to enable everything to be connected through networks, which attributes to its advantages to permit devices to access the network automatically without human intervention [1], [2]. It inevitably promotes a wide range of applications, such as smart grid, smart traffic, and smart meter [3]–[5]. One typical feature of these applications is that there is massive access with sporadic traffic in uplink [6], [7]. Accordingly, the efficiency of system to support the massive access with small packets in uplink is a significant challenge in M2M communication.

In general, most M2M communication systems are implemented by the solutions based on Long Term Evolution (LTE) cellular system due to its ubiquitous coverage [8]. Before data transmission, a random access (RA) procedure should be performed, which consists of four steps of handshaking, including RA preamble transmission, RA response, connection request and connection resolution. Unfortunately, this scheme is optimized for human-to-human communication, such as voice and video streaming transmitted in high data rates by few devices. It inevitably causes signaling overhead and large latency for small packet services of M2M system, this dramatically decreases the spectral efficiency [9]. To address the overhead problem, a contention-based access in uplink is proposed in [10], called grant-free multiple access (GFMA), for the handshaking process is avoided. But the access efficiency is still at a low-level due to the collision problem.

As collision problem is closely related to the aggregate traffic load, the researchers developed some adaptive load control strategies. A dynamic access class barring (ACB) scheme is proposed in [11] to adjust the access probability of each node, based on the real-time load of the aggregate traffic. In order to obtain accurate load data, several estimation algorithms are developed to track the real-time number of
access devices [11], [12]. Furthermore, [13] suggested a new control strategy based on statistical information to optimize the long-term network performance, which is more suitable for the implementation.

Basically, load control strategies are high efficiency to prevent some devices to join the access, but the collision between the permitted devices cannot be avoided. It is proposed to adopt the carrier sense multiple access (CSMA) to improve the performance by reducing collision from other devices at the transmission phase. Each device should sense the channel before transmission, and it transmits data only when the channel is sensed as idle [14]. However, the hidden terminal problem would cause degradation of throughput. Against this problem, CSMA with collision avoidance (CSMA/CA) is proposed, which is adopted by IEEE 802.11 [15].

Note that the essence of both load control strategies and CSMA is to achieve collision avoidance between devices, meanwhile, the researchers also proposed another approach, collision resolution method, which can also be useful to mitigate the collision problem. Different from the collision avoidance method that is based on orthogonal multiple access (OMA), collision resolution method is mostly combined with non-orthogonal multiple access (NOMA). Uncoordinated power domain NOMA is introduced to random access in [16], known as power domain multiple access (PDMA), where a pre-determined power level manner is used. Each device can determine its transmit power according to the randomly selected pre-determined power level, and base station (BS) decodes the received signals by successive interference cancellation (SIC). The lower bound of throughput is further derived in [17], which indicates that the throughput can improve a lot without bandwidth expansion. Furthermore, the performance is discussed under Rayleigh fading and path loss in [18].

Code domain NOMA, as another scheme of NOMA allows devices to transmit over multi-slot is also suggested in M2M and collision resolution could be conducted by BS through multi-user detection algorithms [19]. Since the sporadic access characteristic of the M2M in uplink, the compressive sensing (CS) framework is introduced to solve the multi-user detection problem [20]–[23]. Several detection algorithms, based on orthogonal matching pursuit (OMP) algorithm [24], [25] or approximate message passing (AMP) [26], [27] are proposed to improve the bit error rate (BER) performance.

Through the above discussion, both collision avoidance and collision resolution methods are useful to deal with collision problem. To capture the MAC layer performance of these methods under grant-free protocol, an analytical framework should be established. Aggregate traffic model based approaches, which consider the total number of requests in each time slot, are commonly used to analyze the performance [28]–[30], whereas it can’t reflect the difference between grant-based protocol and grant-free protocol. Note that the aggregate traffic is determined by the interaction of each node’s queue, an access network can be regarded as a multi-queue-single-server system [31]. A double-queue model is established to characterize the grant-based random access process, where the performance is mainly determined by the request queue [13], [32]. Differently, for GFMA, the key lies on the interaction of Head-Of-Line (HOL) packets in nodes’ data queues. In [33], an approach based on Markov chain is proposed, where each state represents the queue length of each device. But with the growth of state space, it would be difficult to conduct analysis.

In this paper, we conduct a comprehensive study on CA method at the user side, and CR method at the BS side from MAC layer for exploring the potential to support massive access with sporadic traffic in uplink. The main contributions of this paper are summarized as follows:

We establish a distributed queue model to describe the queue behavior of each device and the interaction between devices under grant-free protocol.

We derive the upper bound of the throughput and the success probability of CA method, and find that there is a hopeful upper bound for this method.

We also deduce the close-form of the throughput and the success probability of PDMA, and validate that the performance can be further improved by the extension of power level.

We further conduct the analysis on delay and stability, and note that grant-free protocol is suitable for access when the input traffic is below a critical threshold, otherwise packets would be blocked at the queue and the delay would increase infinitely.

The other parts of this paper are organized as follows. Section II presents the distributed queue model under grant-free protocol. In section III, the closed forms of the throughput and the success probability are derived under single-channel scenario and then are extended to multi-channel scenario in section IV. The access delay and the stability are analyzed in section V. Finally, the overall of this paper is summarized in section VI.

II. SYSTEM MODEL
In this section, we will first introduce the general grant-free protocol and then establish a distributed queue model to accurately characterize the performance of grant-free protocol.

A. GRANT-FREE PROTOCOL
Grant-free protocol allows devices to transmit data without grant procedure, the overall procedure only consists of two steps, as shown in Fig. 1.

At the first step, each device transmit packet in a time slot within available resource, if the packet is successfully decoded, the acknowledgement (ACK) message would be transmitted to the devices from the BS in the step two. If the transmission is failed, the above steps will be repeated to avoid data loss.

B. DISTRIBUTED QUEUE MODEL
A more suitable traffic model should be established to characterize the effect of grant-free protocol. Note that the
aggregate traffic is determined by the interaction of each node’s queue, an access network can be regarded as a multi-queue-single-server system [31]. Based on this theory, a distributed queue model is proposed as shown in Fig. 2. We consider a single cell with $N$ homogeneous devices in its coverage and assume that each device has an infinite memory to buffer those new packets generated by Poisson distribution with arrival rate of $\lambda$. Under grant-free protocol, the performance is mainly determined by the interaction of HOL packets in nodes’ data queues. Here, it is assumed that time axis is divided into slot and all devices are synchronized to transmit packet at each slot with probability $p$. Then, each device’s queue can be modeled as an M/G/K queue, the service time distribution will be characterized in the following part.

A Markov chain is proposed to characterize the state transition process of HOL, as shown in Fig. 3. A new access request is initiated at state T, and it will stay at this state only when the transmission is successful. Otherwise it transfers into state W, and would stay at state W until the transmission is successful. The steady-state probability distribution of the HOL’s Markov chain can be obtained as

$$
\begin{align*}
\pi_T &= p, \\
\pi_W &= 1 - p,
\end{align*}
$$

where $p$ is the steady-state probability of successful transmission of HOL packet. Then it can be further used to analyze the access delay and we take a slot as time unit. Let $D_i (i = T$ or W) denotes the time spent from state $i$ until the packet is successfully transmitted, they can be described as

$$
D_T = \begin{cases} 
1 & \text{with probability } p \\
1 + D_W & \text{with probability } 1 - p.
\end{cases}
$$

$$
D_W = \begin{cases} 
1 & \text{with probability } p \\
1 + D_W & \text{with probability } 1 - p.
\end{cases}
$$

Note that the request is started at state T and also ended when it shifts back to state T, then $D_T$ is the service time of each packet [34]. The probability generating function of $D_T$ can be calculated as

$$
G(z) = \frac{zp}{1 - z + zp}.
$$

The mean service delay of each request can be obtained as

$$
E[DT] = G'(1) = \frac{1}{p},
$$

the second moment of service delay is

$$
E[D_T^2] = G'(1) + G''(1) = E[DT] (2E[DT] - 1).
$$

According to the M/G/K queue theory, the probability that a device’s queue is nonempty is

$$
\rho = \lambda \cdot E[DT],
$$

then each device’s transmit probability $p_t$ is gotten as

$$
p_t = \rho.
$$

The mean access delay which consists of waiting delay at the queue and service delay is

$$
E[D] = E[DT] + \frac{\lambda E[D_T^2]}{2(1 - \rho)}.
$$

III. COLLISION AVOIDENCE VS COLLISION RESOLUTION

In this section, we first introduce how collision avoidance and collision resolution work, and then derive the throughput and the success probability for device’s transmit probability $p_t$. Here, throughput is defined as the mean packets successfully transmitted during a slot and success probability is the probability that a packet is successfully transmitted. Single-channel scenario is first considered and it will be extended to multi-channel scenario in the following part.

A. SLOTTED ALOHA

As the basics, the slotted ALOHA in uplink will be first analyzed. We assume constant modulation is used by devices to transmit signals when its queue is nonempty. The received signal of device $n$ at the BS can be expressed as

$$
y_n = h_n \sqrt{P_n s_n} + n_n,
$$

where $h_n, P_n, s_n, n_n$ represent the channel coefficient, transmit power, modulated signal and background noise respectively. The channel state information (CSI) is assumed known at the device which is also kept in other parts of this section.
Then the transmit power of each device is determined by the decode threshold $\gamma$, it can be calculated as

$$
\gamma = \frac{|h_n|^2 p_n}{N_0},
$$

(11)

$N_0$ is the power spectral density of the background noise. Under this power setting, one packet is successfully decoded when there are no concurrent transmissions in this slot. Then the success probability under slotted ALOHA is written as

$$
P_{S\text{-ALOHA}} = (1 - p_t)^{N-1},
$$

(12)

and the throughput can be further gotten as

$$
T_{S\text{-ALOHA}} = Np_t (1 - p_t)^{N-1}.
$$

(13)

B. COLLISION AVOIDENCE

Different from the slotted ALOHA, even though there is more than one device has access request, one packet can also be transmitted successfully by collision avoidance method. The main idea of these methods is to avoid collision with each other. The ideal condition is that collision can be avoided perfectly, and then the performance achieved at this ideal condition is the upper bound, this upper bound will be analyzed in this subsection.

The same power value as slotted ALOHA is assumed, it indicates that one slot can only be occupied by one device. Then for an active device, its success probability is determined by the number of simultaneous transmission. The access chance is shared among these devices fairly as there is no priority between devices. The number of active devices except the reference device obeys the following distribution:

$$
f(m) = \binom{N-1}{m} p_t^m (1 - p_t)^{N-1-m}.
$$

(14)

Then the success probability of a device can be obtained as

$$
p_{CA} = \sum_{i=0}^{N-1} f(i) \frac{1}{i + 1}
= \sum_{i=0}^{N-1} \binom{N-1}{i} p_t^i (1 - p_t)^{N-1-i} \frac{1}{i + 1},
$$

(15)

and the throughput can be further given as

$$
T_{CA} = Np_t p_{CA}
= N \sum_{i=0}^{N-1} \binom{N-1}{i} p_t^{i+1} (1 - p_t)^{N-1-i} \frac{1}{i + 1}.
$$

(16)

The throughput can be simplified to

$$
T_{CA} = 1 - (1 - p_t)^N,
$$

(17)

it can be explained as that the channel can be occupied by a device except there is no active device.

C. COLLISION RESOLUTION

Collision resolution is another efficient method to improve the throughput and the success probability. A typical CA method based on PDMA is analyzed in this subsection. Different from the above methods, multiple predetermined received power levels at the BS are used in this method. Suppose that there are predetermined $R$ power levels that are denoted by

$$
L_1 > L_2 > \ldots > L_R > 0.
$$

(18)

When an active device has packet to transmit, it can randomly select one of these power levels, and then determine its transmit power according to the selected power level and channel coefficient. According to the decode principle, the signals can be decoded and removed by SIC in descending order of power level at the BS. The higher power level signal is decoded first, treating the lower power level signals as noise. As the power level is chosen in random mechanism, there would be a condition that a power level is chosen by multiple active devices, and we call this phenomenon as power collision. Then all these signals at this power level would not be decoded due to power collision. Whereas the power collision is not an independent event, the signals at lower power level cannot be decoded because of the descending decode order.

We will take Fig. 4 as example to show the decode procedure. The signal at the power level $L_1$ is first decoded, as there is no power collision, the signal can be successfully decoded when its signal-to-interference-plus-noise ratio (SINR) is above the decoded threshold $\gamma$. The effect from lower power levels can be managed by the setting of power of each level, and there is an ideal condition that the decode procedure cannot be affected by the interference from lower power levels. There are two devices choosing the power level $L_3$ at the same time, a power collision is happened, both the signals cannot be decoded, as well as the signals at the lower power levels.

We will analyze the capability achieved by PDMA method under ideal condition in detail. The above analysis indicates that a device’s signal can be decoded when there is no power collision at the power level chosen by this device and the higher power levels under ideal condition. If power level $L_i$ is chosen by a device, its transmission is successful when this power level is not chosen by other devices, and any power

![Figure 4. Example of power level selection.](image-url)
levels higher than $L_i$ should not be chosen by more than one device. Then the probability that a transmission is successful at power level $L_i$ is

$$p_{\text{level}_i} = \sum_{j=0}^{i-1} \binom{i-1}{j} \left( \frac{N-1}{j} \right) \left( \frac{p_t R}{j} \right)^j \left( 1 - \frac{i p_t R}{j} \right)^{N-1-j},$$

the success probability at all the possible power levels can be expressed as

$$p_{\text{PDMA}} = \frac{1}{R} \sum_{i=1}^{R} \sum_{j=0}^{i-1} \binom{i-1}{j} \left( \frac{N-1}{j} \right) \left( \frac{p_t R}{j} \right)^j \left( 1 - \frac{i p_t R}{j} \right)^{N-1-j}. \tag{20}$$

And the throughput can be further obtained as

$$T_{\text{PDMA}} = \frac{Np_t}{R} \sum_{i=1}^{R} \sum_{j=0}^{i-1} \binom{i-1}{j} \left( \frac{N-1}{j} \right) \left( \frac{p_t R}{j} \right)^j \left( 1 - \frac{i p_t R}{j} \right)^{N-1-j}. \tag{21}$$

### D. PERFORMANCE ANALYSIS

In this subsection, we present simulations to analyze the performance of these discussed methods.

The performance of the throughput is first shown in Fig. 5, when the transmit probability $p_t$ of each device ranges from 0 to 0.25, $N = 20$, $R = 2$ or 5. Simulation results are obtained by $10^5$ realizations. We take $Np_t$ as aggregate traffic, used as x-axis. We can see that analytical results and Monte Carlo simulations agree well in the whole region. As expected, both CA and PDMA methods greatly outperform the slotted ALOHA method. The throughput of CA gradually approaches 1 without performance loss, while there is a peak value for PDMA method, and the peak value can increase with more power level. It shows that the peak value achieved by $R = 5$ can be 1.3, which doubles that of PDMA with $R = 2$ and is also higher than CA method. This indicates that the performance of PDMA can be further improved by variable power level.

The relationship between throughput of PDMA and the number of power level is further analyzed in Fig. 6. The parameters are set as $p_t = 0.1$ or 0.2, $N = 20$, the number of power level ranges from 2 to 6. We can see that the throughput increases with more power level, but the increase rate becomes slow. This demonstrates that each power level is not independent, and reminds us to cautiously select power level to balance the gain and cost.

The success probability is also analyzed as shown in Fig. 7, the parameters are set as the same with that used in Fig. 5. A perfect match is observed between the simulation and the analysis. And we can see that success probability tends to decrease with the transmit probability, as packet collision becomes worse. In particular, when transmit probability stays at a low value; both CA and PDMA methods are greatly better than slotted ALOHA. And the performance of PDMA can be further improved if more power levels are set, the success probability achieved by PDMA with $R = 5$ when transmit probability is equal to 0.25 is even higher than that of slotted ALOHA when transmit probability is equal to 0.1. This indicates that PDMA can achieve good performance at a wide range of transmit probability.
IV. EXTENSION TO MULTI-CHANNEL SCENARIO

Note that the above analysis is based on single-channel scenario, in this section the analysis will be extended to multi-channel scenario.

A. MULTI-CHANNEL MODEL

When there are multiple channels for devices to access, the contend between devices would decrease, and then the throughput can be improved. In this part, we will analyze the performance of CA and CR method under multi-channel scenario, $M$ channels are considered in the following analysis.

As channel is selected by device in random manner, the probability that a channel is selected by any device decreases from $p_t$ to $p_t/M$ in multi-channel scenario. Then the success probability of CA method can be extended from (15), as

$$p_{m-CA} = \sum_{i=0}^{N-1} \binom{N-1}{i} \left( \frac{p_t}{M} \right)^i \left( 1 - \frac{p_t}{M} \right)^{N-1-i} \frac{1}{i+1},$$

(22)

the throughput is obtained as

$$T_{m-CA} = M \left( 1 - \left( \frac{p_t}{M} \right)^N \right).$$

(23)

Similarly, the probability that one power level of a channel is chosen decreases from $p_t/R$ to $p_t/MR$ for PDMA method. Then, the success probability extended from (20) is

$$p_{m-PDMA} = \frac{1}{R} \sum_{i=1}^{R} \sum_{j=0}^{i-1} \binom{i-1}{j} \left( \frac{p_t}{MR} \right)^j \left( 1 - \frac{i p_t}{MR} \right)^{N-j} \left( \frac{p_t}{MR} \right)^i \left( 1 - \frac{i p_t}{MR} \right)^{N-1-j},$$

(24)

the throughput can be obtained as

$$T_{m-PDMA} = \frac{N p_t}{R} \sum_{i=1}^{R} \sum_{j=0}^{i-1} \binom{i-1}{j} \left( \frac{p_t}{MR} \right)^j \left( 1 - \frac{i p_t}{MR} \right)^{N-j} \left( \frac{p_t}{MR} \right)^i \left( 1 - \frac{i p_t}{MR} \right)^{N-1-j}.$$  

(25)

B. SIMULATION RESULTS

In this subsection, we present the simulation results under multi-channel model.

Fig. 8 shows the throughput for varying aggregative traffic, when $p_t$ ranges from 0 to 0.25, $N = 20$, $M = 1$ or 3, $R = 2$ or 5. Lines and markers indicate the analytical results and simulation respectively. The result shows that the throughput increases a lot when there are more channels, as resource contention between devices is remitted. More importantly, we can see that the performance achieved by PDMA method with $M = 1$, $R = 5$ is better than that of slotted ALOHA with $M = 3$. This indicates that the increase of power level has a similar effect with channel extension.

Fig. 9 shows the throughput for varying channel number when $p_t = 0.05$ and $N = 20$, it shows that PDMA with $M = 2$, $R = 5$ and PDMA with $M = 6$, $R = 2$ have almost the same throughput, further proving that the increase of power level has the similar effect with channel extension. But the growth rate decreases with channel number, and this reminds us that channel extension can be combined with power level extension for PDMA method to achieve better performance gain.

V. DELAY AND STABILITY ANALYSIS

The closed forms of the throughput and the success probability are derived in the above part; in this section the performance of delay and stability is analyzed.

A. DELAY ANALYSIS

To get the access delay of each packet based on (9), the relationship between input traffic and the success probability should be built. We separately take $p_t = \lambda/p_{m-CA}$ and $p_t = \lambda/p_{m-PDMA}$ into (22) and (24) according to (5), (7) and (8), then the following equations are gotten:

$$p_{m-CA} = \sum_{i=0}^{N-1} \binom{N-1}{i} \left( \frac{\lambda}{M p_{m-CA}} \right)^i \left( 1 - \frac{\lambda}{M p_{m-CA}} \right)^{N-1-i} \frac{1}{i+1},$$

(26)
Both of these equations are non-linear, and they are hard to solve directly. On the other hand, there is a condition that the service rate of each queue drops below the input rate, and then all devices would stay in active status. Packets are blocked at the queue, and the delay of the packet will increase infinitely, it is an unstable state for system. To get the access delay of the packet and study the stability of the system, two numerical algorithms based on CA and PDMA methods are proposed, they are summarized as Algorithm 1 and Algorithm 2.

Algorithm 1: The Proposed Iterative Algorithm for CA

**Input:** input traffic of each queue $\lambda$, channel number $M$, device number $N$ and tolerance $\varepsilon$.

**Output:** $P_{m-CA}$, $E[D]$.

1. **Initialize** $j = 1$.
2. $P_{m-CA}^{(1)} = \frac{N}{i=0} \left( N-1 \right)^{(i-1)} \left( \frac{\lambda}{M} \right)^i \left( 1 - \frac{\lambda}{M} \right)^{N-1-i}$
3. **repeat**
   1. $j = j + 1$
   2. $P_{m-CA}^{(j)} = \frac{N}{i=0} \left( N-1 \right)^{(i-1)} \left( \frac{\lambda}{M_{m-CA}} \right)^i \left( 1 - \frac{\lambda}{M_{m-CA}} \right)^{N-1-i}$
   3. **until** $\left( |P_{m-CA}^{(j)} - P_{m-CA}^{(j-1)}| \leq \varepsilon \right)$
4. **if** $\frac{\lambda_{m-CA}}{P_{m-CA}} \geq 1$
   1. $P_{m-CA} = \frac{N}{i=0} \left( N-1 \right)^{(i-1)} \left( \frac{\lambda}{M_{m-CA}} \right)^i \left( 1 - \frac{\lambda}{M_{m-CA}} \right)^{N-1-i}$
5. **else**
   1. $P_{m-CA} = P_{m-CA}^{(j)}$, $E[D] = \frac{1}{P_{m-CA}} + \frac{\lambda(2-P_{m-CA})}{2P_{m-CA}(P_{m-CA} - \lambda)}$
6. **end if**

Fig. 10 shows the convergence of two proposed algorithms when $\lambda = 0.1$, $M = 1$, $N = 5$ and $R = 2$, the success probability under both algorithms converges to the final value within a few iteration steps. This indicates that our proposed algorithms are efficient to solve the non-linear problem.

**B. SIMULATION RESULTS**

The performance of delay and stability for varying input traffic is shown in Fig. 11 and Fig. 12. Parameters are set as $N = 5$, $M = 1$, $R = 2$ or 5 and $\varepsilon = 10^{-3}$.

We can see that the access delay increases with input traffic in Fig. 11, since each device’s success probability is reduced due to more collision, each packet should cost more time at the access procedure and wait more time at the queue. The delay for PDMA can be reduced by the increase of power level, and then PDMA can achieve lower delay than CA method.

Fig. 12 shows the stability of two methods through success probability, the simulation shows that the success probability decreases with the growth of input traffic, and stays at a fixed value when the input traffic is above a threshold value. The latter phenomenon happens when data packets are blocked at the queue, and all the devices always have access request. The delay of each packet would grow infinitely, and the system drops into unstable state. We can see that the stable region
can be further extended by the increase of power level for PDMA method.

VI. CONCLUSION

In this paper, we explore the potential of two typical methods, one is the CA method and the other is a typical CR method, known as PDMA to support massive access with sporadic traffic in uplink under grant-free protocol. A distributed queue model is established to describe the queue behavior of each device and the interaction between devices under grant-free protocol. Moreover, we thoroughly investigated the performance in terms of throughput, success probability, delay, and stability. Through simulations, we can see that the upper bound of throughput of CA method approaches 1 without performance loss; on the other hand, the performance of PDMA method can be further improved with variable power level. Furthermore, the analysis is extended to multi-channel scenario, the performance can greatly be improved with more channel resources. And we can see that power level extension has a similar effect with channel extension, besides channel extension can be combined with power level extension for PDMA method to achieve better performance gain.  

At last, we note that grant-free protocol is suitable for access when the input traffic is below a critical threshold, otherwise packets would be blocked at the queue and the delay would increase infinitely. The performance of both methods in terms of energy efficiency will be further studied in our future work.

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For Massive Access With Sporadic Traffic in M2M Communication: CA or CR

T. Qi, Y. Wang: For Massive Access With Sporadic Traffic in M2M Communication: CA or CR

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