Adaptive Hybrid MAC Protocol with Novel MOB Backoff Scheme for Massive M2M Communications

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Abstract. This paper targets on solving the high collision problem in the massive machine-to-machine communications. The main idea is to restrict the numbers of allowable contentions to the low-energy devices (LEDs) by using the proposed make-or-break (MOB) backoff scheme such that the unnecessary energy consumption can be reduced. And, consequently, the high-energy devices (HEDs) can have higher probability to attain time slots for data transmissions. However, the restriction mechanism may detain the data forwarding process. To solve this dilemma, the adaptive frame structure is developed to compensate the loss of throughput. The analytical as well as simulation results demonstrate that with a huge amount of machine type devices (MTDs), the proposed scheme can outperform the conventional counterpart in the aspects of the head-of-line delay, energy efficiency and accommodation of the MTDs.

Keywords: Machine-to-Machine (M2M) communications · Media access control (mac) protocol · Collision avoidance · Energy efficiency.

1 Introduction

Nowadays, the Internet of things (IoT) is an evolutionary concept to develop an infrastructure for interconnecting massive objects without humans' interventions. The machine-to-machine (M2M) communications has been regarded as one of the most potential and pivotal innovations to carry out the IoT concept. However, the voluminous data transmissions between massive devices can result in excessive energy consumption and unacceptably high collision probability [1]. To tackle this problem, numerous media access control (MAC) protocols have been proposed in the literature [2–10].

In [2,3], to improve the energy efficiency, the M2M devices were categorized into three types and each type can exclusively occupy its dedicated time slots to forward data packets. In [4], the tree algorithm was applied to proposed a time slot assignment to alleviate the collision problem. In [5], the distributed queueing access technique was developed to avoid the loss of a whole data packet caused by

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the collision problem. In [6], the backoff time for the clustered M2M networks was generated according to the volume of the pending data, i.e. the larger the volume, the shorter the backoff time. In [7], the successive-interference-cancellation-based (SIC-based) protocol was proposed to transmit several replicas of the same data packet using variant time slots. In [8], by taking historical records, the access grant time interval (AGTI) was allocated to the clusters which were formed based on the requirements of the quality-of-service (QoS). In [9], an optimized hybrid protocol was proposed to apply the well-known the p-persistent carrier sense multiple access (CSMA) protocol and time division multiple access (TDMA) mechanism to manage the transmissions during contention only period (COP) and transmission only period (TOP), respectively. Moreover, to take the fairness and priority into account, the contending probability for each device can be set and adjusted according to its QoS requirement and its historical accessibility record [10].

In this paper, we propose an adaptive hybrid MAC protocol together with the make-or-break (MOB) backoff scheme by taking the residual energy into account. The main idea is motivated by the biological instinct to reduce the body activities when a creature is weak. Specifically, the unnecessary energy consumption (body activities) caused by collisions is more harmful to the low-energy devices (LEDs, i.e. the weak creatures). The restriction of contending attempts to the LEDs can be an effective method to save energy for lifetime extension, and at the same time effectively increase the successful probability for the high-energy devices (HEDs). In this fashion, the length of the COP can be reduced such that more time slot can be utilized for data transmissions during TOP (more details will be expounded in Sect. 3). Consequently, the detained data forwarding process of an LED can then be expedited whenever it is recharged to become an HED. It should be noticed that using the conventional scheme in [10], a device can repeatedly send the contending request during the COP. Also, the time durations of the COP, TOP and data transmission time for each MTD are fixed rather than adaptively adjusted using the proposed scheme. The simulation results demonstrate the advantage of the proposed scheme in terms of the MTD accommodation, energy efficiency and head-of-line (HOL) delay.

The remainder of this paper is organized as what follows. Section 2 introduces the system model of the massive M2M network, including the MAC protocol and its corresponding time frame structure. In Sect. 3, the problem of high collision probability and its associated energy consumption are firstly defined. Then, we propose the adaptive hybrid MAC protocol together with the MOB backoff scheme. Section 4 demonstrates the simulation and numerical results. Section 5 gives the concluding remarks, including the potential topics for future works.

2 System Model

In this paper, the system model and assumptions are mainly based on those in [9]. Therein, a BS is deployed in the center of the network, and there are K machine-type devices (MTDs) uniformly distributed over the BS's coverage

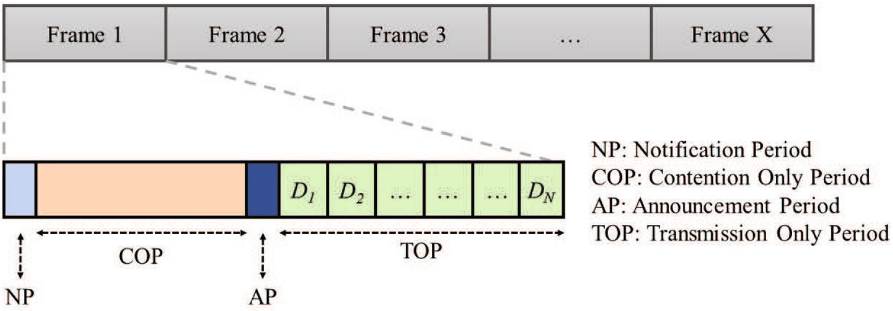

Fig. 1. Time frame structure, where D_n $\forall n = 1, 2, \cdots, N$ are the transmission time slots for the N winning MTDs.

area. Note that a winning MTD is the one who wins the competition during the COP, whereas a losing MTD is the one who fails. Also, the hybrid MAC protocol operates according to the time frame structure shown in Fig. 1. As shown in the figure, a frame consists of four time periods, including the COP, TOP, notification period (NP) and announcement period (AP). Observing the frame structure, one can realize that the term "hybrid" presents the applications of the p-persistent CSMA protocol and TDMA mechanism for the COP and TOP, respectively.

To reach the highest aggregate throughput (denoted by γ), the duration of TOP (T_{TOP}) should be maximized such that it can accommodate the optimal number of winning MTDs (N_{opt}). Based on the structure of the considered time frame, it can be realized that the maximization of T_{TOP} is equivalent to the minimization of T_{COP}. According to the derivations in [9], the T_{COP} can be approximated by

$$T_{COP}(M, N, p) = N \left\{ \frac{1}{Mp} T_{idle} + T_{suc} + T_{col} \left(\frac{1}{Mp(1-p)^{M-1}} - \frac{1}{Mp} - 1 \right) \right\} , \tag{1}$$

where M and N are the numbers of active and winning MTDs; p is the contention probability;

$$T_{suc} = T_{req} + SIFS + T_{ack} + BIFS ; \tag{2}$$

$$T_{col} = T_{req} + BIFS ; \tag{3}$$

$$T_{idle} = T_{req} + BIFS ; \tag{4}$$

$SIFS$ and $BIFS$ are the short interframe spacing and backoff interframe spacing; T_{req} and T_{ack} represent the duration of the request and ACK signals.

Now, the optimization problem can be defined as

$$\begin{aligned} \max_{M,N,P} \quad & \gamma = NR_D T_{tran} \\ \text{subject to} \quad & T_{cop}(M,N,p) + NT_{tran} \leq T_{frame} \\ & 0 \leq p \leq 1 \end{aligned} \tag{5}$$

where T_{tran} and R_D represent a transmission time slot during the TOP and its corresponding data rate of each MTD. Then, T_{COP} is minimized by searching for the optimal contending probability (p_{opt}) and the corresponding number of winning MTDs (N_{opt}). Note that the convexity of T_{COP} with respect to N and p can be proved by showing $\partial^2 T_{COP}/\partial N^2 \geq 0$ and $\partial^2 T_{COP}/\partial p^2 \geq 0$, respectively.

3 Adaptive Hybrid MAC Protocol with MOB Backoff Scheme

3.1 Problem Formulation

Based on the Hybrid MAC protocol (as introduced in Sect. 2), there are two criteria for terminating the COP: (1) T_{COP} expires; (2) the number of winning MTDs reaches the optimal value, i.e. $N = N_{opt}$. However, it is highly possible that T_{COP} expires before $N = N_{opt}$. In this situation, the T_{TOP} reserved for the N_{opt} MTDs can not be fully utilized. Similarly, when the condition of $N = N_{opt}$ is satisfied before the expiry of T_{COP}, the predefined T_{COP} is not fully utilized as well. Furthermore, considering an LED, the stringent collision problem can seriously reduce its lifetime. For example, when the number of active MTDs is large, keen competition can happen during the COP. That means each MTD could possibly win after a lot of request attempts, which can consume extensive energy. Thus, in this paper, we aim to solve the above three problems by proposing an adaptive hybrid MAC protocol and MOB backoff scheme.

3.2 Adaptive Hybrid MAC Protocol with MOB Backoff Scheme

Let $\mathbf{M}$, $\mathbf{M}_L$ and $\mathbf{M}_H$ denote the index sets of all the active MTDs, LEDs and HEDs, respectively. Then, it gives $\mathbf{M} = \mathbf{M}_L \cup \mathbf{M}_H$. Also, let ξ_{th} and ξ_i represent the energy threshold and level of the i-th active MTDs for all $i \in \mathbf{M}$. Thus, one can realize that $i \in \mathbf{M}_L$ if $\xi_i \leq \xi_{th}$; on the contrary, $i \in \mathbf{M}_H$ if $\xi_i > \xi_{th}$. In order to formulate the restriction on the LED's contending privilege, let's define $\eta_{th,i}$ and η_i $\forall i \in \mathbf{M}$ as the number of allowable and accumulated requesting attempts during a COP for the i-th MTD, respectively. Then, it leads to

$$\eta_{th,i} = \begin{cases} \eta_{th} & \forall i \in \mathbf{M}_L \\ \eta_{max} & \forall i \in \mathbf{M}_H \end{cases}, \tag{6}$$

where η_{th} is a predefined limit on the number of allowable contentions for LEDs; η_{max} is the maximal number of allowable contentions for HEDs.

Algorithm 1. The Procedure of Adaptive Hybrid MAC Protocol with MOB Backoff Scheme

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$T$: The elapsed time within each frame;
$\mathbf{C}$: The set includes the MTDs who experience collisions during COP;
$\varnothing$: An empty set;
Let $T = 0$, $N = 0$ and $M = \rho \times K$;
while $T < T_{COP}$ or $N < N_{opt}$ do
    The $M$ MTDs issue their request signals based
    on the $p$-persistent CSMA mechanism with $p = p_{opt}$;
    if a successful event occurs then
        $N++$;
        $M--$;
        Remove $i$ from $\mathbf{M}$;
        $T += T_{req} + SIFS + T_{ack} + BIFS$;
    else if an idle event occurs then
        $T += T_{req} + BIFS$;
    else if a collision event occurs then
        $T += T_{req} + BIFS$;
        Remove $i$ from $\mathbf{M}$ $\forall i \in \mathbf{C}$ if $\xi_i \leq \xi_{th}$ and $\eta_i =$
        $\eta_{th,i}$ are satisfied;
        Let $\mathbf{C} = \varnothing$;
    end if
end while
BS announces the time slot arrangement and the adjusted $T_{tran}$ to all winning MTDs during AP;
The $N$ winning MTDs sequentially forward their accumulated data packets during TOP;
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It should be emphasized that restricting the contending privilege of the LEDs can extend their lifetime. Moreover, it increases the probability of successful contention since the number of competitors can be decreased by using a proper value of η_{th}. That is to say it can be very helpful to satisfy the second criterion for terminating the COP, i.e. $N = N_{opt}$. If the second criterion can be achieved priori to the first one, i.e. the expiry of T_{COP}, the additional time $\triangle T_{COP} = T_{COP} - T'_{COP}$ can be equally shared by these N_{opt} MTDs, where T_{COP} and T'_{COP} are the predefined and practical time duration of COP, respectively. In this case, $T_{tran} = (\triangle T_{COP} + T_{TOP})/N_{opt}$. However, it is still possible that the first criterion is satisfied earlier. Then, the reserved T_{TOP} can be fully utilized by all the winning MTDs. That means each winning MTD can own $T_{tran} = T_{TOP}/N$ time resources (in this case $N < N_{opt}$). It should be noticed that, by using the proposed scheme, T_{tran} can be adaptively adjusted rather than the fixed as that in (5) such that each winning MTD can forward its accumulated data packets in the more efficient way. Furthermore, it can be realized that the conventional scheme in [9] is a special case of our proposed scheme by setting $\eta_{th} = \eta_{max}$ or the percentage of LEDs to be zero, i.e. $\rho_L = 0$. Algorithm 1 summarizes the proposed Adaptive Hybrid MAC Protocol and MOB Backoff Scheme.

3.3 Semi-Analysis of Head-of-Line Delay

Define p_{sc} as the successful probability for an MTD to win a transmission opportunity during the COP. Then, an arbitrary MTD may spend n time frames to win an opportunity with probability $(1-p_{sc})^{n-1}p_{sc}$. Thus, the probability mass function (pmf) for an MTD to win at the n-th frame can be written as

$$f(n) = (1-p_{sc})^{n-1}p_{sc} \quad n \geq 1 \ ; \tag{7}$$

whereas the corresponding cumulative distribution function (*cdf*) can then be written as

$$F(n) = \sum_{i=1}^{n}(1-p_{sc})^{n-1}p_{sc} \quad n \geq 1 \ . \tag{8}$$

Owing to the random backoff operations and different allowable contentions for HEDs and LEDs, it is difficult to obtain a closed-form expression for p_{sc}. Thus, we obtain p_{sc} via simulations such that (8) can be utilized to verify the simulation results (as shown in the following Fig. 5).

4 Numerical and Simulation Results

In this section, the impact of the number of allowable requesting attempts (η_{th}) on the proposed scheme is firstly evaluated in terms of the number of winning MTDs. Based on this result, a proper value of η_{th} can be decided. Moreover, to demonstrate the superiority of the proposed scheme over the conventional counterpart in [9], the following performance comparisons are conducted in terms of the energy efficiency, head-of-line delay and number of winning MTDs.

4.1 Simulation Setup

In addition to the system depiction in Sect. 2, the mobility of MTD, differentiated priorities among MTDs and erroneous control messages are not taken into account. Also, to clearly demonstrate the impact of the LEDs, the percentage of LEDs among all MTDs is fixed during the simulations. That means the energy level of an HED will not be significantly reduced to become an LED. Also, an LED will not be charged to become an HED. A winning MTD transmits data packets using a fixed transmission rate $R_D = 250$ kbps. To make the energy consumption model complete, four operation states for each MTD are considered, i.e. the transmission, receiving, idle and sleeping states [5]. As implied by the name, the transmission and receiving states mean the MTD of interest is now transmitting and receiving signals, respectively. Whereas, except issuing request signal, an MTD remains in the idle state if it has not yet won during COP. Also, a winning MTD stays in the idle state if it has not yet finished the data transmissions during TOP. Moreover, it can switch into the sleeping state when it has finished the data transmission task during TOP. Besides, a losing MTD can also switch into the sleeping state when the T_{COP} expires. Note that the time and energy consumption for an MTD to switch between active and inactive modes are ignored here [5]. Table 1 summarizes the parameters in the following simulations.

Table 1. Simulation parameters

Simulation parameters	Values
Number of MTDs (K)	1–1000
Ratio of active MTDs (ρ)	0.5
Percentage of LEDs (ρ_L)	0–100 %
Duration of NP	10.2 µs
Duration of AP	10.2 µs
Duration of time frame (T_{frame})	50 ms
Duration of transmission time slot (T_{tran})	1 ms
$SIFS$	2.5 µs
$BIFS$	7.5 µs
Duration of requesting signal (T_{req})	22.2 μs
Duration of ACK (T_{ack})	7.5 µs
Data transmission rate (R_D)	250 kbps
Transmission power (P_{tx})	100.8 mW
Receiving power (P_{rx})	66.9 mW
Idling power (P_{idle})	525 µW
Sleeping power (P_{sleep})	60 nW
Limit on the allowable contentions (η_{th})	1, 2, 3
Maximum allowable contentions (η_{max}) [11]	16

4.2 Effect of η_{th}

Figure 2 demonstrates the number of winning MTDs N with respect to the total number of MTDs K for various number of allowable requesting attempts η_{th}, where the percentage of LEDs $\rho_L = 50\%$. One can find that, with a small amount of MTDs, a larger η_{th} can contribute to a greater amount of winning MTDs, whereas, when the number of MTDs becomes huge, a smaller η_{th} can accommodate more winning MTDs. For example, at $K = 100$, the numbers of winning MTDs N are 40.7, 36.1 and 26.6 for the cases with $\eta_{th} = 3$, 2 and 1, respectively. However, at $K = 800$, they become 31.4, 31.4 and 36.1. This is because, with a smaller K, the competition is not quite violent. Thus, there is no need to restrict the contending privilege of the LEDs. On the contrary, when the competition becomes stringent, restriction on the LEDs' activity can effectively increase the probability of successful contention. To sum up, one can say that the proposed MOB backoff scheme can be more effective when the number of MTDs is huge. Moreover, in the following simulations, $\eta_{th} = 1$ is adopted.

4.3 Number of Winning MTDs

To demonstrate the effectiveness of our proposed scheme for improving the contention efficiency by limiting the LED's contention attempts, Fig. 3 shows the

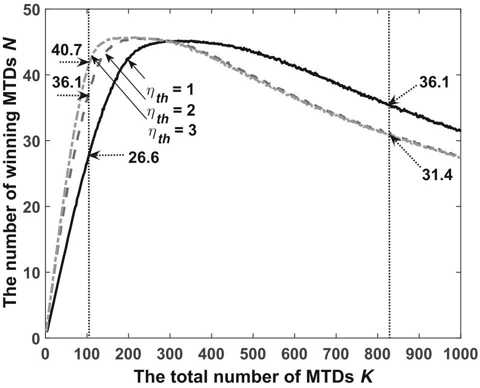


Fig. 2. The number of winning MTDs N with respect to the total number of MTDs K for various numbers of allowable requesting attempts η_{th}, where the percentage of LEDs $\rho_L = 50\%$.

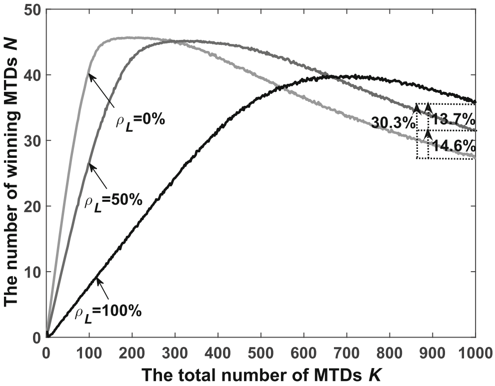


Fig. 3. The number of winning MTDs N with respect to the total number of MTDs K for various percentages of LEDs ρ_L. The curve with $\rho_L = 0\%$ corresponds to the conventional hybrid MAC protocol in [9].

number of winning MTDs N with respect to the total number of MTDs K for various percentages of LEDs ρ_L. Note that the higher the number of winning MTDs, the higher the contention efficiency during COP. Also, the curve with $\rho_L = 0\%$ corresponds to the conventional hybrid MAC protocol in [9]. Apparently, when the traffic is heavy, the proposed MOB backoff scheme with $\rho_L \neq 0\%$ can outperform the conventional counterpart with $\rho_L = 0\%$. Comparing with the conventional scheme at $K = 1000$, the proposed scheme can accommodate 14.6% (from 27.4 to 31.4) and 30.3% (from 27.4 to 35.7) more winning MTDs for the cases with $\rho_L = 50\%$ and 100%, respectively.

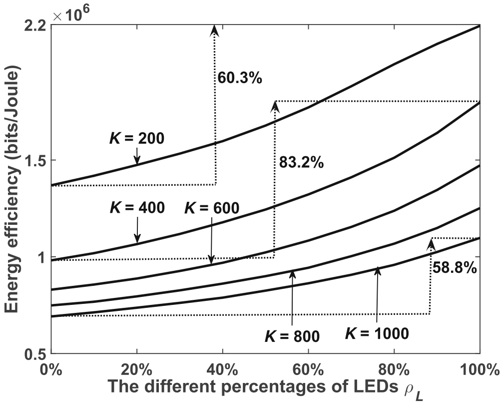


Fig. 4. Performance of average energy efficiency μ with respect to the percentage of LEDs ρ_L for various total numbers of MTDs K.

4.4 Energy Efficiency

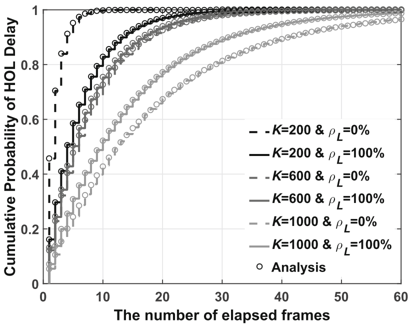
To demonstrate the advantage of the proposed scheme in reducing energy consumption and raising the utilization of time resources (i.e. T_{COP} and T_{TOP}), the performance metric of average energy efficiency μ within a frame is defined as

$$\mu = E\left[\frac{\text{BS's total received data bits}}{\text{Total energy consumption of all active MTDs}}\right], \qquad (9)$$

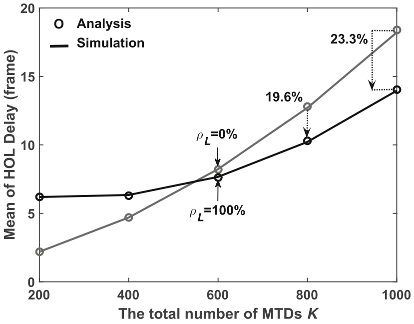
where $E[z]$ is to take the expectation of variable z [12]. Note that the effect of the prolonged lifetime for the LEDs reflects on the reduced energy consumption (as aforementioned which is achieved by eliminating the ineffective contentions). Figure 4 illustrates the performance of average energy efficiency μ with respect to the percentage of LEDs ρ_L for various total numbers of MTDs K. It is obvious that the proposed scheme can effectively improve the average energy efficiency. With $K = 200$ and $K = 1000$, the average energy efficiency for both cases can be improved by an approximately equal amount, i.e. 60.3% (from 1.369×10^6 to 2.194×10^6) and 58.8% (from 6.916×10^5 to 1.098×10^6), respectively. Moreover, this improvement can be 83.2% with $K = 400$. Thus, it can be concluded that the proposed scheme can be more effective in raising the average energy efficiency with an appropriate amount of traffic.

4.5 Head-of-Line Delay

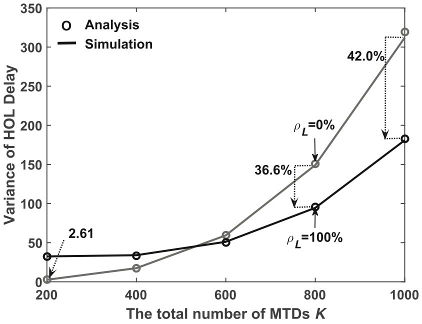
Figure 5 exhibits the (a) cumulative density functions (cdfs), (b) mean and (c) variance of the head-of-line delay with various numbers of MTDs for the conventional and proposed schemes, where $\rho_L = 100\%$ is presumed for the proposed scheme. Firstly, the simulation and numerical results can be supported by each other. Moreover, as shown in the figure, the advantage of the proposed scheme



(a) cdfs



(b) Mean



(c) Variance

Fig. 5. (a) Cumulative distribution functions (cdfs), (b) mean and (c) variance of the head-of-line delay with various numbers of MTDs for the conventional and proposed schemes, where $\rho_L = 100\%$ is presumed for the proposed scheme.

in the heavy traffic situations is verified again. Phenomenally, as K grows, the curves of proposed scheme (i.e. the ones with $\rho_L \neq 0$) move leftwards relative to the curve of the conventional scheme (i.e. the curve with $\rho_L = 0$). Comparing at

$K = 200$, 90% of the MTDs can transmit their data packets no later than 4 and 13 time frames by using the conventional and the proposed schemes. Conversely, with $K = 1000$, these values become 41 and 31. Furthermore, observing Figs. 5(b) and 5(c), the lower mean and variance values obtained by using the proposed scheme for the cases with more MTDs can also explain this phenomenon. Most importantly, the proposed scheme can be less sensitive to the increase of MTDs, i.e. the lower slope compared with the conventional counterpart.

5 Conclusions and Future Works

In this paper, we have proposed an effective but simple adaptive hybrid MAC protocol to solve the high collision problem in the massive M2M communication systems. Motivated by the biological instinct to restrict the numbers of allowable contentions to the LEDs, not only can the successful contending probability of the HEDs be raised, but also the lifetime of the LEDs can be extended. Moreover, adaptively adjusting the time duration for the COP and TOP can contribute to the higher throughput of data signals. In one of our considered cases, the analytical and simulation results have illustrated the additional 30.3% of MTD accommodation; and the average HOL delay can be reduced by 23.3% as well. Most importantly, the remarkable 83.2% enhancement of the energy efficiency can be attained. It is believed that the proposed scheme can be applicable and helpful to improve the overall system performance of the massive M2M networks. Some suggestions for the possible future works could be: (1) adjusting the contending probability p and the numbers of allowable contentions $\eta_{th,i}\ \forall i = M$ for the differentiated priorities of MTDs and (2) the complete analysis of the HOL delay, energy efficiency and the number of winning MTDs.

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