A Scalable Hybrid MAC Protocol for Massive M2M Networks

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Abstract—In Machine to Machine (M2M) networks, a robust Medium Access Control (MAC) protocol is crucial to enable numerous machine-type devices to concurrently access the channel. Most literatures focus on developing simplex (reservation or contention based) MAC protocols which cannot provide a scalable solution for M2M networks with large number of devices. In this paper, a frame-based Hybrid MAC scheme, which consists of a contention period and a transmission period, is proposed for M2M networks. In the proposed scheme, the devices firstly contend the transmission opportunities during the contention period, only the successful devices will be assigned a time slot for transmission during the transmission period. To balance the tradeoff between the contention and transmission period in each frame, an optimization problem is formulated to maximize the system throughput by finding the optimal contending probability during contention period and optimal number of devices that can transmit during transmission period. A practical hybrid MAC protocol is designed to implement the proposed scheme. The analytical and simulation results demonstrate the effectiveness of the proposed Hybrid MAC protocol.

I. INTRODUCTION

Machine-to-Machine (M2M) communications is defined as the information exchange between machines and machines without any human interaction. With interconnection to the Internet and deployed in different environments, a large number of devices are autonomously organized to constitute an M2M network. M2M networks are expected to be widely utilized in many fields of pervasive applications [1], including industrial and agricultural automation, health care, transport systems, electricity grids, etc. There are two main characteristics of M2M networks: 1) tremendous number of devices in service and concurrent network access attempt from these devices; 2) high level of system automation in which the devices and systems can exchange and share data. Therefore, the massive access management and medium access protocol are the major issues in M2M communications to build up a scalable, flexible, and automatic communication system [2].

Recently, the enormous economic benefits of the M2M communications drive intensive discussion in international standardization activities. In [3]–[6], 3GPP and IEEE studied M2M requirements and possibilities. In order to handle the massive access in M2M, 3GPP LTE has several work items defined on M2M communications, primarily with respect to overload control [3] [4]. IEEE 802.16p proposals [5]–[9] addressed enhancements for IEEE 802.16m standard to support M2M applications. It is noted that the massive access management of M2M communication over wireless channels generally happen at the Medium Access Control (MAC) layer. Hence, the design of a smart and efficient MAC protocol remains a key requirement for successful deployment of any M2M networks.

As discussed by 3GPP and IEEE 802.16, the MAC protocol for M2M communications focused on contention-based Random Access (RA) schemes [7] [8] that allow all of the devices obtain the transmission opportunities. The contention based RA is popular due to its simplicity, flexibility and low overhead. Devices can dynamically join or leave without extra operations. However, the transmission collisions are eminent when huge number of M2M devices trying to access the base station all at once. Reservation-based schemes such as Time-Division Multiple Access (TDMA) [9], is well known as the collision-free access scheme. In this scheme, the transmission time is divided into slots. Each devices transmits only during its own time-slots. The main defects of TDMA is the low transmission slot usage if only a small portion of devices have information to transmit. Hybrid schemes attempt to combine the best features of both of reservation-based and contention-based while offsetting their weaknesses, e.g. [10] [11] try to adapt to different bandwidth conditions depending on demand.

In this paper, we first propose a hybrid MAC protocol for M2M networks, which will combine the benefit of both contention-based and reservation-based protocols. In this scheme, each frame is composed of two portions: Contention Only Period (COP) and Transmission Only Period (TOP). The COP is based on CSMA/CA access method, and is generally used for devices to contend for the transmission slots in TOP. Only successful contending devices are allowed to transmit data during the TOP that provides TDMA type of data communication. Given the frame duration, it is expected that the number of the successful devices increases when the COP duration is prolonged. However, the COP duration increases at the expense of shortening the TOP which results in the decrease of transmission slots. To achieve the optimal tradeoff between the contention and transmission period in each frame, an optimization problem is formulated to maximize the throughput by deciding the optimal contending probability during COP, and the optimal number of devices to transmit during TOP (which is related to the duration of...
COP). Then, we design a hybrid MAC protocol to implement the proposed scheme in a practical environment. The analytical and simulation results demonstrate the effectiveness of the proposed hybrid MAC protocol.

The remainder of this paper is organized as follows. In Section II, we describe the system model of a M2M network. Then, we propose a hybrid access control scheme by optimizing the duration of COP and TOP in Section III. In Section IV, we design a hybrid MAC protocol to implement the proposed scheme. Performance study and evaluation are given in Section V. Section VI concludes the paper.

II. SYSTEM MODEL

We consider a M2M networks which consists of one base station (BS) and K number of devices. BS dominates medium access control for all the devices and there are L number of devices that have data to transmit during one frame (the values of K and L may vary from frame to frame). Hence in every time frame, there are K − L silent devices that can put into sleep mode as they have no data to transmit. In our system model, we assume that a homogeneous scenario where all of the devices have same amount of data with same priority. Hence, each device has to contend the transmission opportunities when it has data to transmit. We assume there M devices succeed in COP, and secure a transmission time slot in TOP. The fairness for different types of M2M devices with different QoS requirement will be our future work.

To show the universality of our model, the basic timing unit of the access operation is the frame which is composed of four portions as depicted in Fig. 1: Notification Period (NP), Contention Only Period (COP), Announcement Period (AP) and Transmission Only Period (TOP). The BS broadcasts notification messages at NP to all devices to notify the beginning of the contention. The L devices has data to transmit will contend the channel during COP. The COP is based on p-persistent CSMA access method [12], and is generally used for devices to randomly send the transmission requests to BS. Based on p-persistent CSMA in COP period, when a contention attempt is completed (successfully or with a collision), each contending device (i.e. the device with packets ready for transmission) will start a contention attempt with probability p. Here, we define the successful contention as the event that the transmission request from a device is successfully received by BS. Let $t_i$ denote the time between the $(i-1)$th and the $i$th successful contention. Considering the behavior of the p-persistent CSMA, we let $N_i^c$ denote the number of collisions that occur during $t_i$, then

$$t_i = \sum_{j=1}^{N_i^c} [\text{Idle}_{i,j} + \text{Coll}_{i,j}] + \text{Idle}_{N_i^c+1} + S_i$$

where $\text{Idle}_{i,j}$ is the duration of the $j$th idle time that precedes the channel busy period (either collision or success) in each $t_i$ duration. $\text{Coll}_{i,j}$ is the duration of the $j$th collision given that a collision occurs, and $S_i$ is the length of the request message. Let $T_{COP}$ denote the duration of the COP in each frame. Then, we have

$$T_{COP} = \sum_{i=1}^{M} t_i$$

$$= \sum_{i=1}^{M} \left\{ \sum_{j=1}^{N_i^c} [\text{Idle}_{i,j} + \text{Coll}_{i,j}] + \text{Idle}_{N_i^c+1} + S_i \right\}$$

Since $T_{COP}$ is the sum of random variable $t_i, (i = 1, \cdots, M), the T_{COP}$ is also a random variable with $E[T_{COP}]$ the average time for $M$ number of successful contentions. To obtain the close-form expression of the $T_{COP}$, we then focus on deriving the $E[T_{COP}]$ in order to determine $M_{opt}$ and $p_{opt}$. Due to the independently distributed $t_i$, we have

$$E[T_{COP}] = \sum_{i=1}^{M} E[t_i]$$

$$= \sum_{i=1}^{M} \left\{ (E[N_i^c] + 1)E[\text{Idle}_i] + E[N_i^c]E[\text{Coll}_i] + E[S_i] \right\}$$

where $E[N_i^c], E[\text{Idle}_i], E[\text{Coll}_i]$ and $E[S_i]$ are the average number of collisions, the average duration of a idle time,
According to [12], we have the following expressions:

\[
E[N^c_t] = \frac{1 - (1 - p)^{L-i}}{(L-i)p(1-p)^{L-i-1}} - 1 \\
E[\text{Idle}_{t}] = \frac{(1-p)^L}{1 - (1-p)L^{-1}} \cdot \delta_{\text{idle}}
\]

where \(\delta_{\text{idle}}, \delta_{\text{coll}} = E[\text{Col}_{t}]\) and \(\delta_{\text{suc}} = E[S_{t}]\) are constant [12]. Then, \(E[T_{\text{TOP}}]\) is the function of \(M\) and \(p\). Let \(T_{\text{TOP}}(M, p) = E[T_{\text{TOP}}]\), after some algebraic manipulations:

\[
T_{\text{TOP}}(M, p) = \sum_{i=1}^{M} \left\{ \frac{(1-p)^L}{(L-i)p(1-p)^{L-i-1}} \cdot \delta_{\text{idle}} + \left( \frac{1 - (1-p)^{L-1}}{(L-i)p(1-p)^{L-i-1}} - 1 \right) \cdot \delta_{\text{coll}} + \delta_{\text{suc}} \right\}
\]

Given \(T_{\text{frame}}\), longer \(T_{\text{TOP}}(M, p)\) allow more devices succeed in contention. However, the incremental \(T_{\text{TOP}}(M, p)\) will reduce the duration of \(T_{\text{TOP}}\) subjecting to the constraint as \(T_{\text{TOP}}(M, p) + T_{\text{TOP}} \leq T_{\text{frame}}\). To balance this tradeoff, we formulate an optimization problem to maximize the aggregate throughput in each frame. Here, the aggregate throughput is defined as the sum of the throughput obtained by all the devices which are allocated the transmission slots during each frame. Let \(T_{\text{tran}}\) and \(R\) denote the transmission time slot and data rate of each device which are constant. Then, we can maximize the aggregate throughput, denoted by \(C_{\text{total}}\), for each frame as

\[
\begin{align*}
\{M_{\text{opt}}, p_{\text{opt}}\} &= \max_{M, p} C_{\text{total}} = \max_{M, p} MRT_{\text{tran}} \\
&\text{s.t.} \quad T_{\text{TOP}}(M, p) + MRT_{\text{tran}} \leq T_{\text{frame}}
\end{align*}
\]

(5)

Then, we try to prove the convexity of above optimization problem. Since the objective function in (5) is a convex function of \(M\) and constraint (8) is linear. Lemma 1 below shows that, asymptotically, for M2M networks with tremendous number of devices, i.e. \(L\) is large, the constraint (7) is also a convex function.

**Lemma 1.** For \(L \rightarrow \infty\), \(T_{\text{TOP}}(M, p)\) can be obtained as a convex function of \(M\) and \(p\).

**Proof:** Since the duration of \(T_{\text{frame}}\) has a finite value, as \(L \rightarrow \infty\), it is easy to obtain \(L \gg M\), then we have

\[
T_{\text{TOP}}(M, p) = M \left\{ \frac{(1-p)^L}{Lp(1-p)^{L-1}} \cdot \delta_{\text{idle}} + \left( \frac{1 - (1-p)^{L-1}}{Lp(1-p)^{L-1}} - 1 \right) \cdot \delta_{\text{coll}} + \delta_{\text{suc}} \right\}
\]

Moreover, \((1-p)^{L-1}\) tends to \((1-p)^L\) if \(L\) sufficiently large. Hence, we can obtain the approximated transformation of the above equation as

\[
T_{\text{TOP}}(M, p) = M \left\{ \frac{1}{Lp} \cdot \delta_{\text{idle}} + \delta_{\text{suc}} + \left( \frac{1}{Lp(1-p)^{L-1}} - \frac{1}{Lp} - 1 \right) \cdot \delta_{\text{coll}} \right\}
\]

Taking the second derivative of \(T_{\text{TOP}}(M, p)\) with respect to \(M\) and \(p\), respectively, gives

\[
\frac{\partial^2 T(M, p)}{\partial M^2} = 0 \\
\frac{\partial^2 T(M, p)}{\partial p^2} = \frac{2}{Lp^2} \delta_{\text{idle}} + \left( \frac{1 - (1-p)^{L+1} + Lp}{p^2(1-p)^{L+2}} \right) \delta_{\text{coll}} > 0
\]

Consequently, we conclude that \(T_{\text{TOP}}(M, p)\) is a convex function of \(M\) and \(p\) [13].

Therefore, the optimization problem is a convex programming problem and can be solved easily with off-the-shelf toolbox. And the optimal period of COP, \(T_{\text{TOP,opt}} = T_{\text{TOP}}(M_{\text{opt}}, p_{\text{opt}})\).

**IV. A PRACTICAL HYBRID MAC PROTOCOL DESIGN**

In this section, we design a practical hybrid MAC protocol for the M2M networks. The operations of the proposed hybrid MAC are separated into frames for contention and data transmission as shown in Fig. 1. As mentioned early, each frame is divided into four periods: NP, COP, TOP, and AP. The specific description of each period is given as follows:

**A. Notification Period (NP)**

At the start of every time frame, the BS broadcasts an advertisement message (ADV) to all \(K\) number of devices. BS then estimate the number of devices that have information to transmit (i.e. value of \(L\)), one way is by using the estimation method proposed in [10]. Then, the BS broadcast the duration of contention period \(T_{\text{TOP,opt}}\) and the contending probability \(p_{\text{opt}}\) based on optimization solution in Section III. And the networks enters COP.

**B. Contention Only Period (COP)**

In this period, \(L\) number of the devices contend the transmission opportunities based on \(p\)-persistent CSMA method, with contending probability of \(p_{\text{opt}}\). The contending devices randomly send the transmission request (Tran-REQ) message to the BS. The contention is declared as success only when one device send the Tran-REQ message. When more than one devices are sending Tran-REQ, the collision occurs. The idle period is a time interval in which the contention is not happening. Under \(p\)-persistent CSMA, the success period and collision period can be given as \(\delta_{\text{coll}} = E[\text{Col}] = T_{\text{req}} + BIFS\) and \(\delta_{\text{suc}} = E[S] = T_{\text{req}} + SIFS + T_{\text{ACK}} + BIFS\), where \(T_{\text{req}}\) is the length of Tran-REQ message, \(T_{\text{ACK}}\) is the duration of ACK, and \(BIFS\) and \(SIFS\) are the backoff inter frame space and short inter frame space respectively.

If a Tran-REQ message successfully received, the BS increments the counter by one. To control the number of successful devices, the optimal \(M_{\text{opt}}\) which obtained by (10) is used as
the threshold. Recall that the calculation of \( M_{opt} \) in (10) is based on the expected value calculation which is not able to manifest the variability of the devices’ random contention. To avoid performance degradation caused by the difference between the analytical and practical results, we propose a two thresholds scheme to control the duration of COP as shown in Fig. 2. In this scheme, the BS stop the COP period not only depending on the number of successful devices \( M \), but also the contention period \( T_{COP} \). Either the counter value exceed \( M_{opt} \) or the real contention time longer than \( T_{COP,opt} \), the BS will stop the COP and declare the next period, i.e., announcement period. Hence there will be at most \( M_{opt} \) devices has the right to transmit during TOP.

\[
\text{Initialize } t=0 \text{ and } \text{counter}=0
\]

At the beginning of each frame, solves optimization problem (6) and obtains \( M_{opt} \) and \( p_{opt} \). Allows the contention start

\[
\text{Calculates } T_{COP,opt} \text{ according to } M_{opt} \text{ and } p_{opt} \\
\text{Does Tran_REQ is received?}
\]

\[
\text{counter} = \text{counter} + 1
\]

\[
t = t + 1
\]

\[
\text{counter} > M_{opt} \text{ or } t > T_{COP,opt} \text{?}
\]

\[
\text{Stops contention period}
\]

Fig. 2. A flowchart of the two thresholds scheme.

C. Announcement period (AP)

After the contention finished, BS initiates and broadcasts the announcement message to all of the contending devices. The announcement message consists of two parts: (i) successful devices’ ID and (ii) the transmission schedule. If the device verify its’ ID in the message, the device should send data at the assigned transmission slots. If the device do not verify its’ ID, the device should go into the sleep mode and wait for the next frame. Such arrangement keep the wake-up time of a device at minimal, and we will further investigate the energy consumption of the proposed schemes in the future work.

D. Transmission Only Period (TOP)

In the data transmission period, the successful device turns on its radio module and sends its data to the BS over its allocated time slots, and turns its radio module off at all other times. Though only uplink is mentioned, some modification to the protocol can be applied to downlink where the devices would like to receive information from the BS. While we only focus on homogenous scenario, we will extend the work further by considering each device has a different priority, and different data size.

V. PERFORMANCE STUDY AND EVALUATION

In the following sections, we will compare the proposed hybrid MAC protocol with contention-based protocol - slotted Aloha [8] and reservation-based protocol - TDMA [9] in terms of throughput, utility and average transmission delay. The simulation parameters are shown in Table I.

Table I: The simulation parameters

| Parameter | Value | Description |
|-----------|-------|-------------|
| \( T_{NP} \) | 10.2 \( \mu s \) | The duration of NP |
| \( T_{AP} \) | 10.2 \( \mu s \) | The duration of AP |
| \( T_{tran} \) | 1 ms | The transmission time of each device |
| \( R \) | 1.728 Gbps | The data rate |
| \( T_{req} \) | 22.2 \( \mu s \) | The length of Tran-REQ message |
| \( T_{ACK} \) | 7.5 \( \mu s \) | The duration of ACK frame |
| SIFS | 2.5 \( \mu s \) | The duration of short interframe spacing |
| BIFS | 7.5 \( \mu s \) | The duration of backoff interframe spacing |

Table II: The optimization results

| Frame | \( M_{opt} \) | \( p_{opt} \) | \( L \) | \( M_{opt} \) | \( p_{opt} \) |
|-------|-------|-------|-----|-------|-------|
| 100   | 46    | 0.06  | 100 | 92    | 0.06  |
| 200   | 46    | 0.03  | 200 | 92    | 0.03  |
| 300   | 46    | 0.02  | 300 | 92    | 0.02  |

In Table II we present \( M_{opt} \) and \( p_{opt} \) in terms of the duration of the frame \( T_{frame} \). When the number of the contending devices \( L \) equals to 100, 200 and 300, respectively. It is observed that \( p \) decreases as \( L \) increases which shows the overload control ability of our scheme. Moreover, the number of the successful devices \( M_{opt} \) is double if \( T_{frame} \) is doubled. This indicates that our scheme is very efficient, as we can set \( T_{frame} \) to be small, and it works well for any values of \( L \) without any lost in efficiency.

A. Throughput

Then, we compare the aggregate throughput in terms of the total number of the devices (\( K \)). Here, the transmission probability in slotted-ALOHA is set as 0.08. Under such setting-up, the relationship between \( K \) and \( L \) is \( L = 10\%K \), \( L = 30\%K \) and \( L = 50\%K \). As shown in Fig. 3 the aggregate throughput in the proposed hybrid protocol is always higher than TDMA, and will higher than slotted-ALOHA as \( K \) and \( L \) increase. That is, the proposed hybrid protocol can optimally control the contention probability \( p \) and the number of successful devices to maximize the aggregate throughput. While slotted-ALOHA performs well only at low-load condition, and TDMA performs well only at heavy-load condition. While our hybrid scheme may not perform the best under low-load condition (e.g. \( L = 10\%K \) and \( K \) is small), our hybrid scheme outperform the other two when \( L \) is increased.
The aggregate throughput in terms of the number of the contending devices $L$ for different value of the $T_{frame}$ is shown in Fig. 4(a). For a given $T_{frame}$, it is observed that the throughput linearly increase at first as the number of the contending devices increases until the maximal throughput is obtained. Then, the aggregate throughput has a slight drop after the number of contending device $L$ exceed $M_{opt}$.

Fig. 3. The aggregate throughput comparison in terms of the total number of the devices when $T_{frame} = 50\text{ms}$.

Fig. 4. The aggregate throughput and utility in terms of the number of the contending devices.

B. Utility Comparison

In this paper, we define the utility as the ratio of transmission period ($T_{TOP}$) to the period of each frame ($T_{frame}$). Let $U$ denote the utility, we have

$$U = \frac{T_{TOP}}{T_{frame}} \quad (11)$$

To illustrate the performance of utility, we also compare our proposed protocol with the slotted-ALOHA and TDMA. Similarly, the transmission probability in slotted-ALOHA is set as 0.08.

Fig. 5 shows the utility in terms of the total number of devices when $T_{frame} = 50\text{ms}$. Under such setting-up, the relationship between $K$ and $L$ is $L = 10\%K$, $L = 30\%K$ and $L = 50\%K$. We observe that the utility of the proposed hybrid protocol is lower than that in slotted-ALOHA when the number of the contending devices is low. However, as the number of the devices increases, the collision caused by slotted-ALOHA will increase which can drastically reduce the utility. Since the hybrid protocol use the TDMA mechanism for transmission, the successful devices can transmit data without collision. In addition, the utility in proposed hybrid protocol is especially higher than that in TDMA. This is because the proposed hybrid protocol only allow the devices with data to transmit to participate in the contention. Hence, the transmission slots assigned to the successful devices can be fully utilized. Comparatively, the slots assignment in TDMA is fixed and static for each device without considering the thorough channel utilization.

Fig. 4(b) shows the utility in terms of the number of contending devices. For a given $T_{frame}$, it is observed that the utility linearly increase at first and then decrease as the number of the contending devices increases. Together with the results in Table III and Fig. 4, we can set the $T_{frame}$ to be some small value, and yet it can achieve the same normalized throughput / utility as high value of $T_{frame}$. This eliminate the worry about the value of contending devices $L$ when setting $T_{frame}$, as in practical network $L$ may not known before hand.

C. Average Transmission Delay

In this subsection, we aim to compare the average transmission delay among the proposed hybrid protocol, slotted-ALOHA and TDMA. The transmission delay is defined as the time elapsed between the start of a frame and the end of its transmission to the BS during a frame. Without loss of generality, the transmission probability in slotted-ALOHA is set as 0.08, and $T_{frame} = 200\text{ms}$. Meantime, the relationship between $K$ and $L$ is $L = 10\%K$, $L = 30\%K$ and $L = 50\%K$. From Fig. 5, it is easy to obtain the average transmission delay in slotted-ALOHA and TDMA. Then, we focus on evaluating the average transmission delay for the proposed hybrid protocol. Let $T_{delay}$ denote the average transmission
delay, we have
\[ T_{delay} = T_{NP} + T_{COP} + T_{AP} + T_{TOP} \]
where \( T_{COP} = \overline{T}_{COP} \). After contention, the BS initiates and broadcasts a transmission schedule for the successful devices. After receiving the schedule, each successful device sends its data packet to the BS at its scheduled time slots \( T_{tran} \) following TDMA mechanism. Hence, the average delay for a device during a single frame is
\[ T_{TOP} = \overline{T}_{TOP} - T_{COP} - T_{NP} - T_{AP} \left( 1 - \frac{1}{M_{opt}} \right) + T_{tran}. \]

Fig 6. The comparison of average transmission delay in terms of the total number of devices when \( T_{frame} = 200\text{ms} \).

Fig 6 shows the average transmission delay comparison among Slotted-ALOHA, TDMA and proposed hybrid protocol. The comparison indicates that hybrid protocol is able to achieve lower delay than Slotted-ALOHA. This is because hybrid protocol only allow the device transmit a small command message during contention period. The waiting time during collision can be greatly reduced. Moreover, when the number of the devices becomes large, our hybrid scheme not only control the number of the served devices but also control the transmission probability to mitigate the congestion of the devices. In addition, proposed scheme has litter higher but closed results compared to the TDMA scheme. That is, in the proposed scheme, devices have to spend more waiting time during the contention period, however, this is the trade-off to achieve a higher utility of channel.

VI. CONCLUSION

In this paper, we focused on studying the massive access control scheme for M2M networks. In our scheme, the operation of each frame is mainly divided into two parts: contentention only period (COP) and transmission only period (TOP). The devices only send contending commands during COP and transmit data during TOP. Under such mechanism, the BS can easily maximize the aggregate throughput by controlling the duration of COP and TOP which are decided by the contending probability of the devices and the number of the served devices. An optimization is formulated to solve the problem, and we show analytically the problem is convex. To implement the scheme, we then presented a hybrid MAC protocol for the M2M networks. We analyzed the aggregate throughput, utility and the average transmission delay to show the effectiveness of the proposed hybrid MAC protocol.

In the future, we will consider the fairness for our proposed scheme and in a more practical environment: heterogeneous M2M network where the devices may have different service requirements. In order to fairly assign the resources to these devices, a QoS provisioning access control scheme should be considered. In that case, new constraints should be added in the optimization problem to cover the heterogenous among all type of devices.

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