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Energy Efficient MAC for Cellular-Based M2M Communications*

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Abstract—**In Machine-to-Machine (M2M) networks, an energy efficient scalable medium access control (MAC) is crucial for serving massive battery-driven machine-type devices. In this paper, we investigate the energy efficient MAC design to minimize battery power consumption in cellular-based M2M communications. We present an energy efficient MAC protocol that not only adapts contention and reservation-based protocols for M2M communications in cellular networks, but also benefits from partial clustering to handle the massive access problem. Then we investigate the energy efficiency and access capacity of contention-based protocols and present an energy efficient contention-based protocol for intra-cluster communication of the proposed MAC, which results in huge power saving. The simulation results show that the proposed MAC protocol outperforms the others in energy saving without sacrificing much delay or throughput. Also, the lifetimes of both individual nodes and the whole M2M network are significantly extended.**

Index Terms—**Machine-to-Machine communications, Internet of Things, Cellular Networks, MAC, Energy efficiency.**

I. INTRODUCTION

INTERNET of Things (IoT) enables smart devices to participate more actively in every day life, business, industry, and health care. Among large-scale applications, cheap and widely spread machine-to-machine (M2M) communications supported by cellular networks will be one of the most important approaches for the success of IoT [1]. M2M communications, also known as machine-type communication (MTC), means the communications of machine devices without human intervention [2], which is applicable to health monitoring, smart metering, remote security, and so on [3]. Smart devices are usually battery-driven and long battery life is crucial for them, especially for devices in remote areas, as there would be a huge amount of maintenance effort if their battery lives are short. This problem is similar to the lifetime problem in wireless sensor networks. Medium access control (MAC) design, data gathering, and clustering design for wireless sensor networks is extensively studied in literature [4]-[6]. However, regarding the particular characteristics of the M2M communications such as the massive access request, energy efficiency, and fairness, these MAC protocols are failed to address large-scale concurrent channel access in an M2M network [7]. Also, the existence of the base station with global system information and coverage provides opportunities for cellular-based M2M which are not available in sensor networks. It is raised by the 3GPP that the required efficiency for enabling M2M communications in current cellular network infrastructure, which is designed for human-to-human communication, is missing [8]-[9]. Regarding the fundamental differences between M2M and human-to-human communications, many research works have been launched to understand how current infrastructure need to change to be able to provide large-scale massive access [10]-[11].

3GPP LTE have defined research projects to support massive machine access [12]. The random access mechanism of LTE and a survey of improved alternatives for serving cellular-based machine devices are investigated in [9]. Some challenges in LTE networks for supporting M2M communication have been investigated in [10]-[11]. In [13], massive access management in cellular networks for satisfying delay requirements of machine nodes is considered. Also they proposed to divide machine nodes into clusters based on the different QoS requirements. Power-efficient multiple access protocols for a limited number of machine devices with reliability constraints in cellular networks are considered in [14]. The study of these research works has been focused on improving network performance for supporting massive access, but the energy efficiency in massive machine access has not been considered. Notice that contention-based MAC protocols for wireless sensor networks, e.g. IEEE 802.15.4, can not be used here as they are designed for short-range ad hoc or mesh type of networks [15]. In addition, their designs are not designed for enabling a massive number of devices accessing the BS at the same time. Addressing the numerous concurrent machine access with current cellular network infrastructure is still an open problem. This is the focus of the paper.

In this paper, energy efficient MAC design for M2M communications is considered. We present a large-scale energy efficient MAC protocol for cellular-based M2M communications. We will investigate the energy efficiency of contention-based protocols and devise a multi-phase protocol for intra-cluster communications in the proposed MAC. The simulation results show that the proposed MAC protocol outperforms the others in energy saving without sacrificing much delay or throughput.

The remainder of this article is organized as follows: In the next section, system model and related works are introduced. In section III, MAC design for cellular-based M2M is proposed. Performance evaluation and improvement for contention-based protocols are presented in section IV. In section VI, we present the simulation results. Concluding remarks are presented in section V.

II. SYSTEM MODEL AND MEDIUM ACCESS

Consider a single cell with one base station (BS) and N static machine nodes that are uniformly distributed in the cell. The packet arrival at the machine nodes follows a Poisson distribution [16]. The packet arrival rate for each node is very low and the packet size is small, but the overall network load is dependent upon the number of active machine nodes in the cell. When a packet is generated at a machine node, it tries to access the base station. The machine nodes are battery driven and desire long battery life. The objective is to extend the battery life of the whole network, while minimizing the implementation and maintenance costs.

As M2M usually has small size packets, it make no sense to perform Ping-Pong authentication and transmit some reservation packets, while the actual data packet size is comparable with or even smaller than the reservation packet size [9]. Therefore it wastes a lot of energy if M2M devices send

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data directly to the BS, which implements reservation-based protocols. On the other hand, contention-based protocols are not energy efficient for massive machine access because of collisions in massive access and idle listening. To address the energy efficient massive access problem in cellular networks, we introduce partial clustering with hybrid MAC protocol in this section.

A. Partial Clustering

With clustering, the cluster head (CH) relays the messages from the cluster members to the base station. This reduces the contention for channel access between nodes and saves energy. Clustering always decreases the number of direct access requests to the base station and makes the protocol scalable; however, it may not be always energy efficient in data transmission, owing to relatively the same distance from BS to both cluster head and member. To achieve the highest energy efficiency, we propose partial clustering, in which only machine nodes far from the BS are grouped in clusters. In other words, the communication from the machine nodes to the BS might be in one hop. Simulation results will show that partial clustering outperforms full clustering and non-clustering MAC protocols in energy efficiency.

B. Frame Formation

The frame is divided into two parts, one for the communication from the cluster members to the cluster heads and the other one for sending data from the cluster heads to the BS. We treat unclustered nodes as cluster heads, where their cluster has no member. To be scalable and decrease the deployment costs, we propose to use contention-based protocols for intra-cluster communication. It has been shown that contention-based protocols outperform the others in time efficiency, i.e. delay, while they are not energy efficient, due to the collisions [14]. With clustering, the number of nodes in each cluster is relatively small and then, traffic load within each cluster is too light to cause idle listening or collisions. Therefore we can use carrier sense multiple access-collision avoidance (CSMA/CA) protocol for intra-cluster communications. In the second part of the frame, CHs have different numbers of packets to send to the BS, depending on the cluster sizes. Then to tackle the heterogeneous traffic pattern in CHs and making the communications more energy efficient, we use reservation-based protocols, e.g. dynamic time division multiple access (TDMA) where a short reservation phase is used to schedule the resources for all users, for the communications between cluster heads and the base station. This is also compatible with existing cellular standards.

C. Medium Access Design

To further improve the energy efficiency in intra-cluster communications by reducing collisions and idle listening, the former half of the frame is further split into n phases, where in each phase, a portion of the cluster members transmit their packets using the CSMA/CA protocol. The discussion on how to set the intra-cluster contention parameter n is left due to the page limit. The complete design works as follows:

- For a given SNR requirement at the BS, the transmission power of each node can be calculated. The nodes whose transmission power is higher than a threshold, T, are grouped into clusters. Inside each cluster, the machine node with the lowest transmission power is selected as the cluster head. By feasible increase in the number of clusters, the traffic load of the clustered nodes for communication to the BS will be decreased. The choice of T determines the number of clusters in the cell and the traffic loads in each cluster.
- In the intra-cluster communication phase, each cluster head divides its members into n groups and allocates n phases to them. Each member node wakes up for data transmission only in its assigned phase.
- In the dynamic TDMA period, the cluster heads and the unclustered nodes communicate directly to the base station. In the notification phase, the base station broadcasts the reservation probability, q, and the number of reservation slots. The reservation is made with probability q, i.e., nodes with probability q randomly choose a reservation slot to send reservation packets and with $1-q$ wait for the next beacon.
- In the transmission phase, nodes wake up and send packets into corresponding slots. After this phase, the unclustered nodes switch to the sleep mode and cluster heads start to listen to their cluster members in the next CSMA phase.

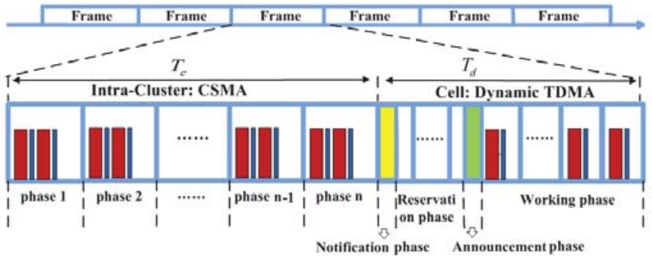

Fig. 1. Frame formation of the proposed MAC protocol

The basic idea behind two-hop transmission for cellular-based machine devices is similar to the relay-aided cellular networks in [17]-[18], however, the design objective here is energy efficiency for a large number of short-lived sessions and in those works the objective is maximizing the spectral efficiency for a small number of long-lived sessions.

III. Energy efficiency evaluation and improvement for Intra-cluster communication

When network load increases, collisions and idle listening cannot be avoided in contention-based protocols. In the following we evaluate the performance of multi-phase CSMA/CA scheme for intra-cluster communication to avoid idle listening and as many collisions as possible. The goal is to realize a close-to-zero power-wasting MAC protocol.

A. Energy Efficiency and Network Capacity

Different transmission algorithms can be used in CSMA/CA, for example 1-persistent CSMA (1P-CSMA), p-persistent CSMA, non-persistent CSMA (0P-CSMA), or RTS/CTS mechanism. As M2M has very small packet sizes, we choose 0P-CSMA. This also achieves the lowest implementation cost. In non-persistent CSMA, the machine node waits for a random amount of time after sensing a busy channel and repeats this algorithm until finding the channel idle, to transmit data. In following, we investigate the energy efficiency and access capacity of non-persistent CSMA protocol. Define the aggregated packet arrival rate of a machine node as g, which includes both new arrivals and retransmitted ones. We assume that the acknowledgment packets are transmitted in a separate collision free channel to simplify the analysis. By long-term observation of the channel, one can see two different periods in channel utilization: idle period and busy period, where the the transmission in the later can be either successful or unsuccessful. We consider a 2-state Markov model for idle and busy states of the channel utilization that is shown in Fig. 2. Based on this model, the probability of the idle and busy states are the same, i.e. $\pi_I = \pi_B = 0.5$. Also, the probability of each possible transition between states is 1. Define $\tau_s = \tau_p + \tau_r$, where τ_p and τ_r stand for transmission delay and round trip time delay from successful packet transmission to the acknowledgment packet arrival respectively. The average duration of the idle state is the average time between each pair of consecutive packets, i.e. $B_I = 1/g$. The average duration of busy period is $B_B = \tau_p + \delta + \hat{Y}$, where $\hat{Y}$ denotes the average time at which the last interfering packet is scheduled within a transmission period that started at time 0, and is calculated as follows:

$$F_Y(y) = pr(\text{no arrival during } \delta_d - y) = e^{-g(\delta_d - y)} \quad (1)$$

$$\longrightarrow \hat{Y} = \delta - (1 - e^{-g\delta_d})/g \quad (2)$$

where δ_d is the detection delay. Packet transmission will be successful if it starts after an idle period and no other node starts transmission after it. Then, the probability of successful packet transmission is the multiplication of time-averaged idle channel probability (p_i) and no collision after that (p_t), as follows:

$$\begin{aligned} p_s = p_i \times p_t &= \frac{\pi_I B_I}{\pi_I B_I + \pi_B B_B} \times pr(\text{no transmission in } \delta_d) \\ &= 1/(g[\tau_p + \delta_d + \delta]e^{g\delta_d} + 1) \quad (3) \end{aligned}$$

The average packet delay is derived by considering the average time spent in backoffs and retransmissions before a successful packet transmission, as follows:

$$\begin{aligned} D^{cs} = \tau_s + \sum\nolimits_{k=0}^{K} (1 - p_s)^k p_s k [\frac{1 - p_i}{1 - p_s}\theta_b \\ + p_i \frac{1 - p_t}{1 - p_s}(\theta + \tau_s)] \quad (4) \end{aligned}$$

in which, $\frac{1-p_i}{1-p_s}$ and $p_i \frac{1-p_t}{1-p_s}$ are the probability of unsuccessful transmission due to a busy sensed channel and collision respectively. Also K is the maximum number of times that a machine node tries to transmit a specific packet, and θ, θ_b are the average backoff after sensing a busy channel and collision respectively. Define the power consumption in listening and transmitting modes for node i as P_l and $P_{t_i} + P_c$ respectively, where P_c is the circuit power consumed by electronic circuits in the transmission mode. The Bit per Joule energy efficiency of system is derived by considering the number of successfully transmitted bits in time interval T_c and the energy consumption in that interval for listening to the channel, data transmission (successful or unsuccessful), and idle listening. Then one can derive the energy efficiency of node i as follows:

$$\begin{aligned} EE_i^{cs} &= \\ &\frac{gT_c\alpha p_s}{gT_c(p_i[(P_c + P_{t_i})\tau_p + P_l(\tau_r + (1 - p_t)\theta)] + [1 - p_i]P_l\theta_b)} \\ &= \frac{\alpha p_s}{p_i[(P_c + P_{t_i})\tau_p + P_l(\tau_r + (1 - p_t)\theta)] + (1 - p_i)P_l\theta_b} \end{aligned}$$

Under a delay constraint, one can find the threshold probability of successful transmission, p_s^{th}, from (4). Then the network capacity, i.e. the maximum number of sustained machine devices is derived from (3) as

$$N_{max} = \frac{p_s^{th}\text{LW}(\delta_d[1/p_s^{th} - 1]/[\tau_p + \delta_d + \delta])}{\delta_d \lambda_0} \quad (5)$$

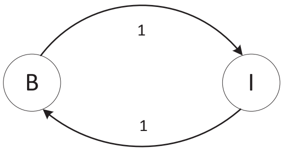

Fig. 2. State transitions of non-persistent CSMA

in which, λ_0 is the packet arrival rate of each node and LW is the LambertW function [19].

B. Multi-Phase CSMA Protocol

Idle listening in CSMA is the time when colliding nodes are backing off and keeping sensing the channel, which consumes energy. As the number of nodes increases, the probability of collision increases, which results in more energy consumption. To save energy, we try to reduce the contention between nodes. The proposed multi-phase CSMA divides each contention interval into multi phases (Fig. 3). In each phase, only a portion of the nodes are permitted to compete for channel access. Before the allocated phase starts, each node keeps sleeping instead of listening. Potential arrived packets in inactive phases are buffered. With this multi-phase scheme, the probability of successful packet transmission increases, then the number of collisions and the idle listening time can be shortened significantly.

To design the proposed multi-phase protocol with the optimal number of phases, in the following we derive the energy efficiency and packet delay versus the number of phases. Because of the page limit, we derive the performance metrics for ALOHA as an extreme case of 0P-CSMA instead of the general case to simply the analysis. The general analysis will be provided in the journal version. The probability of successful packet transmission for slotted ALOHA system with N machine nodes is derived in [20] as

$$N\sigma(1 - \sigma)^{N-1},$$

where σ is the probability of packet generation in a time slot for each machine node. Using the proposed n-phase protocol, the probability of packet generation in each subslot of the active phase will be $n\sigma$, due to the packet buffering in $n - 1$ inactive phases. Then, the probability of successful packet transmission for the proposed protocol is calculated as follows:

$$p_s = N\sigma(1 - n\sigma)^{\frac{N}{n} - 1} \quad (6)$$

The energy efficiency of the n-phase protocol is derived by considering the number of successfully transmitted bits in time interval T_c, the energy consumption in that interval for data transmission (successful or unsuccessful), and backoff after collisions. Then, one can derive the energy efficiency for node i as follows:

$$\begin{aligned} EE_{al}^i &= \frac{gT_c p_s}{gT_c p_s[(P_c + P_{t_i})\tau_p + P_l\tau_r + (1 - p_s)P_l\theta]} \quad (7) \\ &= \frac{p_s}{(P_c + P_{t_i})\tau_p + P_l\tau_r + (1 - p_s)P_l\theta} \quad (8) \end{aligned}$$

It is evident that by the feasible increase in the number of phases, n, the probability of successful transmission and energy efficiency of the system increase. Also, as machine nodes buffer arrived packets in inactive phases, the packet delay increases in the proposed scheme. The average packet delay for proposed scheme is derived as follows:

$$D_{al} = \sum\nolimits_{k=0}^{K} (1 - p_s)^k p_s \big(\tau_s + k\theta + (k + 1)d_a\big) \quad (9)$$

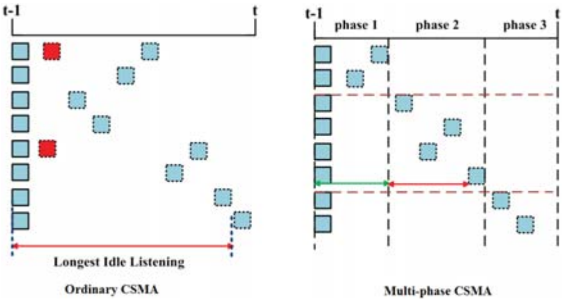

Fig. 3. Ordinary CSMA and Multi-phase CSMA. The idle listening and collisions are decreased.

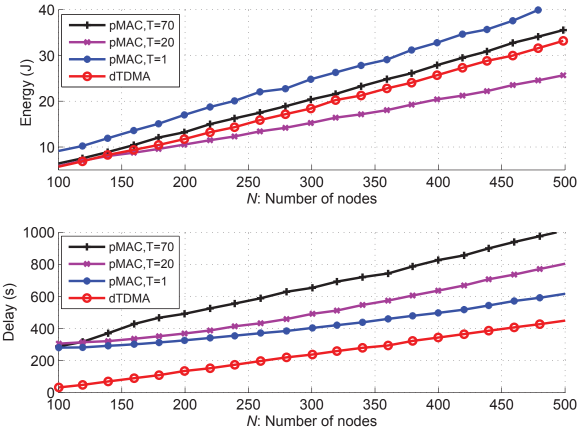

Fig. 4. Delay and energy performance evaluation for pMAC and dTDMA

where d_a is the access delay caused by dividing the contention window into n phases and is calculates as:

$$d_a = \gamma \sum_{i=1}^{\frac{(n-1)T_c}{n\gamma}} i\sigma(1-\sigma)^{(n-1)\frac{T_c}{n\gamma}-i} \qquad (10)$$

in which, γ is the length of each time slot and T_c is the length of n-phase contention window. Using performance metrics in (6)-(9), one can derive the optimal number of phases for proposed multi-phase protocol.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed medium access design. The machine devices are randomly deployed in the cell and traffic generation in machine nodes follows a Poisson distribution. For intra- and inter-cluster communications in the proposed protocol, 4-phase 0P-CSMA and dTDMA are implemented, respectively. The parameters for M2M communications are based on [21], where they consider M2M communications over LTE networks. We compared the proposed MAC (pMAC) protocol against reservation-based dynamic TDMA (dTDMA) that consists of reservation and transmission periods [22]. Fig. 4 shows the energy consumption and delay for dTDMA and pMAC with different clustering thresholds, T. Machine nodes whose transmission power is higher than T will be clustered. From the energy consumption point of view, it is evident that the proposed MAC with 20 mW as the threshold consumes the least power, which means partial clustering outperforms non-clustering (big threshold) and complete-clustering (small threshold) in energy efficiency. By increasing the threshold, fewer clusters will be formed and the average distance between clusters and the BS will be increased. As putting machine nodes which are near BS into clusters, or having many unclustered nodes wastes energy, then there is an optimum threshold that minimizes the overall energy consumption. Furthermore in Fig. 4, one can see that the delay performance of proposed MAC has been sacrificed for getting less power consumption, then proposed MAC has higher delay than [22]. The gap between delay performance of two schemes, which seems to be high, can be reduced significantly by decrease in the backoff time, however, it increases the energy consumption of the system and here, we evaluate the system without strict delay requirement to find bounds on the energy efficiency of the system. Finally, we considered the battery life performance in Fig. 5. It is obvious that the proposed MAC protocol has extended the battery life of machine nodes to a much higher level. The extension is 500% on average and can even be as large as 800% at some points. On the other hand, the battery life of cluster heads is sacrificed by 50%. Since the overall system energy consumption can be reduced by choosing appropriate thresholds, the profits on individual node lifetime is sufficient to overcome the loss in lifetime of cluster heads. To avoid exhausting cluster heads too fast, one way is letting cluster members be the head in turn. The discussion on cluster head rotation is beyond the scope of this paper. The reader is referred to our further work in [23] for more information.

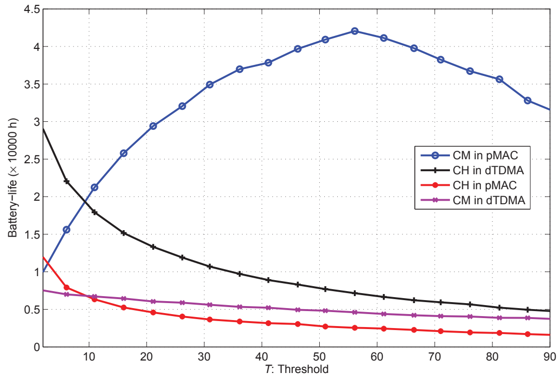

Fig. 5. Battery lives of cluster heads (CH) and members (CM) for pMAC and dTDMA

V. CONCLUSION

In this paper, energy efficient MAC protocols have been studied to minimize the battery power consumption of M2M communications. We have proposed a new MAC protocol for massive machine access support in cellular networks. This solution not only adapts contention and reservation-based protocols for M2M communications, but also takes the advantage of partial clustering in cellular networks to be scalable. The proposed hybrid protocol combines the advantages of contention-based and -free medium access designs. Also, we have investigated the energy efficiency of the proposed protocols and given the optimal design. Simulation results showed that with the proposed MAC protocol, the lifetimes of both individual nodes and the whole M2M network are significantly extended.

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