Packet size adjustment for minimizing the average delay in buffer-aided cognitive machine-to-machine networks☆,☆☆

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ABSTRACT

In this paper, a cognitive machine-to-machine (CM2M) network is considered in which underlaid on a macro cell, there exist some co-existing small cell based M2M networks. In each small cell, M2M network is comprised of some machine type devices (MTDs) and an MTD gateway. The MTD gateway collects data of MTDs within each small cell and transmits it to the small cell base station reusing the spectrum of the macro cell. To avoid data loss, MTD gateway is equipped with a buffer. In the considered CM2M network, MTDs with delay sensitive application are prioritized over MTDs having delay tolerant packets. In order to minimize the average delay of the MTDs, a novel packet adjustment scheme is proposed. The average delay and the average throughput of the CM2M network are computed. Simulation results show that the proposed scheme outperforms conventional policy without packet adjustment in terms of average delay of MTDs.

1. Introduction

Recently machine-to-machine (M2M) communications have attracted much attention in the literature and the number of machine-type devices (MTDs) are predicted to be in billions by 2020 [1–3]. In M2M systems, different types of MTDs including actuators, sensors, and smart meters are connected wirelessly via the reliable links. Generally speaking, MTDs transmit short data packets with low data rate compared to the conventional cellular communication. To deal with this inherent characteristics of MTDs, capillary architecture has been recently proposed, in which data of MTDs is transmitted using a hybrid structure instead of the cellular network [4]. More specifically, in the capillary M2M network, the data packets are exchanged between MTDs close together and are transmitted to the cellular network via the aggregator nodes, i.e., MTD gateway [5].

Cognitive Radio Networks (CRN) have been emerged as a promising approach to overcome the problem of spectrum shortage, and to further increase the spectral efficiency by the opportunistic utilization of the spectrum [6]. In the CRN, secondary users use the spectrum which is licensed to primary users when they are inactive [7,8]. The white space is defined by the U.S. Federal Communications Commission (FCC) as the channels that are unexploited at a certain time and location. Therefore, it is pivotal for cognitive radio based applications to precisely detect the white space [9].

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By applying buffer-aided relaying in a three-node cooperative network, considerable performance gains in terms of the throughput can be achieved [10]. In [11], a buffer-aided CRN is considered, where the secondary relay is equipped with the buffer, stores the received data from the primary source, and transmits it to the secondary destination in an appropriate time slot. A buffer-aided link selection policy in the secondary network is proposed in order to maximize the secondary throughput under the constraint of the quality of service preservation in the primary network [11]. Authors in [12] introduce a novel buffer-aided relay selection scheme in a bidirectional CRN in which the secondary throughput is maximized. In [12], the interference between the secondary and the primary networks is eliminated via the successive interference cancellation approach, and the secondary power consumption is minimized. In [13], buffer-aided relaying concept is generalized to a full duplex CRN in order to further maximize the throughput of the secondary network.

To cope with the density of MTDs in the future Internet of things (IoT) and 5G wireless networks, new approaches to manage the radio spectrum are needed. In particular, the use of cognitive M2M (CM2M) has gained significant attention recently, in which the MTDs opportunistically reuse the resources of the cellular network [14], or TV white space [15]. Authors in [16] survey the possible application of cognitive radio concept for M2M communications from a practical point of view. In [17], a new learning approach for M2M communications is proposed. In [18], authors show how cognitive radio techniques can be deployed for M2M communication in a heterogenous small cell environments. An opportunistic relay protocol is presented in [5] for sensing the radio spectrum and canceling the interference between the cellular network and the MTDs in the CM2M network. In [19], a joint power allocation and MTDs selection policy is proposed for the buffer-aided CM2M network in which by using a buffer-aided scheme the overall throughput of the MTDs is maximized. In [20], a novel medium access control is introduced for improving the sum-rate of the MTDs and managing the total delay of M2M network. However, these existing works do not study the effects of packet adjustment on the overall delay of the M2M communications.

The main contribution of this paper is as follows:

- We propose a novel buffer-aided packet adjustment scheme at the level of the MTD gateway to minimize the average waiting time delay of the MTDs’ packets in a small cell based CM2M network based on the MTDs’ priority orders. In particular, by using the proposed approach, some of the arriving packets can be properly combined into a larger packet or a given packet can be split into some smaller packets at the MTD gateway. In the proposed protocol, the MTDs that provide urgent application are prioritized over the MTDs with delay tolerant packets. The MTD gateway does not require the instantaneous channel state information (CSI) to adjust the packet size. On the other hand, for adjusting the packet size, the MTD gateway needs the status of traffic flows and the ergodic capacity of the channel between the MTD gateway and the small cell base stations (SBS). Therefore, in the proposed policy, the packet size is determined based on the statistical CSI.
- For this proposed buffer-aided packet adjustment policy, we derive the average delay and the overall throughput of the CM2M communication network in each small cell.
- Using extensive simulations, the proposed policy is compared with a conventional scheme in which the packet of MTDs are transmitted with their original size. Simulation results show that the average delay of the CM2M network can be reduced up to 25% in the first priority class of MTDs compared with the conventional policy. To the best of our knowledge, the packet adjustment technique for the delay minimization in the CM2M network is proposed for the first time in this paper.

The reminder of the paper is organized as follows. Section 2 introduces the system model. In Section 3, the priority based packet size adjustment scheme is proposed for the two cases of perfect and imperfect spectrum sensing. Section 4 presents the simulation results, while Section 5 concludes the paper.

2. System model

Consider a two-tier cellular network composed of a macro base station (MBS), and N SBSs, where each small cell consists of M types of MTDs, and an MTD gateway for data collection, as shown in Fig. 1. In each small cell, MTDs transmit data to the MTD gateway, and the MTD gateway forwards data of MTDs to the SBS. The network architecture in Fig. 1 mimics a capillary network, where the basic idea is to enable an efficient co-existence of the M2M data communication and cellular network. More specifically, the MTD gateway collects data of MTDs within each small cell and transmits it to the SBS. It is assumed that the small cells and the M2M communication network within them can opportunistically exploit the radio resources of the macro cell. In practice, for alleviating the negative effects of the M2M communications on the cellular network, the communications between the MTD gateway and the SBS is based on a standard 5G or LTE, whereas the communications between the MTDs and the MTD gateway is done via IEEE 802.15.x protocols [21]. Therefore, the data transmission between the MTD gateway and the SBS can cause interference to the macro cell. The macro cell can be seen as a primary network, and the small cells including the M2M communication network can be seen as secondary networks. Since the macro cell has usually a high traffic, the primary user activity can be modeled as a high primary user activity. In this model, the primary user exploits the spectrum most of time and the spectrum is available to secondary users for short duration of time [7]. The considered system model is an interweave CRN in which one of the SBSs senses the radio spectrum used in the macro cell and allocates the unused spectrum among the small cells. In order to avoid data loss, the MTD gateway is equipped with a buffer and stores the received data from MTDs. The transmit powers of the MTD gateway and the macro cell user equipments (MUEs) are denoted by $P_1$ and $P_2$ in Watts/Hz.

Because the uplink spectrum is typically lighter loaded than the downlink spectrum, we assume that the uplink radio resources of the macro cell can be reused by the small cells including M2M networks [22]. In the considered M2M communication network, there
exist $M$ classes of MTDs within each small cell in which each class provides a specific application with its own delay sensitivity. Furthermore, since the macro cell has the role of the primary network in the considered CM2M scheme, it has the highest priority over the MTDs. In this paper, we assume that the macro cell including MUEs is in the priority class of 0 and the priority orders of the MTDs are in the range of $[1, M]$. Therefore, the considered CM2M network can be modeled as a $M + 1$-class priority based system where the macro cell and the MTDs that provide more delay sensitive application are in the higher priority orders. For instance, the MTDs that provide application in the emergency situations are prioritized over the other MTDs. The average waiting time of MTDs belonging to a priority class $i$ is denoted by $W_i$ and can be written as:

$$W_i = Q_i + I_i + T_i + S_i,$$

where $Q_i$ and $I_i$ are the average queuing time of the packet till the first transmission, and the average interruption time of the packet when a packet belonging to a higher priority class appears, respectively. Furthermore, $T_i$ and $S_i$ denote the average transmission time of the packet, and the average sensing time of the radio spectrum before the transmission of the packet in the $i$th priority class, respectively. For each MTD of priority class $i$, we assume an independent and identically distributed (i.i.d.) Poisson data arrival with mean $\lambda_i$ packets per time slot and packets length of $l_i$ bits. The wireless link between the MTD gateway and the base station is impaired by additive white Gaussian noise (AWGN) with zero mean and power spectral density of $N_0$ Watts/Hz. The time slot duration is denoted by $T$.

Let $h$ and $g_k$ denote, respectively, the Rayleigh block fading coefficients of the link between the MTD gateway and the SBS and the interference link from $k$th MUE to the SBS. The fading coefficients $h$ and $g_k$ are complex Gaussian distributed with zero mean and variance $\sigma^2_h$ and $\sigma^2_k$, respectively. In addition to the small scale fading, the aforementioned links undergo free space path loss with path loss exponent $\epsilon$. Therefore, the received power from the MTD gateway and the $k$th MUE to the SBS are impaired by $-d_0\epsilon$ and $-d_k\epsilon$ respectively. The variables $d_0$ and $d_k$ are the distances between the SBS and the MTD gateway and between the SBS and $k$th MUE, respectively. Since the location of the MTD gateway is fixed, $d_0$ is a deterministic variable, while $d_k$ is a random variable depending on the location of $k$th MUE. It is supposed that $d_k$ has an uniform distribution in the range of $[D_1, D_2]$. The signal-to-noise-ratio (SNR) and the bandwidth between the MTD gateway and the SBS are given by $\gamma$ and $B$, respectively. One of the SBSs senses the spectrum of the macro cell for $s$ seconds from the beginning of the time slot. By taking into account the spectrum sensing, the MTD gateway transmits data to the SBS within $T-s$ seconds. The mean service rate and the expected service time of the packets in the $i$th priority class are denoted by $\mu_i$ and $E[X_i]$, respectively. The channel utilization factor of the $i$th priority class, for $0 \leq i \leq M$, is given:

$$\rho_i = \lambda_i E[X_i] = \frac{\lambda_i}{\mu_i}.$$  

In our proposed policy, if a packet belonging to a higher priority class arrives, the transmission of the packet at the lower priority order is interrupted. In addition, as soon as the transmission of the packet at the higher priority class is finished, the transmission of the packet at the lower priority order is resumed at the point at which it was halted. Therefore, the proposed priority-based packet adjustment policy can be modeled as an M/G/1 preemptive queuing system. By modeling the queuing system at the MTD gateway as

\[\text{Cellular Link} \quad \text{IEEE 802.15.x} \quad \text{------} \]

![Fig. 1. The proposed system model.](image-url)
M/G/1 preemptive queuing system, the average delay of the MTDs in the \( i \)th priority class, for \( 1 \leq i \leq M \), will be given by [23]:

\[
W_i = \frac{\mathbb{E}[X_i]}{1 - \sum_{j=0}^{i-1} \rho_j} + \frac{\sum_{j=0}^{i-1} \lambda_j \mathbb{E}[X_j^2]}{2\left(1 - \sum_{j=0}^{i-1} \rho_j\right)\left(1 - \sum_{j=0}^{i} \rho_j\right)} + \left[\frac{\mathbb{E}[X_i]}{T - s}\right], \tag{3}
\]

in which \( \frac{\mathbb{E}[X_i]}{T - s} \) represents the average sensing time of the packet in \( i \)th priority class. A system with multiple queues is stable when all the queues are stable. In order to verify the stability of a queue, Loyne’s theorem can be used [23]. According to this theorem, if for a queue with the strictly stationary arrival and service processes, the average arrival rate is lower than the average service rate, then the queue is stable. In other words, the queue is unstable if the average service rate is lower than the average arrival rate. Therefore, in order to have a stable queue in the \( i \)th priority class of MTDs, the constraint of \( \lambda_i \leq \mu_i \) should be satisfied.

Our goal is to adjust the packet size of the MTDs at the MTD gateway to minimize the average delay of each priority order of MTDs. In particular, at the MTD gateway, the packets of MTDs may be combined into a larger packet or divided into smaller packets. To the best of our knowledge, the effect of the packet adjustment on the average delay is not investigated for the CM2M network in the literature.

3. Proposed packet adjustment policy

3.1. Perfect spectrum sensing

Next, we introduce and solve the optimization problem to minimize the MTDs’ average delay in each small cell for the ideal case without spectrum sensing errors. The results derived here can be interpreted as a lower bound of the average delay for the practical cases which exhibit spectrum sensing imperfections. The service rate of MTDs of priority \( i \) can be given by [23]:

\[
\mu_i = \frac{1}{\mathbb{E}[X_i]} = \frac{C}{l_i}, \quad \text{for } 1 \leq i \leq M, \tag{4}
\]

where \( C \) denotes the ergodic capacity of the link between the MTD gateway and the SBS and is given by:

\[
C = \int_0^\infty B \log_2(1 + \gamma) P(\gamma) d\gamma, \tag{5}
\]

in which \( P(\cdot) \) denotes the probability density function.

For each priority order of MTDs, the packet size is derived as a solution of the delay minimization problem. Based on (3), the average delay of MTDs in the \( i \)th priority order depends on the packet size of MTDs in the higher priority classes, i.e., priority order 0, 1, ..., \( i - 1, i \). Therefore, in the proposed packet adjustment scheme, the packet size of the higher priority classes should be determined first. The average delay of MTDs in the \( i \)th priority class (\( 1 \leq i \leq M \)) can be minimized by solving the following optimization problem.

\[
\begin{align*}
\text{minimize} & \quad \frac{\mathbb{E}[X_i]}{1 - \sum_{j=0}^{i-1} \rho_j} + \frac{\sum_{j=0}^{i-1} \lambda_j \mathbb{E}[X_j^2]}{2\left(1 - \sum_{j=0}^{i-1} \rho_j\right)\left(1 - \sum_{j=0}^{i} \rho_j\right)} + \left[\frac{\mathbb{E}[X_i]}{T - s}\right], \\
\text{s. t.} & \quad \lambda_i \leq \mu_i. \tag{6}
\end{align*}
\]

Note that the constraint C1 ensures the stability of queues in the MTD gateway.

**Theorem 1.** For MTDs of priority class \( i \) (\( 1 \leq i \leq M \)), the packet size that minimizes the average delay is given by:

\[
\bar{l}_i = \left[\frac{\sqrt{\theta_i} C \bar{\lambda}_i + \frac{\lambda_i}{T - s} \left[2C^2(\alpha_i - 1)^2 + \lambda_i \bar{\beta}_i\right]}{\lambda_i} + \frac{C \theta_i \lambda_i + \frac{s}{T - s}(\alpha_i - 1)^2}{\lambda_i^2} \right] / 4, \tag{7}
\]

where \( \alpha_i \) and \( \beta_i \) are given as

\[
\alpha_i = \frac{\sum_{j=0}^{i-1} \lambda_j l_j}{C}, \quad \beta_i = \frac{\sum_{j=0}^{i-1} \lambda_j l_j^2}{C^2}. \tag{8}
\]

**Proof.** Refer to Appendix A. □

The constant \( \theta_i \) is the Lagrangian multiplier for the constraint C1 in (6), and is obtained from one dimensional search such that this constraint is verified. Based on (7), the packet size of \( i \)th priority class is dependent on the mean arrival rate of \( i \)th priority order,
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compute $\alpha_1$ and $\beta_1$ using (8)</td>
</tr>
<tr>
<td>2</td>
<td>Derive $l_1$ with aid of (7)</td>
</tr>
<tr>
<td>3</td>
<td>Repeat</td>
</tr>
<tr>
<td>4</td>
<td>Calculate $\alpha_i$ and $\beta_i$ using (8), for $2 \leq i \leq M$.</td>
</tr>
<tr>
<td>5</td>
<td>Derive $l_i$ with aid of (7), for $2 \leq i \leq M$.</td>
</tr>
<tr>
<td>6</td>
<td>$i = i + 1$.</td>
</tr>
<tr>
<td>7</td>
<td>Stop criterion: $i = M$.</td>
</tr>
</tbody>
</table>

**Algorithm 1.** The iterative approach for minimizing the averaged delay of MTDs' packets based on their priority order for the perfect spectrum sensing assumption.
the ergodic capacity of the channel between the MTD gateway and the SBS, the time slot duration, the spectrum sensing time, and the traffic flows at the higher priority classes. Therefore, the MTD gateway do not require instantaneous CSI of the channel between the MTD gateway and the SBS to adjust the packet size of ith priority class. On the other hand, the packet size adjustment would take place based on the status of traffic flows at the higher priority orders, and ergodic capacity of the channel, i.e., statistical CSI, between the MTD gateway and the SBS. In addition, according to (7) and (8), the packet length of MTDs in the ith priority order depends on the packet size of MTDs in the higher priority classes. Therefore, in the proposed policy, first, the packet length of the MTDs in the first priority order is derived and, then, the packet size of the MTDs in the second priority class is derived, and so forth, the packet size of the MTDs in the ith priority class should be determined before the i + 1th priority order. The proposed priority based approach is depicted in Algorithm 1.

Based on expressions in (7) and (8), when the packet traffic in the higher priority classes are low, dividing the arriving packets results in reducing the delay and when the packet traffic in the higher priority orders are high, combining the arriving packets is a good idea. In addition, in order to find the new packet structure and for ease of decoding at the SBS, the MTD gateway appends some overhead bits to the new packet structure containing information about the packet size.

### 3.2. Spectrum sensing with imperfections

Here, a packet adjustment policy is proposed for the delay minimization in the CM2M network for scenarios that can experience erroneous spectrum sensing. To this end, we take into account the outage probability, the false alarm and misdetection imperfections during the spectrum sensing in the considered CM2M network. Let $P_{r,s}$ and $P_{md}$ be the probability of false alarm and the probability of misdetection of traffic in the macro cell, respectively. Then, by taking into account the imperfection, the mean service rate of the $i$th priority class, for $1 \leq i \leq M$, in (4) can be rewritten as

$$\mu_i = (P_{md} \pi \Phi_{out,1} + (1 - P_{fa})(1 - \pi)) \Phi_{out,2} C \frac{\mu}{l_i},$$

(9)

where $\pi$ and $\Phi_{out,1}$ are the probability of nonzero traffic in the macro cell, and the probability of successful communication when both of the macro cell and MTD communication exist concurrently, i.e., the interference channel, respectively. In addition, $\Phi_{out,2}$ denotes the probability of successful communication when only the MTD communication exists, i.e., the interference free channel. $\pi$ equals to $\frac{\lambda_0}{C \mu_0}$ in which $\lambda_0$ and $\mu_0$ being the mean arrival and service rate for the uplink transmission in the macro cell, respectively. The probability of successful communication for the MTDs in priority class $j$ for the case of interference from macro cell and the case of interference free can be calculated as follows, respectively.

$$\Phi_{out,1} = 1 - \int_{D_1}^{D_2} \Pr\left\{ \log_2 \left( 1 + \frac{d_0^{-\beta} P_i |h_i|^\alpha}{N_0 + d_k^{-\beta} P_k |h_k|^\alpha} \right) < R_f \right\} f_{d_k} \, d_{d_k}$$

$$= 1 - \int_{D_1}^{D_2} \frac{1}{D_2 - D_1} \log_2 \left( 1 - \frac{-N_0 \frac{2^R_f - 1}{2^{\frac{\alpha}{\beta}}} \frac{d_k^{-\beta} P_k |h_k|^\alpha}{\sigma^2 P_i d_0^{-\beta}}}{1 + (2^{R_f} - 1) \frac{d_k^{-\beta} P_k |h_k|^\alpha}{\sigma^2 P_i d_0^{-\beta}}} \right) d_{d_k},$$

(10)

$$\Phi_{out,2} = 1 - \Pr\left\{ \log_2 \left( 1 + \frac{d_0^{-\beta} P_i |h_i|^\alpha}{N_0} \right) < R_f \right\} = \exp \left( -N_0 \frac{2^{R_f} - 1}{\sigma^2 P_i d_0^{-\beta}} \right).$$

(11)

where $R_f = \frac{\lambda_0}{\mu_0}$ is the data transmission rate of the MTDs that has the priority order $i$, and $f_{d_k}$ is the uniform distribution of the random variable $d_k$. The integral in (10) is not in a standard format, and thus, it could be solved by adopting numerical methods such as Gaussian Quadrature method.

By assuming exponentially distributed service time of the packets, the second moment of the service time of MTDs in the ith priority class can be written as $E[X_i^2] = 2E[X_i]^2 = \frac{\mu_i^2}{\lambda_i}$ [24]. In the case of imperfect spectrum sensing, by substituting (9) in (6), we have the following optimization problem for minimizing the average delay:

$$\text{minimize } \quad W_i, \quad \text{for } 1 \leq i \leq M,$$

$$\text{s. t. C1: } \quad \lambda_i \leq (P_{md} \pi \Phi_{out,1} + (1 - P_{fa})(1 - \pi)) \Phi_{out,2} C \frac{\mu}{l_i},$$

(12)

where $W_i$ is given by
\[ W_i = \frac{l_i s}{C(T - s)} + \frac{l_i}{1 - \sum_{j=0}^{i-1} (P_{MD\pi}Pr_{out,1} + (1 - P_{FA})(1 - \pi)Pr_{out,2})} \]
\[ + \frac{2\lambda_i l_i}{\sum_{j=0}^{i-1} (P_{MD\pi}Pr_{out,1} + (1 - P_{FA})(1 - \pi)Pr_{out,2})^2 C^2} \]
\[ + \frac{\lambda_i l_i}{1 - \sum_{j=0}^{i-1} (P_{MD\pi}Pr_{out,1} + (1 - P_{FA})(1 - \pi)Pr_{out,2})} \]
\[ + \frac{2(1 - \sum_{j=0}^{i-1} (P_{MD\pi}Pr_{out,1} + (1 - P_{FA})(1 - \pi)Pr_{out,2}))}{C} \]  

Note that \( W_i \) in the above optimization problem has positive hessian, and thus, the minimization problem in (12) is convex. According to the expression in (13), the cost function in the aforementioned optimization problem is complex, and therefore, the analytical closed form solution cannot be derived easily using Lagrangian method. Instead, the iterative Newton’s algorithm with logarithmic barrier approach is exploited to solve the problem [25]. In Newton’s method, the packet size for the perfect spectrum sensing case in (7) can be used as a starting point which is denoted by \( l_i^{\text{start}} \). In the logarithmic barrier approach, instead of (12), the following unconstrained optimization problem is solved
\[ \min_{l_i} \varphi W_i + \phi_i \]  

where \( \phi_i = -\log_{10}((P_{MD\pi}Pr_{out,1} + (1 - P_{FA})(1 - \pi)Pr_{out,2})^C - \lambda_i) \).

In the case of imperfect spectrum sensing, the packet size that minimizes the average delay of the priority class is obtained via the two iterative policies in Algorithm 2 and Algorithm 3. In particular, the scheme in Algorithm 2 is implemented at first and at the third step of it, the policy in Algorithm 3 is done. For the backtracking line search in the fifth step of Algorithm 3, the search approach in Algorithm 4 is used.

Note that by setting \( P_{MD\pi} \) to zero in (9), the misdetection never occurs at the MTD gateway and the same packet size adjustment policy can be driven for the spectrum sensing with false alarm imperfection and without misdetection.

### 3.3. Average throughput

In this subsection, the average throughput of the proposed packet adjustment scheme is investigated. According to Little’s law, the average number of packets in the queue of MTDs in the \( i \)th priority class, \( m_i \), is given by:
\[ m_i = \lambda_i (Q + l_i) = \lambda_i (W_i - T_i), \quad \text{for } 1 \leq i \leq M. \]  

Using Little’s law, the average throughput of the MTDs in the \( i \)th priority order, \( \tau_i \), is given by:
\[ \tau_i = \frac{m_i}{W_i} = \frac{\lambda_i (W_i - T_i)}{W_i}, \quad \text{for } 1 \leq i \leq M, \]  

where \( W_i \) can be achieved in (3) and \( T_i \) is the average transmission time which is equal to \( \frac{l_i}{C} \).

### 4. Simulation results

For the simulations, the bandwidth between the MTD gateway and the SBS and the length of time slot are assumed to be 2 MHz and 0.5 ms, respectively [20]. In the considered CM2M network, in each small cell, 4 different priority orders of MTDs exist. The MTDs in each of them have an independent and identically distributed (i.i.d.) Poisson data arrival with mean in the range of [0,1] packets per time slot [20]. We consider M/G/1 preemptive queuing system as the priority model. Throughout this section, we assume AWGN and Rayleigh block fading with zero mean and unit variance. In addition to the small scale fading, the aforementioned links undergo free space path loss with path loss exponent \( \epsilon = 2 \). The transmit power of the MTD gateway and the MUEs are 3 dB, and omnidirectional antenna is assumed to be used at the transmitters. In the case of imperfect spectrum sensing, the probability of misdetection and the probability of false alarm are assumed to be 0.1. The mean arrival and service rates for the macro cell are 2 and 4 packets per time slot.

The comparison between the average waiting time of the packets in the proposed scheme and the conventional policy without packet adjustment is done in Fig. 2. In the conventional scheme, the packet of MTDs are transmitted with their original size, and the MTD gateway does not change the packet size. In other words, in the conventional policy, packet size of MTDs in different priority orders is static and is not adjustable. In contrast, in our proposed policy, for each priority class of MTDs, the packet length is adjusted so that the average waiting time of the packets of the MTDs is minimized. Therefore, it is expected that our proposed scheme achieves better performance in terms of average packet delay for all priority classes compared to the conventional policy. As Fig. 2 shows, our proposed packet adjustment scheme yields up to 25% lower average waiting time of packets in the first priority class compared with...
1: The starting point, $l_i^{\text{init}}$, is obtained via (7). Let $\varphi = 10$, $\mu = 2$ and $\epsilon = 0.1$.
2: Repeat
3: Update $l_i := l_i^*$ by solving the optimization problem in (14) using Newton’s method given in Algorithm 3.
4: Stop criterion: quit if $\frac{1}{\varphi} < \epsilon$.
5: Increase $\varphi$, i.e., $\varphi := \mu \varphi$.

**Algorithm 2.** The iterative barrier approach for packet adjustment in the case of erroneous spectrum sensing.

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1: The starting point is obtained via (7). Let $\epsilon = 0.1$
2: Repeat
3: Compute the Newton’s step and the decrement via $\Delta l_i := -\nabla^2 W_i^{-1} \nabla W_i$, and $\eta^2 := \nabla W_i \nabla^2 W_i^{-1} \nabla W_i$, respectively.
4: Stop criterion: quit if $\frac{\eta^2}{2} \leq \epsilon$ holds.
5: Line search: the step size $t$ is chosen by backtracking line search in Algorithm 4.
6: Update $l_i := l_i + t \Delta l_i$

**Algorithm 3.** The iterative Newton’s method for packet adjustment in the case of erroneous spectrum sensing.

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1: Let $a = 0.2$ and $b = 0.4$ are two constants of the line search and $\Delta l_i$ is a step direction in Newton’s method.
2: $t := 1$
3: While $W_i(l_i + t \Delta l_i) > W_i + a t \nabla D_i \Delta l_i$, do $t := bt$.

**Algorithm 4.** The backtracking line search for Newton’s method.
the conventional policy. In addition, the average waiting of the packets in the case of imperfect spectrum sensing is higher than the average waiting in the perfect spectrum sensing case.

Fig. 3 depicts the throughput of different priority classes in the proposed packet adjustment scheme and the conventional policy versus the average arrival rate for $P_{MD} = P_{FA} = 0.1$. In our proposed algorithm, by adjusting the packet length of each priority order of MTDs based on the traffic of the higher priority classes, the average packet delay is reduced, and hence, the packet of MTDs can be transmitted faster with improved throughput in comparison with traditional policy. Clearly, from Fig. 3, it can be seen that our proposed scheme achieves a higher performance in terms of the average throughput in comparison with the conventional policy without packet adjustment. This improvement of the average throughput reaches up to 20% for the first priority class, compared with the conventional policy. Furthermore, the average throughput in the case of imperfect spectrum sensing is lower than the perfect spectrum sensing case.

Fig. 4 shows the throughput of our proposed scheme and the conventional policy versus the false alarm probability for $\lambda_i = 1$. As it
can be seen from Fig. 4, by increasing the false alarm probability, the average throughput in all of the priority orders tends to zero. Furthermore, in the case of variable false alarm probability, our proposed scheme outperforms the conventional policy without packet adjustment in terms of the average throughput.

In our proposed scheme, the average delay of the MTDs is minimized which leads to a reduced average number of packets wait in the CM2M network and an increased packet transfer rate. In consequence, the throughput of each priority class of MTDs is also improved. Clearly, the simulation results in Figs. 2–4 show that our proposed policy outperforms the conventional scheme without packet adjustment in terms of the average delay and the average throughput of the packets at the same time.

5. Conclusion

In this paper, we have proposed a novel packet adjustment scheme that can be used by an MTD gateway to minimize the average waiting time delay of MTDs. In the considered CM2M network, MTDs that have delay sensitive packets are prioritized over MTDs having delay tolerant packets, and thus, MTDs having urgent packets experience a lower delay. In order to minimize the average waiting time delay of the MTDs, a novel packet adjustment scheme was proposed in which some of the arriving packets may be combined into a larger packet or a packet may be split into some smaller packets at the MTD gateway. The proposed packet adjustment policy was investigated for the two cases of perfect and imperfect spectrum sensing. The average delay of the MTDs was derived, and thereafter, the average throughput of the CM2M network in each small cell was computed using Little’s theorem. Simulation results showed that the proposed scheme can reduce up to 25% the average delay of the MTDs in the first priority class compared with the conventional policy for M2M communication without the packet adjustment scheme. The proposed policy and system model of this paper can be extended to the energy harvesting, and/or full duplex scenarios in future.

Appendix A

In this Appendix, the optimal solution of the average delay minimization problem in the case of perfect spectrum sensing is obtained via the Karush–Kuhn–Tucker (KKT) conditions. As in practice, we assume that the service time of the packets is exponentially distributed [24]. Thus, the second moment of the service time of MTDs in the ith priority class can be written as:

$$\mathbb{E}[X^2] = 2!\mathbb{E}[X]^2 = \frac{2l_i^2}{C_i^2}.$$ (17)

According to the expressions in (2)–(4) and (17) and after some mathematical simplification, the optimization problem in (6) can be rewritten as:

$$\min \quad \frac{l_i}{C - C_\alpha} + \frac{2C^2\bar{\lambda}_i + 2\bar{\lambda}_i l_i^2}{2C(1 - \alpha_i)(C - C_\alpha - \bar{\lambda}_i l_i)} + \frac{l_i s}{C(T - s)} + 1$$

s. t. C1: \(\bar{\lambda}_i l_i \leq C_i\). (18)
The Lagrangian function for the minimization problem in (18) is as follows [25]:

\[
\mathcal{L}(l_i, \theta_i) = \frac{l_i}{C - C\alpha_i} + \frac{C_i^2 \lambda_i + \lambda_i l_i^2}{C(1 - \alpha_i)(C - C\alpha_i - \lambda_i l_i)} + \frac{l_is}{C(T-s)} + 1 + \theta_\lambda \lambda_i - \theta_i C,
\]

in which \(\theta_i\) is the Lagrangian multiplier for the constraint C1 in (18). Since the constraint C1 is an inequality constraint, \(\theta_i \geq 0\) holds. By equating the derivative of the Lagrangian function with respect to \(l_i\) to zero, we have:

\[
\frac{\partial \mathcal{L}}{\partial l_i} = \frac{1}{C - C\alpha_i} + \frac{2l_i\lambda_i(1 - \alpha_i)(C - C\alpha_i - \lambda_i l_i)}{(C(1 - \alpha_i)(C - C\alpha_i - \lambda_i l_i))^2} + \frac{C(1 - \alpha_i)\lambda_i(C_i^2 \lambda_i + \lambda_i l_i^2)}{(C(1 - \alpha_i)(C - C\alpha_i - \lambda_i l_i))^2} + \theta_i \lambda_i + \frac{s}{C(T-s)} = 0.
\]

By solving the above equation and after some algebraic manipulation, the packet length of the MTDs in the ith priority order, for \(1 \leq i \leq M\), is derived as in (7). In addition, the positive value of \(\theta_i\) can be found by one dimensional search such that the constraint C1 in (18) is held. Thus, the positive value of \(\theta_i\) should be determined such that the following equation hold:

\[
\theta_i C(\alpha_i - 1)^2 + \frac{\sqrt{8\theta_i C\lambda_i^3[2C^2(\alpha_i - 1)^2 + \lambda_i^2]}\lambda_i}{4C\lambda_i^2} \leq C.
\]

The goal of our proposed policy is to minimize the average delay of the MTDs’ packets based on their priority orders. In other words, for \(1 \leq i \leq M - 1\), minimizing the average delay of the ith priority order of the MTDs is more important than minimizing the average delay of the + 1 priority class of the MTDs. Thus, according to the expressions in (7) and (8), the packet length of MTDs in priority order \(i\) depends on the packet size of MTDs in the higher priority classes. Therefore, in the proposed policy, first, the packet length of the MTDs in the first priority order is derived and, then, the packet size of the MTDs in the second priority class is derived, and so on. Therefore, the packet size of the MTDs in priority class \(i\) should be determined before priority order \(i + 1\) using (7) and (8).

The M sub-problems in Section 3.1 are not independent from each other. In particular, minimizing the average delay of priority class \(i\) of MTDs depends on the packet length of MTDs in the higher priority classes of \(j\), with \(1 \leq j \leq i - 1\). However, next, we prove that our proposed approach that divides the optimization problem into \(M\) sub-problems and solves them using KKT condition is the best approach that we can adopt for minimizing the average delay of MTDs in order of their priority classes.

Let \(l_1^*, l_2^*, \ldots, l_M^*\) be the unique optimal length of the MTDs’ packets in the priority orders of 1, 2, ..., \(M\), respectively, which are derived from our proposed approach in (7), (8). Alternatively, one can solve the following M optimization problems at the same time

minimize \(W_i(l_i)\),

s. t. C1: \(\lambda_i \leq \mu_i\),

\[
\begin{align*}
& l_i, l_{i\min} = \min_{l_i} \; W_i(l_i, l_i), \\
& \text{s. t. C1: } \lambda_i \leq \mu_i, \\
& \text{s. t. C2: } \lambda_i \leq \mu_i, \\
& \text{minimize } l_i, l_{i\min} = W_i(l_i, l_i), \\
& \text{s. t. C1: } \lambda_i \leq \mu_i, \\
& \text{s. t. C2: } \lambda_i \leq \mu_i, \\
& \text{s. t. CM: } \lambda_M \leq \mu_M.
\end{align*}
\]

Assume that the optimal packet length resulting, respectively, from (22), (23), and (24) are denoted by \(l_{1,1}^*, (l_{1,2}^*, l_{2,2}^*), \text{ and } (l_{1,M}^*, l_{2,M}^*, \ldots, l_{M,M}^*)\). It is trivial that \(l_{i,k}^*\) is equal to \(l_{i,1}^*\). Clearly, solving the optimization in (22), (23), and (24) simultaneously results in different Lagrangian functions rather than the Lagrangian function derived in our proposed scheme in (19). Thus, \(l_{i,k}^*\) and \(l_{i,1}^*, l_{i,2}^*, l_{i,3}^*, \ldots, l_{i,M}^*\) are not equal necessarily. Therefore, we have

\[
W_i(l_{i,k}^*) \leq W_i(l_{i,1}^*), \quad \text{for } i \in \{2, \ldots, M\}.
\]

Since minimizing \(W_1\) is more important than minimizing the average delay of other priority classes, \(l_{1}^*\) is the optimal packet length of the first priority class of MTDs. Similarly, \(l_{1}^*\) and \(l_{2}^*, l_{3}^*, \ldots, l_{M}^*\) are not equal necessarily, and thus, we have

\[
W_i(l_{i,k}^*) \leq W_i(l_{i,1}^*), \quad \text{for } i \in \{2, \ldots, M\}.
\]

Since minimizing \(W_2\) is more important than minimizing the average delay of other remaining priority classes, \(l_{2}^*\) is the optimal packet length of the second priority class of MTDs. In a similar way, we can show that the optimal packet length of MTDs in the priority order \(i\), with \(3 \leq i \leq M\), is \(l_{i}^*\) and can be derived by our iterative priority based approach introduced in Algorithm 1. In a nutshell, our iterative approach for solving the Mth sub-problems in (7) and (8) suits best for the minimizing the average delay of the MTDs based on their priority orders. Furthermore, the dependency between the \(M\) sub-problems does not deteriorate the optimality of our proposed policy. This completes the proof.
References


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