Analysis of Delay-Energy Tradeoff and Energy Minimization Schemes for Group-based Machine-to-Machine Communications in OFMDA Cellular Networks

Chieh Yuan Ho
Department of Electronics Engineering
National Chiao Tung University
HsinChu, Taiwan
Thorpe.ee94g@nctu.edu.tw

Ching-Yao Huang
Department of Electronics Engineering
National Chiao Tung University
HsinChu, Taiwan
cyhuang@mail.nctu.edu.tw

***Abstract*—Machine-to-Machine (M2M) communication has recently become a hot topic in 4G Standardization Committee, such as IEEE 802.16p and LTE-A. In an OFDMA cellular network embedded with a M2M system, we characterize system energy consumption (EC) and average delay for the M2M system and propose energy-efficient Machine Node (MN) access control schemes, jointly implementing MN grouping and coordinator selection, under a 2-hop transmission framework to minimize system EC with limited resource amount assigned by BS while satisfying the system delay requirement. In the simulation results, the tradeoff between EC and delay is investigated with respect to given resource amount, and the relationship between number of coordinators and total energy consumption is studied. Furthermore, the proposed schemes need relatively less coordinators to achieve very low EC, and can achieve near-optimal EC with any delay requirement.**

Keywords- Machine-to-Machine, M2M, MTC, delay-energy, energy minimization

I. INTRODUCTION

Machine-to-machine (M2M) communication has recently been intensively discussed in Standardization Committee, LTE-A and IEEE 802.16p, and been considered as a new type of communication, enabling machine automations, such as smart grids, and will share the same air interface and radio resource with Human-to-Human (H2H) communication. In [1]-[3], 3GPP and IEEE studied M2M requirements and possibilities. One of the critical issues of M2M is how to deal with large number of accesses from massive amount of machine nodes while maintaining low energy consumption of the embedded M2M system with tolerable latency. In [4], the protocol stack and applications of M2M are discussed. In [5], authors analyze the energy-delay tradeoff of a M2M system with focus on channel coding. In [6], a QoS-guaranteed massive access management scheme for M2M communication is proposed to minimize energy expenditure and end-to-end delay with the given number of groups. A mobility control algorithm for downlink multi-cell OFDMA is proposed for M2M communications in [7]. In [8], Authors presented a optimal cluster formation for the home energy management system (HEMS) and proposed a dynamic programming approach to minimize the defined cost function of HEMS.

In this paper, we consider an OFDMA cellular network embedded with a M2M system. With the consideration of maximal available radio resource amount given by base station (BS), we propose and evaluate several MN energy minimization schemes, which iteratively execute MN grouping and selects the most effective MNs as the coordinators for accesses to the cellular network, to optimize total Energy Consumption (EC) of the M2M system while satisfying the average delay constraint. Moreover, tradeoff between EC, assigned resource amount, number of coordinators, and system delay are investigated. In numerical experiments, it shows that the proposed schemes can reach low EC with few coordinators and achieve near-optimal EC.

II. SYSTEM MODEL AND ASSUMPTIONS

Consider an OFDMA cellular network with one single cell centered by a BS. There are *M Machine Nodes (MN)*, equipped with wireless transmission devices, distributed within the cell. Let $\mathcal{F} = \{m_i | i = 1,2,\dots,M\}$ denote MNs, where *i* is the index of MN. According to the features of M2M [1]-[3], all MNs should be designed to be simple, one-way communication (uplink), low cost, and long battery life. Each MN is nomadic and initially located in a geographic coordinate, and periodically transmits their measured data, such as temperature, humidity, traffic load, and so on, to the backbone server via BS. Due to the simplicity of MNs, each MN can transmit only one fixed-size packet, assumed to be *S* bits, with fixed transmit power, p_{MN}, at one transmission. Assume that Channel State Information (CSI) for MN-to-MN link and MN-to-BS link is known by both BS and MN sides. In addition, due to the feature of low transmit power we assume each MN can have at most *2-hop* transmission between MN and BS. That means each MN can transmit it's own packet to BS via at most one other MN which relays that packet to BS after its own packet is sent. We name the relaying MNs as *Coordinators (Coor)*, and a *Group* consists of the coordinator and the set of MNs relayed by it. Note that each group can only have one coordinator.

Let $c_i \in \mathcal{F}$ denotes the MN index of the coordinator of *Group i*, where $i \in \{1,2,\ldots,k\}$, and k is the number of groups in the M2M system, and G_i denote the index set of the MNs, excluding the *Coor*, in *Group i*. Finally, we assume that BS assigns L Resource Units (RU), defined as one subcarrier and one OFDM symbol, to be used by the embedded M2M system in each uplink OFDMA frame, and only the coordinators can access to BS with the assigned resource while other MNs are only able to communicate with coordinators on a frequency band different from the cellular network, so there is no interference between the MN-to-Coor link and the Coor-to-BS link. Note that the communication system between MN and Coor, e.g. TDMA, can be different from the one between Coor and BS, which is OFDMA-based, and the additional transceiver can be installed in MNs which are selected as Coors to enable their communication ability with BS. Assume each coordinator receives at least one packet from its group members after transmitting a packet to BS. Because all MNs are assumed to be static, all MNs only suffer slow-fading in which the channel state remains constant for a relatively long period, e.g. several transmission frames. In addition, many M2M applications are built in rural areas where there are fewer obstacles, e.g. tall buildings, standing between the transmitter and receiver, and it directly results in less multi-path effect causing shorter delay spread and wider coherence bandwidth. Therefore, we assume both the MN-to-Coor link and the Coor-to-BS link experience slow- and flat-fading. Let B_c and N_0 denote the subcarrier bandwidth and noise power spectral density respectively. the rate of the *Coor-to-BS* link can be written as:

$$r_{c_i} = B_c\, log_2\left(1 + p_{MN}\left|h_{c_i}\right|^2/N_0B\right),$$

where r_{c_i} denotes the achievable rate of *Coor* c_i, and h_{c_i} represents the channel coefficient between *Coor* c_i and BS. The rate of the *MN-to-Coor* link can be written as:

$$r_{m_j}^{c_i} = B_m\, log_2\left(1 + p_{MN}\left|h_{m_j}^{c_i}\right|^2/N_0B\right), j \in G_i.$$

B_m is the transmission bandwidth of the *MN-to-Coor* link. $r_{m_j}^{c_i}$ denotes the achievable rate for MN m_j to transmit data to *Coor* c_i, and $h_{m_j}^{c_i}$ denotes the channel coefficient between MN m_j and *Coor* c_i. Note that the coordinators have the same channel gain and rate on all RUs in the flat-fading channel.

III. PROBLEM FORMULATION

As we know, one of the most important features of certain M2M applications is MN battery life. Hence, in this paper, our goal is to minimize system Energy Consumption (EC) of the M2M system, defined as sum of EC of each packet transmission from MN to BS, by properly arranging MNs into *Groups* and *Coordinators*. Firstly, in the slow- and flat-fading channel, where the transmit rate of Coors on all RUs are identical, we can express total EC for MN m_j in *Group i* to transmit a packet to BS via Coor c_i as sum of EC of the *MN-to-Coor* link and EC of the *Coor-to-BS* link:

$$ec_{m_j}^{c_i} = p_{MN}\, S/r_{m_j}^{c_i} + p_{MN}\, S/r_{c_i}, j \in G_i \tag{1}$$

Thus, EC of *Group i* can be written as sum of EC for transmitting packets of MNs to BS and EC for transmitting the packet of *Coor* c_i to BS:

$$ec_i^{c_i} = \sum_{j\in G_i} ec_{m_j}^{c_i} + p_{MN}\, S/r_{c_i} \tag{2}$$

Then, the system EC of the M2M system is:

$$EC = \sum_{i=1}^{k} ec_i^{c_i} \tag{3}$$

As a result, the problem can be formulated as:

$$\begin{aligned} & min_{\{G,c\}}\, EC \\ & s.t. \\ & L \leq \alpha \\ & T_D \leq \beta \end{aligned} \tag{4}$$

The objective aims to minimize system EC by properly arranging MNs into groups and coordinators while satisfying the given resource and average system delay constraints. The first constraint implies that the total number of RUs which are assigned to Coors in one OFDMA frame can't exceed the prescribed maximum available RU number, denoted as α. Let T_D denote the system delay, defined as the total consuming time for all MNs to complete with packet transmission (one packet each) to BS. More clearly, T_D represents the time period from the moment when the first packet is transmitted by a MN to the moment when BS receives the last packet from a Coor. As aforementioned, each MN, including Coors, is responsible to transmit one packet to BS via a Coor. The second constraint limits the system delay shall be less then β. Note that in the flat- and slow-fading channel, the channel states of the Coors, which are static, remain the same in both time and frequency domain. Therefore, which RUs are assigned to coordinators doesn't change the energy consumption of Coors. Thus, the RU assignment issue doesn't have to be considered here.

IV. DELAY ANALYSIS AND ENERGY MINIMIZATION SCHEMES FOR M2M COMMUNICATIONS

A. Coordinator Capacity and System Delay Analysis

The number of RUs required for the *Coor* of *Group i* to transmit a packet to BS is $S/\left(r_{c_i}t\right)$. Thus, the total number of RUs required for all coordinators to forward one packet to BS in the flat-fading channel can be expressed as:

$$U = \sum_{i=1}^{k} S/\left(r_{c_i}t\right)$$

where *t* denotes the time duration of a RU.

Lemma: *For uniformly distributed MNs, average number of MNs in a group after grouping can be expressed as M/k. Then, average system delay can be written as:*

$$T_D = \begin{cases} \frac{M}{k}T \, , a < 1 \\ \frac{M}{k}aT \, , a \geq 1 \end{cases} \quad (5)$$

, where $a = U/L$ denotes the ratio of required RU number to number of assigned RUs. T denotes an OFDMA frame duration. The average system delay constraint can be transformed into the constraint of number of coordinators:

$$\begin{cases} \left\lceil \frac{M}{\beta}T \right\rceil \leq k \leq M \, , a < 1 \\ \left\lceil \frac{M}{\beta}aT \right\rceil \leq k \leq M \, , 1 \leq a \leq \frac{\beta}{T} \\ Outage \, , \ a > \frac{\beta}{T} \end{cases} \quad (6)$$

Proof: With the assumption mentioned in Section II that each Coor can only forward one packet to BS at each transmission, the total number of packets in the M2M system forwarded to BS in one transmission is *k*. In the case of $U < L$, the *k* packets can be transmitted to BS in one OFDMA frame, but it requires more than one OFDMA frame in the case of $U > L$. The total data amount to be transmitted in the M2M system is *M* packets. Then, it leads to the straight-forward result of Eq. (5). By substituting Eq. (5) into the second constraint in (4), we can derive the corresponding range of number of coordinators to meet the average delay constraint, Eq. (6). ■

B. Energy Minimization Schemes via 2-hop MN Access Management

The proposed schemes perform MN grouping and coordinator selection iteratively until the result converges. Firstly, MNs are divided into groups with given coordinators. After that, each group re-selects a proper MN as the coordinator to relay packets of other MNs in the same group to BS. The two steps execute alternately until the result of groups and coordinators remains unchanged.

1) Machine Node (MN) Grouping

a) Minimum Energy Consumption (Min-EC) Scheme

With given coordinators, in order for minimizing EC, the scheme assigns MN m_i to *Group n* which achieves minimum EC with *Coor* c_n. That is:

$$G_n = \left\{ i \middle| n = arg\, min_j \, ec_{m_i}^{c_j} \, , for \ \forall i \right\} \quad (7)$$

, where $ec_{m_i}^{c_j}$ can be obtained from Eq. (1).

b) Minimum Channel-Inverse (Min-ChInv) Scheme

To further reduce computational operations of the above scheme, some mathematical manipulations can be done to approximate Eq. (7) as follows:

$$G_n = \left\{ i \middle| n = arg\, min_j \left(1/h_{m_i}^{c_j} + 1/h_{c_j} \right) \right\}, \forall i \quad (8)$$

As a result, MN m_i is assigned to the coordinator achieving minimum sum of channel inverse of the *MN-to-Coor* link and the *Coor-to-BS* link.

2) Coordinator Selection

a) Best Channel Gain (Best-K) Scheme

With a given grouping result, the scheme chooses the MN m_i as the coordinator of *Group n* if m_i has the maximum channel gain with BS. That can be expressed as:

$$c_n = m_i \, , if \ h_{m_i} > h_{m_j}, for \ \ i, \forall j \in G_n, i \neq j \quad (9)$$

, where h_{m_i} represents the channel between MN m_i and BS.

b) Optimal Coordinator (Opt-Coor) Scheme

With a given grouping result, for a certain group, the MN which can achieve minimum group EC is chosen as the coordinator. That can be written as:

$$c_n = m_i \, , if \ ec_n^{m_i} < ec_n^{m_j}, for \ \ i, \forall j \in G_n, i \neq j \quad (10)$$

, where $ec_n^{m_i}$ denotes EC of *Group n* with MN m_i as the coordinator, which can be obtained from Eq. (2).

3) Combined Scheme

The combined scheme can accomplish MN grouping and Coordinator selection in one time without iteratively executing the two steps.

a) K-Max Channel(K-MaxCh) Scheme

It is not hard to see from Eq. (1)~(3) that the channel quality between Coors, which transmit all other MNs' packet in the group, and BS influences EC significantly. Therefore, this scheme chooses *k* MNs with top *k* best channel gains of the *MN-to-BS* link, to be the coordinators. Then, each MN is assigned to the *Coor* which achieves maximum channel gain for the *MN-to-Coor* link. That can be written as:

$$G_n = \left\{ i \middle| n = arg\, max_j \, h_{m_i}^{c_j} \ , \forall i \right\} \quad (11)$$

Corollary: *With given resource constraint, the M2M system can achieve minimum EC by exploiting maximal number of available RUs ($L = \alpha$), while satisfying the delay requirement.*

Proof: From Fig. 1(b), it can be observed that the system EC, Eq. (3), is a bowl-shaped function, where a minimum point exists, with respect to number of coordinators, *k*. According to Eq. (6), more resources assigned to the M2M system, namely larger *L*, results in a wider range of *k*, for which the average system delay constraint is met, due to smaller '*a*'. It is obvious that the optimal point of Eq. (3) which achieves minimum EC is more likely to be covered in a wider range of *k*. Therefore, *L* is chosen to be α to guarantee the minimum system EC. ■

Proposed Scheme

A. Min-ChInv + Opt-Coor Scheme
B. Min-ChInv + Best-K Scheme
C. Min-EC + Opt-Coor Scheme
D. K-MaxCh Scheme

All proposed schemes execute the following steps:

Step1: With given α, β, according to the lemma and corollary, we set $L = \alpha$ and choose *k* random MNs as initial coordinators, where *k* is the lower bound of Eq. (6) for the first iteration.
Step2: Execute MN grouping based on the chosen scheme.

Step3: Select the coordinators based on the chosen scheme.
Step4: Repeat Step 2 and 3 until the result remains unchanged.
Step5: Calculate EC by Eq. (3) and store it with given k.
Step6: Repeat Step 1~5 with k obtained from Eq. (6).
Step7: Select the assignment result achieving minimum EC.

V. Complexity Analysis

For MN grouping schemes, the Min-EC scheme requires each normal MN to compute the energy consumption of the MN-to-Coor-to-BS link for each Coor and select the minimal one. Hence, the complexity of the Min-EC scheme is $O(k(M-k))$. Similarly, the Min-Chinv scheme also has the complexity $O(k(M-k))$. For coordinator selection, assume each group has M/k MNs in average. The complexity of the Best-K scheme is $O(M)$. In each group, the Opt-Coor scheme needs to compute the total energy consumption of the group for each MN acting as a Coor in that group. Thus, the complexity of the Opt-Coor scheme is $O(M^2/k^2)$. As a result, the complexity of each iteration of the proposed Scheme A and C is $O(k(M-k)+M^2/k^2)$, and that of Scheme B is $O((k+1)M-k^2)$. The complexity of Scheme D is $O(M)$.

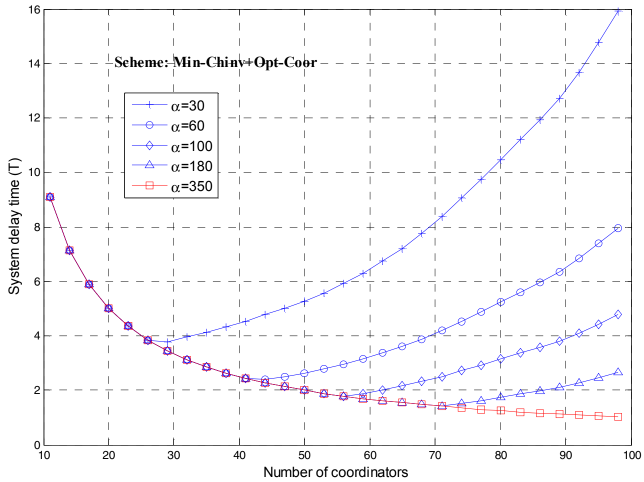

Fig. 1(a) T_D in terms of α with different number of *Coors*; *L*=α, *M*=100.

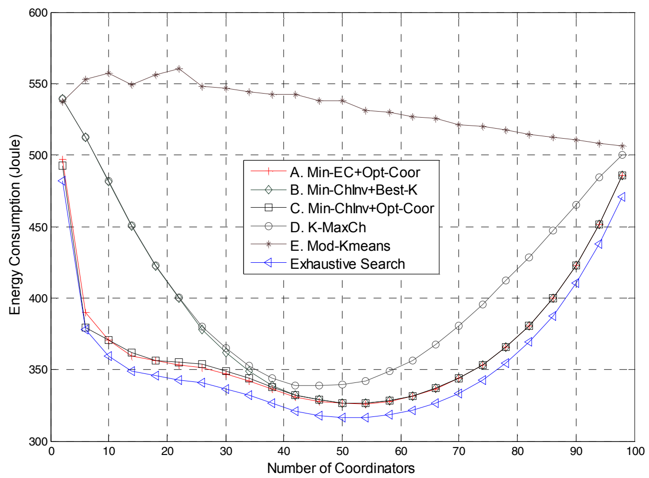

Fig. 1(b) EC for different k; No delay constraint is given; *M*=100.

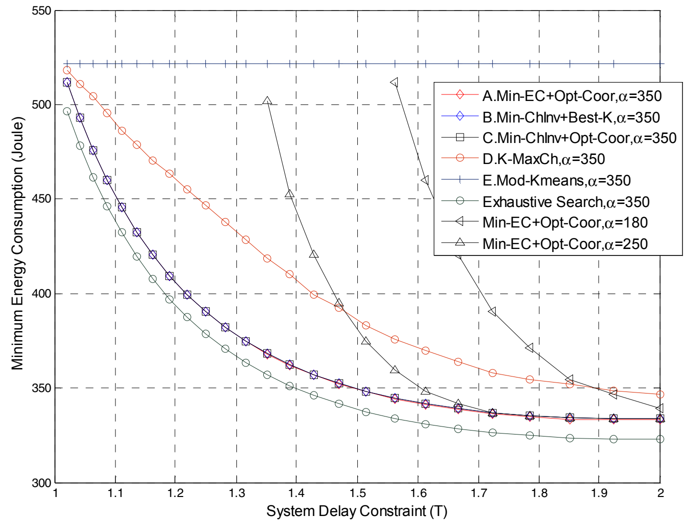

Fig. 2 Performance of min EC with different β (x-axis); *M*=100

VI. Numerical Result and Discussion

Consider a single cell OFDMA cellular network with MNs uniformly distributed within a 700-meter radius cell centered at a BS. Because MNs are nomadic, signals transmitted by MNs only experiences path-loss, modeled as [9]:

$$PL = 128.1 + 37.6\,log_{10} R,$$

where PL and R denote the path loss in dB and distance between the transmitter and receiver in kilometers respectively. Each MN transmits with fixed power, 10 dBm. Assume the packet size is 10 bits. Noise power spectral density, N_0, and bandwidth, B, are -170 dBm/Hz and 15kHz respectively.

Fig. 1 (a) and (b) jointly illustrate the tradeoff between system delay, assigned number of RUs, and system EC. In Fig. 1 (a), T_D decreases as maximum assigned RUs, α, increases, and T_D is plotted as a concave curve due to the rapid increase of the ratio a resulting from more MDs with worse channel condition are chosen as *Coor*s. Fig. 1 (b) compares six proposed schemes in terms of performance of EC. Scheme E implements MN grouping by the conventional K-Means algorithm, and then assigns the MN nearest to the mean point of the group as the coordinator for each group. Note that no T_D is given in Fig. 1(b), which plots EC of each proposed scheme with different number of coordinators. In Fig. 1(b), it can be seen that Scheme C has very similar results to Scheme A while they both can achieve similar performance to the exhaustive search in much lower complexity. Moreover, compared to other schemes, although Scheme A and C have higher computational complexity than Scheme B and D, Scheme A and C can achieve low EC with much fewer coordinator accesses to the cellular network. Therefore, A and C could save BS more resources for other H2H applications. Fig. 2 shows the minimum EC of each scheme with different β. It's shown that both system EC and minimum achievable system delay raises while assigned RUs reduce. Also, the Scheme A, B, and C outperforms Scheme D and E by 16~23% in terms of min EC because they jointly consider the *MN-to-Coor* link and the *Coor-to-BS* link. However, Fig. 1(b) and 2 show that Scheme D achieves moderate results by only considering the channel quality of the *Coor-to-BS* link because the coordinators relaying others' packets contribute a major part of total EC. Scheme E performs worst among all due to considering only MN coordinates.

VII. CONCLUSION

In an OFDMA network embedded with a M2M system, we propose MN energy minimization schemes, implementing grouping and coordinator selection by jointly considering EC of *MN-to-Coor* and *Coor-to-BS* link, to minimize total consumed energy in the flat- and slow-fading environment while satisfying the assigned resource and system delay constraint, and study the tradeoff between average system delay, resource amount, EC, and number of coordinators for the embedded M2M system. Finally, the proposed schemes achieve near-optimal EC with any delay constraints or number of coordinators.

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