Lifetime-Aware Scheduling and Power Control for Cellular-based M2M Communications

Amin Azari and Guowang Miao
KTH Royal Institute of Technology

Abstract—**In this paper the uplink scheduling and transmit power control is investigated to minimize the energy consumption for battery-driven devices deployed in cellular networks. A lifetime metric based on the accurate energy consumption model for cellular-based machine devices is provided and used to formulate the uplink scheduling and power control problems as network lifetime maximization problems. Then, lifetime-aware uplink scheduling and power control protocols which maximize the overall network lifetime are investigated based on the different lifetime definitions. Besides the exact solutions, the low-complexity suboptimal solutions are presented in this work which can achieve near optimal performance with much lower computational complexity. The performance evaluation shows that the network lifetime is significantly extended under proposed protocols.**

Index Terms—**Machine-to-Machine communications, Cellular Networks, MAC, Energy efficiency, Lifetime.**

I. Introduction

INTERNET of Things (IoT) refers to the interconnection of uniquely identifiable smart devices which enables smart devices to participate more actively in everyday life. Among large-scale applications, cheap and widely spread machine-to-machine (M2M) communications embedded in cellular network infrastructure will be one of the most important approaches for the success of IoT [1]-[2]. Machine-type devices are expected to work for long periods of time without human intervention for maintenance. Machine 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. 3GPP LTE has defined research projects to support massive machine access [3], [4]. Some challenges in current cellular networks for supporting M2M communications with random access channel are investigated in [4] -[6]. The authors in [7] proposed to organize the M2M devices with similar QoS requirements into classes where each class is associated with a prescribed QoS profile. Then, fixed access grant time interval (AGTI) is allocated to each class, based on the traffic rate and the priority of each class. This time-controlled scheduling framework for machine devices is widely adopted in the literature as it enables limited-availability instead of always-availability for machine devices [8]-[12]. Most of the existing works in this field are focused on the delay performance in terms of delay due to the massive concurrent access requests and very few of them have investigated the energy efficiency in M2M communications. Power-efficient MAC protocols for machine devices with reliability constraints in cellular networks is considered in [13]. The energy-efficient uplink scheduling in LTE networks with coexistence of cellular users and machine devices is investigated in [14]. In [13] and [14], authors considered a simple model for power consumption considering only transmit power for reliable data transmission and neglect the other energy consumption by the operation of electronic circuits which is comparable or more dominant than the energy consumption for reliable data transmission [15]-[16].

A. Motivation

There are many M2M applications that require very high energy efficiency to ensure the long lifetime of the network. The operation cost of the M2M network with battery-driven nodes increases with the inefficiency in its transmission protocol because it requires more investment on the replacement and maintenance costs. To the best of our knowledge, optimal scheduling and power control for M2M network-lifetime maximization over cellular networks is not considered in literature.

B. Outline of Contributions and Structure of the Article

In this paper, we consider M2M communications over cellular networks with single-carrier frequency division multiple access (SC-FDMA) for the uplink transmission. We will develop an accurate power consumption model for machine devices deployed in cellular networks and then present an accurate metric of machine lifetime. Then, the uplink scheduling and power control problems are formulated as lifetime maximization problems, and optimal algorithms as well as suboptimal easy-to-implement solutions for network lifetime maximization based of the different lifetime definitions are investigated. This work provides insights into the optimal physical resource block allocation and modulation and coding scheme selection for machine devices in cellular networks due to the special characteristics of M2M communications. The numerical results show that the network lifetime can be significantly extended using the proposed scheduling schemes.

The remainder of this paper is organized as follows. In the next section the system model and problem formulation are introduced. The optimal scheduling and power control algorithms are investigated in section III. Low-complexity suboptimal solutions are presented in section IV. The performance evaluation is provided in section V. Concluding remarks are given in section VI.

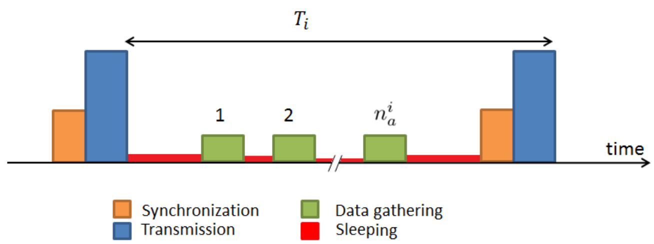


Fig. 1: Different modes of power consumption for node i. Different block heights reflect different levels of power consumption in different modes.

II. System Model and Problem Formulation

A. System Model

Consider a single cell with one base station (BS) and a massive number of static machine nodes, which are uniformly distributed in the cell. To solve the high peak to average power ratio issue in orthogonal frequency division multiple access (OFDMA) scheme, SC-FDMA has attracted much attention in recent years and is adopted for uplink transmission in LTE-Advanced networks [14]. In SC-FDMA, data signals are pre-coded by a Discrete Fourier Transform block before subcarrier mapping at the transmitter. Also, the subcarriers are grouped into chunks, before being assigned to the users, and the transmission power over all subcarriers in each chunk is the same.

B. Lifetime Metric Definition

Define the set and the number of machine devices which must be served at once as $\pounds$ and N respectively. The remaining energy of the ith device at time t_0 is denoted by $E_i(t_0)$, the average time between two successive resource allocation to this node i is denoted by T_i, and the average size of the data packet is denoted by D_i. Define the power consumption in the sleeping and transmitting modes for node i as P_s and $P_{t_i} + P_c$ respectively, where P_c is the circuit power consumed by electronic circuits in the transmission mode and P_{t_i} is the transmit power for reliable data transmission. The expected lifetime for node i at time t_0 is the ratio between remaining energy and the required energy consumption in each duty cycle of the node, as follows:

$$L_i(t_0) = \frac{E_i(t_0)T_i}{E_c + P_s(T_i - \frac{D_i}{R_i} - n_a T_a) + n_a T_a P_a + \frac{D_i}{R_i}(P_c + \alpha P_{t_i})} \tag{1}$$

where R_i is the transmission rate for node i, α is the inverse of power amplifier efficiency, and E_c is the average energy consumption in each duty cycle for synchronization, admission control, and etc. Also, P_a is the power consumption in the active mode for data gathering, T_a^i is the active mode duration, and n_a^i is the number of active modes per T_i for node i (Fig. 1).

C. Lifetime Metric versus Bit-per-Joule Metric

The bit-per-Joule metric for energy-efficient system design is widely accepted and is written as [17]

$$U_i(R_i) = \frac{R_i}{P_c + P_{t_i}(R_i)} \tag{2}$$

It is shown that if $P_{ti}(R_i)$ is strictly convex in R_i, $U_i(R_i)$ is strictly quasiconcave [17]. This metric considers the circuit power consumption and transmit power consumptions as two main sources of power dissipations. As in M2M communications the data transmission duration is negligible in comparison with the duty cycle, we rewrite the average energy consumption in non-transmission modes as:

$$E_s = E_c + P_s(T_i - n_a T_A) + n_a P_a T_a$$

Then, one can write the lifetime metric as:

$$L_i(t_0) = \frac{E_i(t_0)T_i}{E_s + D_i \frac{P_c + P_{t_i}}{R_i}} = \frac{E_i(t_0)T_i}{D_i} \frac{R_i}{P_c + (P_{t_i} + E_s \frac{R_i}{D_i})} \tag{3}$$

Define $\tilde{P}_{t_i}(R_i)$ as $P_{t_i} + \frac{E_s}{D_i} R_i$, one can rewrite (3) as follows:

$$L_i(t_0) = \frac{E_i(t_0)T_i}{D_i} \frac{R_i}{P_c + \tilde{P}_{t_i}} = \frac{E_i(t_0)T_i}{D_i} \tilde{U}_i(R_i) \tag{4}$$

which shows that lifetime is proportional to the energy efficiency $\tilde{U}_i(R_i)$.

D. Network Lifetime Definition

There are different definitions for network lifetime as a function of individual lifetime. We consider three definitions for the network lifetime: (i) The average length of individual lifetimes; (ii) The shortest length of individual lifetimes, which is applicable when losing even a node deteriorates the performance or coverage; and (iii) The longest length of individual lifetimes, which is applicable when the correlation between gathered data by the sensors is high. According to these definitions, the following optimization problems will be investigated in this work:

$$(i) \quad \max \ \frac{1}{N} \sum\nolimits_{i=1}^{N} L_i \tag{5}$$

$$(ii) \quad \max \ \min_{i \in \pounds} \ L_i \tag{6}$$

$$(iii) \quad \max \ \max_{i \in \pounds} \ L_i \tag{7}$$

subject to: Limited time-frequency resources

In the next section the optimization problems in (5)-(6) are solved subject to the constraints in SC-FDMA systems. The solution to the optimization problem in (7) is derived by pursuing the same procedure as problem (6).

III. Lifetime-aware Uplink Scheduling and Power control for SC-FDMA-based systems

Using SC-FDMA as the multiple access scheme for uplink transmission implies restrictions on the power and resource allocation: (i) Each subcarrier can only be allocated to at most one machine node; (ii) Adjacent subcarriers can be allocated to a user; and (iii) The transmit power on all subcarriers assigned to a machine node must be the same [18]. Denote the total number of available chunks as L, where each of them consists of M adjacent subcarriers. Then, the achievable rate for node i is written as follows:

$$R_i = Mc_i w \log(1 + \frac{P_i G_t G_r}{P^i_{loss}\xi\Gamma N_0 w}) \tag{8}$$

where G_t is the transmitter antenna gain, G_r the receiver antenna gain, P_i the transmit power of node i over each assigned subcarrier, c_i the number of assigned chunks to user i, w the bandwidth of each subcarrier, P^i_{loss} the pathloss between node i and the base station, and ξ models other fading losses in the channel. Also, Γ models the signal to noise ratio (SNR) gap between the channel capacity and a practical coding and modulation scheme. One can write the lifetime of node i as a function of P_i as follows:

$$L_i(t_0) = \frac{E_i(t_0)T_i}{\frac{D_i(Mc_i\alpha P_i + P_c)}{Mc_i w \log(1+\frac{P_i G_t G_r}{P^i_{loss}\xi\Gamma N_0 w})} + E^i_s} \tag{9}$$

which is a quasiconcave function. Denote each possible chunk allocation among N machine nodes as a 1-by-N vector $\mathbf{C}$, where its ith element, c_i, shows the number of assigned chunks to node i.

Then, we can formulate two optimization problems to find the optimal number of assigned chunks to user i and the optimal transmit power for each machine node, as follows:

$$(i)\ \max\ \sum_{i=1}^{N} L_i(t_0) \tag{10}$$

$$(ii) \max\ \min_{i\in\pounds} L_i(t_0) \tag{11}$$

$$\text{s.t.:}\ \sum_{i=1}^{N} c_i \leq L \tag{12}$$

$$c_m \leq c_i \leq \frac{P^i_{max}}{P_i M} \quad \forall i \in \pounds \tag{13}$$

$$\frac{D_i}{R_i} \leq t_T \quad \forall i \in \pounds \tag{14}$$

in which c_m is the minimum number of assigned chunks to a user for access guarantee and P^i_{max} is the maximum transmit power for node i. Also, the constraint in (14) is due to the granularity of resource allocation in the time. The joint scheduling and power control problem is hard to solve and is non-convex. Then, we propose a two-step algorithm to solve the problem. In the first step, the optimal transmit power for maximizing the lifetime of each device under each possible chunk allocation will be found. In the second step, the optimal chunk allocation which maximizes the objective function of optimization problem will be selected. In following, we derive the optimum power control policy for a fixed chunk assignment for node i, c_i. As $L_i(t_0)$ is a strictly

Algorithm 1: Solution to optimization problem in (10).

1. Find the set of possible chunk allocation vectors, $\mathbf{C}_k$, under constraint in (12);
2. Calculate $P^*_i, \forall i \in \pounds$, using (15) for all possible chunk allocations and check the constraint in (13). Then the set of valid chunk allocations will be determined as $\mathbf{C}_k$, $\forall k \in \{1, \cdots, K\}$;
3. Calculate ${L_i}^*(t_0)$ and P^*_i, $\forall i \in \pounds$, using (9)-(15) for all valid chunk allocations and denote them for kth possible chunk allocation as P^{*k}_i and ${L^*_i}^k(t_0)$;
4. k^*= arg $\max_{k\in\{1,\cdots,K\}} \sum_{i=1}^{N} {L^*_i}^k(t_0)$;
5. $P^*_i = {P^*_i}^{k^*}, \forall i \in \pounds$;
6. **return** P^*_i, $\forall i \in \pounds$ and $\mathbf{C}_{k^*}$

quasiconcave function of P_i, one can use convex optimization to find the optimal transmit power for node i on each subcarrier as follows:

$${P_i}^* = \max\{P^i_{min}, \frac{1}{bM\alpha c_i}(\frac{bP_c - 1}{\text{lambertw}(\frac{bP_c-1}{e})} - 1)\} \tag{15}$$

where

$$b = G_t G_r/(\Gamma\xi P^i_{loss}\Gamma\xi N_0 w M c_i); \tag{16}$$

$$P^i_{min} = \frac{P^i_{loss}N_0 w}{G_t G_r}(2^{\frac{D_i}{M\alpha c_i w t_T}} - 1). \tag{17}$$

The validity of each chunk allocation must be checked in this step by checking the constraint in (13). Also, one can insert the optimal transmit power on each subcarrier for the ith node, P^*_i, in (9) to find the optimal lifetime for this node, ${L_i}^*(t_0)$. Now, we are able to calculate the objective function in optimization problems (10)-(11) under possible chunk allocations and select the one which maximizes the objective function. Algorithms 1 and 2 which are based on exhaustive search, show the overall solution for optimization problems in (10)-(11) respectively. The outputs of these algorithms are the optimal chunk allocations vector and the optimal transmit power for each node on each assigned subcarrier.

1) Complexity Analysis: The complexity order of search over all possible ways of chunk allocation in Algorithm 1 is $O(\binom{L+N-1}{N-1})$. Algorithm 2 has the same complexity in each iteration, then its overall complexity is $O(N \times \binom{L+N-1}{N-1})$. However this complexity seems to be high, there are practical M2M applications that this complexity is meaningful for them.

This time-controlled scheduling framework for machine devices is widely adopted in the literature as it enables limited-availability instead of always-availability for machine devices [8]-[12].

Consider the time-controlled framework for enabling M2M communications in cellular networks [8]-[12] in which each class of the nodes are assigned a constant amount of resources in regular intervals. Using algorithms 1 and 2, the designed scheduling by the BS for each class of nodes will be valid for a long time-interval, from minutes to months. This is because: (i)

Algorithm 2: Solution to optimization problem in (11).

Define the set of available machine nodes, $S_u = \pounds$, and the optimal chunk allocation vector, $\mathbf{C}^*$=$\mathbf{0}_{L\times N}$;
while $|S_u| > 0$ **do**
  Find the set of possible chunk allocation vectors, $\mathbf{C}_k$, under constraints in (12), (13) and already assigned chunks in $\mathbf{C}^*$;
  Calculate $P_i^*, \forall i \in S_u$, using (15) for all possible chunk allocations and check the constraint in (13). Then the set of valid chunk allocations will be determined, $\mathbf{C}_k, k \in \{1, \cdots, K\}$;
  Calculate ${L_i}^*(t_0)$ and P_i^*, $\forall i \in S_u$, using (9)-(15) for all valid chunk allocations and denote them for kth possible chunk allocation as ${P_i^*}^k$ and ${L_i^*}^k(t_0)$;
  l= arg $\max_{k\in\{1,\cdots,K\}} \min_{i\in S_u} {L_i^*}^k(t_0)$;
  m=arg $\min_{S_u} {L_i^*}^l(t_0)$. Using m, the index of the corresponding node in $\pounds$ is found as n;
  $P_n^* = {P_m^*}^l$;
  $\mathbf{C}^*(:,n) = \mathbf{C}_l(:,m)$;
  Remove node m from S_u;
return P_i^*, $\forall i \in \pounds$ and $\mathbf{C}^*$

the number and position of machine devices are semi-constant due to lake of mobility of most machine devices; (ii) the energy consumption of machine devices in expected to be low, then the change in remaining energy will be low; and (iii) the packet length of machine nodes is constant in most M2M applications. Then, finding the optimal solutions by the BS which are valid for a long time even with high complexity will be meaningful.

A. Low-complexity Uplink Scheduling and Power Control

In this part we assume machine devices have constant transmit power on each assigned subchannel. This power is derived by satisfying the constraint in (14) with equality as in (17). Then, the transmit power for node i is controlled only by the number of assigned chunks as $P_{t_i} = Mc_iP_i$. Under this assumption, the lifetime expression and the scheduling and power control problems in (9)-(11) remains unchanged, however, here the P_i is known a priory and we seek for the optimal chunk allocation vector, $\mathbf{C}^*$. One can see that the lifetime expression in (9) is a concave function of c_i, then the optimization problem is a discrete convex optimization problem and can be solved with much lower complexity in comparison with Algorithm 1 and 2. Using linear relaxation, one can write the Lagrangian function for the optimization problem in (10) as:

$$F = \sum\nolimits_{i=1}^{N} L_i(t_0) - \lambda(\sum\nolimits_{i=1}^{N} c_i - LM)$$

where λ is the Lagrangian multiplier. Then, the optimal number of assigned chunks to node i is derived as follows:

$$c_i^* = \min\{\max\{\frac{1-f\lambda}{h\lambda + h\sqrt{\lambda/f}}, c_m\}, \frac{P^i_{max}}{P_iM}\}$$

TABLE I: Simulation Parameters

Parameter	Value
Cell radius	500 m
Pathloss	$128.1+37.6\log_{10}(r)$ in dB, r in km
Power spectral density of noise	-174 dBm/Hz
No. of nodes in the class	10
Packet size ($D_i + D_{oh}$)	varied
Circuit power (P_c)	10 mW
Time granularity (t_T)	1 msec
Constant energy cons. (E_s)	250 μJoule
Min. assigned chunks (c_m)	1
Full battery capacity	2500 Joule

where

$$f = \frac{P_c}{Mw\log(1+\frac{P_iG_tG_r}{P^i_{loss}\xi\Gamma N_0 w})E_iT_i} \tag{18}$$

$$h = \frac{E^i_s}{E_i(t_0)T_i} + \frac{D_i\alpha P_i}{E_i(t_0)T_iw\log(1+\frac{P_iG_tG_r}{P^i_{loss}\xi\Gamma N_0 w})} \tag{19}$$

Also, λ is found due to the constraint in (12).
For optimization problem in (11), we define $z = \min_{i\in\pounds} L_i(t_0)$ and rewrite the problem as follows:

$$\max \quad z \tag{20}$$

$$\text{s.t.:} \quad \sum\nolimits_{i=1}^{N} c_i \leq LM; \quad c_m \leq c_i \leq \frac{P^i_{max}}{P_iM} \quad \forall i \in \pounds; \tag{21}$$

$$z \leq L_i(t_0) \quad \forall i \in \pounds \tag{22}$$

Using linear relaxation, one can write the Lagrangian function for this optimization problem as:

$$F = z - \lambda(\sum\nolimits_{i=1}^{N} c_i - LM) - \sum\nolimits_{i=1}^{N} \mu_i(z - L_i(t_0))$$

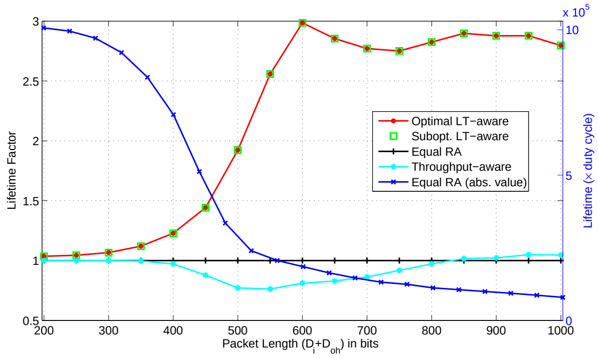
where λ and μ_is are Lagrangian multipliers. Then, the optimal number of assigned chunks to node i is derived as follows:

$$c_i^* = \min\{\max\{\frac{1-f\lambda/\mu_i}{h\lambda + h\sqrt{\lambda/f\mu_i}}, c_m\}, \frac{P^i_{max}}{P_iM}\}$$

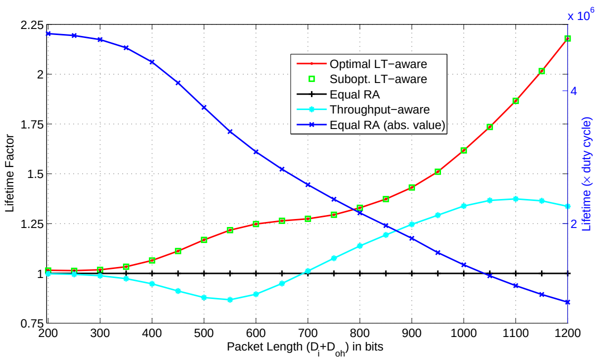
where f and h are defined in (18)-(19). The Lagrange multipliers are found due to the constraint in (12) and $\frac{\partial F}{\partial z} = 0$, which yields: $\sum_{i=1}^{N} \mu_i = 1$.

IV. Performance Evaluation

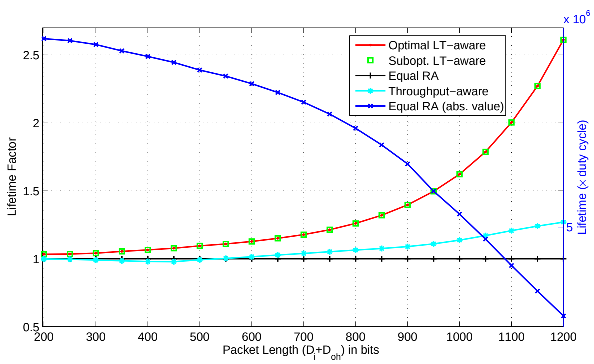
In this section, we evaluate the lifetime performance of the proposed uplink scheduling and power control protocols. We adopt the time-controlled framework for machine-type communication in cellular network [1]-[2] where 0.6 MHz bandwidth is allocated to class n of machine nodes every T_n seconds. Then, fifteen chunks are available for class n, each having 4 subcarriers and



(a) Network lifetime comparison under lifetime definition in (6)

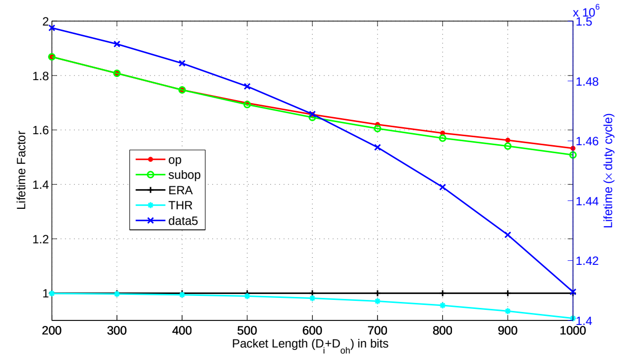


(b) Network lifetime comparison under lifetime definition in (5)

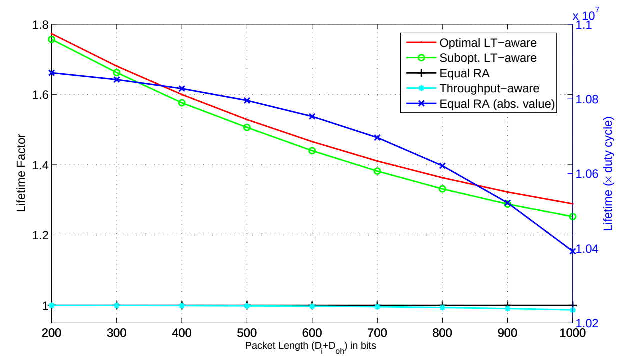


(c) Network lifetime comparison under lifetime definition in (7)

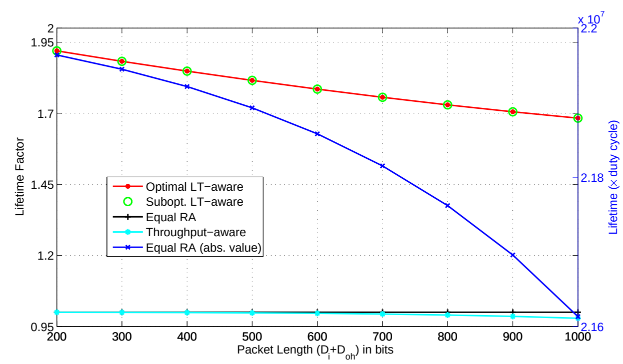
Fig. 2: Performance comparison of different scheduling and power control protocols.



(a) Network lifetime comparison under lifetime definition in (6)



(b) Network lifetime comparison under lifetime definition in (5)



(c) Network lifetime comparison under lifetime definition in (7)

Fig. 3: Performance comparison of different scheduling and power control protocols.

a bandwidth of 40 kHz. The other simulation parameters are presented in Table I. As a benchmark, we compare the lifetime performance of proposed protocols with the results of following schemes: (i) equal resource allocation; and (ii) throughput-aware resource allocation in which machine nodes with better channel condition have priority for channel access. The power control for these schemes is considered to be the same as power control for low-complexity scheme in section III-A. Base station performs the scheduling at time t_0, where the remaining-energy level of each machine device is a random value between zero and full battery capacity.

In following figures we depict the absolute resulted lifetime under equal resource allocation scheme in left vertical axis, and the lifetime factor for other schemes in right vertical axis. The Lifetime factor for scheme x is the ratio between absolute lifetime under scheme x and equal resource allocation.

Fig. 2a shows the lifetime performance of proposed scheduling protocols versus different data packet size, where the minimum individual lifetime is considered as the network lifetime as in optimization problem (6). One can see that the optimal lifetime-aware scheduling significantly increases the lifetime of the network. Also, the achieved lifetime with low-complexity suboptimal solution is in quite match with results of the optimal solution. This happens because in this scenario, the transmission independent energy consumption (E_s) is dominant in small to medium packet length regions ($D_i \leq 400$) where two schemes are different in power allocation. In $D_i \geq 400 \leq 600$, P_i^* in (15) is determined by P_{min}^i which results in the same power allocation as in low complexity scheme. However, when the constant energy consumption is low, these two schemes have different behaviors. The throughput-aware scheme allocates more chunks to closer nodes to the BS which results in short lifetimes for far away nodes with high transmit power. Fig 2b shows the same results when the network lifetime is defined as the average lifetime of machine nodes as in the optimization problem (5). One can see that the achieved network lifetime from suboptimal and optimal solutions are again in quite match. Fig. 2c compares the lifetime performance of different scheduling protocols, when the maximum lifetime of machine nodes is considered as the network lifetime as in optimization problem (7). One can see that the throughput-aware scheduling which allocates more resources to nearby nodes performs better than equal resource allocation scheme in these figures. This is because the closer nodes to the base station, which have priority in throughput-aware scheme, experience lower pathloss and then their transmit power is low. Then, allocating more resources to them and decreasing their transmit power contributes to longer network lifetime. Again here, the achieved network lifetime from lifetime-aware scheduling and power control is much better than the other scheduling protocols. Fig. 3 shows the lifetime performance evaluation when $t_T =$ 5msec, and the other simulation parameters are the same as Table. I. From this figure it is evident that by increase in t_T, the impact of power control on the network lifetime is increased. Then, the performance of optimal solution by algorithm 1 and 2 is superior than the performance of suboptimal low-complexity solution.

V. Conclusions

In this paper, the uplink scheduling and power control is investigated to maximize the lifetime of cellular-based M2M networks. An accurate energy consumption model for machine devices deployed in cellular networks is presented and a lifetime metric based on this model is investigated. Then, optimal and with low-complexity suboptimal scheduling and power control protocols are presented to maximize the network lifetime. The performance evaluation shows that the network lifetime is significantly extended under the proposed scheduling protocols.

References

[1] L. Srivastava, T. Kelly, and et al., “The internet of things,” International Telecommunication Union, Tech. Rep. 7, Nov. 2005.

[2] G. Lu, D. Seed, M. Starsinic, C. Wang, and P. Russell, “Enabling smart grid with ETSI M2M standards,” in *IEEE Wireless Communications and Networking Conference Workshops*, April 2012, pp. 148–153.

[3] 3GPP TS 22.368 V11.1.0, “Service requirements for machine-type communications,” Tech. Rep., 2011. [Online]. Available: http://www.3gpp.org/ftp/Specs/archive/22_series/22.368/22368-b10.zip

[4] A. Laya, L. Alonso, and J. Alonso-Zarate, “Is the random access channel of LTE and LTE-A suitable for M2M communications? a survey of alternatives,” *IEEE Communications Surveys Tutorials*, vol. 16, no. 1, pp. 4–16, 2014.

[5] M. Beale, “Future challenges in efficiently supporting M2M in the LTE standards,” in *IEEE Wireless Communications and Networking Conference Workshops*, April 2012, pp. 186–190.

[6] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, “Radio resource allocation in LTE-advanced cellular networks with M2M communications,” *IEEE Communications Magazine*, vol. 50, no. 7, pp. 184–192, July 2012.

[7] S. Y. Lien and K. C. Chen, “Massive access management for QoS guarantees in 3GPP machine-to-machine communications,” *IEEE Communications Letters*, vol. 15, no. 3, pp. 311–313, March 2011.

[8] A. G. Gotsis, A. S. Lioumpas, and A. Alexiou, “Analytical modeling and performance evaluation of realistic time-controlled M2M scheduling over LTE cellular networks,” *Transaction Emerging Telecommunications Technologies*, vol. 24, no. 4, pp. 378–388, 2013.

[9] ——, “Evolution of packet scheduling for machine-type communications over LTE: Algorithmic design and performance analysis,” in *2012 IEEE Globecom Workshops*, 2012, pp. 1620–1625.

[10] G. Farhadi and A. Ito, “Group-based signaling and access control for cellular machine-to-machine communication,” in *IEEE 78th Vehicular Technology Conference*, 2013, pp. 1–6.

[11] M. K. Giluka, N. S. Kumar, N. Rajoria, and B. R. Tamma, “Class based priority scheduling to support machine to machine communications in LTE systems,” in *Twentieth National Conference on Communications*, 2014, pp. 1–6.

[12] A. Gotsis, A. Lioumpas, and A. Alexiou, “M2M scheduling over LTE: Challenges and new perspectives,” *IEEE Vehicular Technology Magazine*, vol. 7, no. 3, pp. 34–39, Sept. 2012.

[13] H. S. Dhillon, H. C. Huang, H. Viswanathan, and R. A. Valenzuela, “Power-efficient system design for cellular-based machine-to-machine communications,” *IEEE Transactions on Wireless Communications*, vol. 12, no. 11, pp. 5740–5753, Nov. 2013.

[14] A. Aijaz, M. Tshangini, M. Nakhai, X. Chu, and A.-H. Aghvami, “Energy-efficient uplink resource allocation in LTE networks with M2M/H2H co-existence under statistical QoS guarantees,” *IEEE Transactions on Communications*, vol. 62, no. 7, pp. 2353–2365, July 2014.

[15] G. Miao, N. Himayat, G. Li, and S. Talwar, “Low-complexity energy-efficient scheduling for Uplink OFDMA,” *IEEE Transactions on Communications*, vol. 60, no. 1, pp. 112–120, Jan. 2012.

[16] T. Tirronen, A. Larmo, J. Sachs, B. Lindoff, and N. Wiberg, “Reducing energy consumption of LTE devices for machine-to-machine communication,” in *IEEE Globecom Workshops*, Dec 2012, pp. 1650–1656.

[17] G. Miao, N. Himayat, and G. Y. Li, “Energy-efficient link adaptation in frequency-selective channels,” *IEEE Transactions on Communications*, vol. 58, no. 2, pp. 545–554, 2010.

[18] H. Myung, J. Lim, and D. Goodman, “Single carrier FDMA for uplink wireless transmission,” *IEEE Vehicular Technology Magazine,*, vol. 1, no. 3, pp. 30–38, Sept. 2006.