Postprint

Lifetime-Aware Scheduling and Power Control for M2M Communications in LTE Networks

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Abstract—In this paper the scheduling and transmit power control are investigated to minimize the energy consumption for battery-driven devices deployed in LTE networks. To enable efficient scheduling for a massive number of machine-type subscribers, a novel distributed scheme is proposed to let machine nodes form local clusters and communicate with the base-station through the cluster-heads. Then, uplink scheduling and power control in LTE networks are introduced and lifetime-aware solutions are investigated to be used for the communication between cluster-heads and the base-station. Beside the exact solutions, 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 using the proposed protocols.

Index Terms—Internet of Things, Machine-to-Machine Communications, LTE Networks, Scheduling, Power Control, Lifetime.

I. INTRODUCTION

INTERNET of Things (IoT) refers to the interconnections of uniquely identifiable smart devices that enables networked devices to exchange information with reduced human intervention. IoT enables smart devices to participate more actively in everyday life, business, and health-care [1]. Among large-scale applications, cheap and widely spread cellular-based machine-to-machine (M2M) communications is a key enabler for the success of IoT [2]. As most smart devices are battery-driven and they are supposed to be in service for a long time without human intervention for battery replacement, long battery-life is crucial for them. It is raised by 3GPP that this level of required energy-efficiency for enabling M2M communications in existing cellular network infrastructure is missing [3]-[4]. Regarding the fundamental differences between M2M and human-to-human (H2H) communications, many research works have been launched to understand how existing infrastructure needs to be changed to provide large-scale massive access [6]-[7]. In [8] a time-controlled framework is proposed to organize the M2M devices with similar quality of service (QoS) requirements into classes where each class is associated with a prescribed QoS profile. Then, fixed uplink resources are allocated to each class, based on the priority of each class. This time-controlled scheduling framework for constant-rate machine devices is widely adopted in the literature as it enables limited-availability instead of always-availability for machine nodes and improves device energy efficiency [9]-[11].

In a large M2M network, if every device communicates to the base-station (BS) directly, it might cause too many packet collisions. Clustering is as an effective way for addressing the massive access problem [12]. In clustered M2M networks, some devices are selected as the cluster-heads (CH) to relay received packets from the cluster-members (CM) to the base-station. Most of the existing works on M2M communications are focused on the delay performance due to the massive concurrent access requests, and very few of them have investigated the energy efficiency in M2M communications. Energy-efficient medium access control (MAC) protocols for machine devices in cellular networks is considered in [13]-[14]. The energy-efficient uplink scheduling in LTE networks with coexistence of cellular users and machine devices is investigated in [15]-[16].

In this paper we present an accurate energy consumption model for machine-type devices in LTE networks. Then, a low-complexity distributed clustering scheme is proposed which simplifies the scheduling problem and prolongs the network lifetime in a distributed way. Furthermore, uplink scheduling and power control problems are formulated as lifetime maximization problems, and an optimal solution as well as a suboptimal easy-to-implement solution for network lifetime maximization are investigated.

The remainder of this paper is organized as follows. In the next section the system model is introduced. The optimal clustering design is presented in section III. Lifetime-aware solutions for uplink scheduling and power control are presented in section IV. The performance evaluation is provided in section V. The concluding remarks are given in section VI.

II. SYSTEM MODEL

Consider a single cell with one base station and a massive number of static machine nodes, which are distributed according to a spatial Poisson process of intensity λ in a 2-dimensional space. The BS is located at the cell-center and the radius of the cell is R_c, then the average number of nodes in the cell is $N_t = \lambda \pi R_c^2$. The machine nodes are battery-driven and long battery-life is crucial for them. To simplify the scheduling problem for a large-scale M2M network, machine nodes form local clusters and communicate through the cluster-heads with the BS. Clustering addresses the massive access problem by reducing the number of concurrent access requests to the base-station, and increases the CM lifetime by reducing the transmission power because the CM-CH pathloss is less than CM-BS pathloss. However, the CH lifetime decreases due to the energy consumption in the listening and receiving packets from CMs and forwarding high number of packets to the BS. Then, it is necessary to

investigate the impact of clustering on the overall network-lifetime. The network lifetime can be defined as a function of individual lifetime of all machine nodes. Here we use the *first energy drain* (FED) network-lifetime which is defined as the time at which the first node drains out of energy, and is applicable when missing even one node deteriorates the performance or coverage of the M2M network. To form the clusters and enable M2M communications, three questions must be answered: (i) what is the optimal *average cluster size*?; (ii) which node must be the CH in each cluster?; and (iii) how the CHs must be scheduled for communication to the BS? In the following section, questions 1 and 2 are answered. The answer to the final question is presented in section IV.

III. DISTRIBUTED CLUSTER FORMING

To keep the analysis tractable and obtain closed-form expressions for cluster-forming, we consider a homogeneous M2M network in which machine nodes have similar packet length, battery capacity, and packet generation frequency. Then, to achieve the highest FED lifetime in each cluster, machine nodes must be the CH in turn to avoid energy-drain in CHs. If we denote the average cluster-size by g, the battery capacity of nodes by E_0, and the duty-cycle of the cluster by T_c, the expected lifetime of each cluster can be expressed as the ratio between remaining energy of devices and the average energy consumption in each duty-cycle, as follows:

$$L_c = \frac{E_0}{\frac{1}{g}E_h + (1-\frac{1}{g})E_m}T_c. \tag{1}$$

The E_h and E_m are the average energy consumption in the CH and CM roles and are calculated as follows:

$$E_h = E_s^h + \frac{g\tilde{D}P_l}{R_m} + g\tilde{D}\frac{P_c+P_t^h}{R_h}; \quad E_m = E_s + \tilde{D}\frac{P_c+P_t^m}{R_m}$$

where $\tilde{D}$ is the average packet size, P_c the power consumption of electronic circuits in transmission mode, $g\frac{\tilde{D}}{R_m}P_l$ the average energy consumption in listening mode, P_t^m and P_t^h the transmit power for reliable data communication in CMs and CHs respectively, E_s and E_s^h are the average static energy consumption in each duty cycle of CMs and CHs, respectively. Also by using frequency division multiple access, the expected data rates of each CH and CM are found as follows:

$$R_h = \frac{W_h}{N_t/g}\log\left(1+P_t^h/(N_0\frac{W_h}{N_t/g}PL_h)\right) \tag{2}$$

$$R_m = \frac{W_m}{g}\log\left(1+P_t^m/(N_0\frac{W_m}{g}\beta_m d_m^{\gamma_m})\right) \tag{3}$$

where N_0 is the noise power spectral density, W_m and W_h are the bandwidths for intra- and inter-cluster communications respectively, and PL_h is the average inter-cluster communication pathloss which is modeled as $\beta_h d_h^{\gamma_h}$ and $d_h = \frac{2R_c}{3}$ [17]. Also, the intra-cluster communication pathloss PL_m is modeled as $\beta_m d_m^{\gamma_m}$ where d_m is the average distance between CMs and the respective CHs and is found in [18] as $\sqrt{\frac{g}{4\lambda}}$. Now, one can rewrite the lifetime expression in (1) as:

$$L_c = \frac{E_0 T_c}{\frac{E_s^h-E_s}{g} + \frac{\tilde{D}[(g-1)(P_c+P_t^m)+P_l]}{W_m\log(1+A_1 g^{(1-\frac{\gamma_m}{2})})} + \frac{N_t\tilde{D}(P_c+P_t^h)}{gW_h\log(1+A_2/g)}}$$

where $A_1 = \frac{P_t^m(4\lambda)^{\frac{\gamma_m}{2}}}{N_0 W_m\beta_m}$ and $A_2 = \frac{P_t^h N_t}{N_0 W_h PL_h}$. Taking the second derivative of L_c with respect to g, one can see that L_c is a strictly concave function over $g > 0$ and $2 \leq \gamma_m \leq 4$, which is typical for intra-cluster communication. Then using the convex optimization tools, the optimal average cluster-size is found as:

$$g^* = \arg\min_g \ L_c.$$

Base-station derives g^* and broadcasts it to the machine subscribers. In the simple decentralized scheme, each node which receives this g^* can decide to broadcast itself as CH with probability $1/g^*$. However, this scheme will show poor performance as it doesn't prevent low-energy nodes to be in CH mode. In the optimal centralized scheme, the BS performs CH selection in each cluster to maximize the FED lifetime of each cluster. Due to the massive number of nodes and clusters in the cell, the centralized scheme significantly increases the overhead for the BS, however, it provides insights to the sub-optimal distributed CH selection criteria. Then, we investigate the optimal CH selection scheme and utilize it to devise a distributed low-complexity CH selection scheme.

1) Centralized Cluster-head Selection Scheme: Define the set of machine nodes which are grouped in a given cluster as Ψ, and T_c as the duty cycle of the cluster which shows the average time between two uplink scheduling instances for the cluster-head. Then, the expected lifetime expression at time $t_0 + KT_c$ for direct uplink transmission of node j to the BS is written as follows:

$$L_{(j,i^*)}(t_0 + T_c) = \frac{[E_j(t_0) - KE_{(j,i^*)}^c]T_j}{E_s + D_j\frac{P_c+P_t^h}{R_h}} \tag{4}$$

where i^* is the selected CH at time t_0, KT_c is the average time between two CH re-selections, and $E_{(j,i^*)}^c$ is the energy consumption of node j in $(t_0, t_0 + T_c)$ time-period as follows:

$$E_{(j,i^*)}^c = \begin{cases} E_s + D_j\frac{T_c}{T_j}\frac{P_c+P_t^m}{R_m} & j \neq i^* \\ \\ E_s^h + \frac{\psi\tilde{D}P_l}{R_m} + \psi\tilde{D}\frac{P_c+P_t^h}{R_h} & j = i^* \end{cases} \tag{5}$$

where $\hat{D}$ is the average T_cD_i/T_i over cluster nodes, and ψ is the size of Ψ. Now, one can find the index of the optimal CH at time t_0, i.e. $i^*(t_0)$ as:

$$i^*(t_0) = \arg\max_i\left(\min_j L_{(j,i)}(t_0 + KT_c)\right),$$

which maximizes the minimum lifetime of all nodes in the cluster.

2) Distributed Cluster-forming Scheme: From the proposed centralized CH selection metric, one can see that the optimal CH selection is dependent on the remaining energy $E_i(t_0)$ and the transmission energy cost, i.e. average packet size D_i and duty cycle of packet generation T_i. Now, we are able to propose a low-complexity distributed cluster-forming scheme, as follows. Initially, the BS broadcasts the optimal cluster-size g^* to the machine nodes. Machine nodes decide to broadcast themselves as cluster-heads with probability $1/g^*$. Then, the initial sets of clusters will be formed and each node will calculate and send a lifetime factor as $f_i = [E_i(t_0)]^\mu\frac{D_i}{T_i}$ to

the respective CH, where μ is a design parameter. Then, each CH will calculate the average lifetime factor of its respective cluster as F and broadcast it to the respective CMs. In this stage, the network is ready to construct lifetime-aware clusters. To this end, each node decides for broadcasting itself as the CH with probability

$$p^* = \frac{1}{g^*} \frac{[E_i(t_0)]^\mu \frac{D_i}{T_i}}{F}.$$

Cluster-head re-selection: In regular time intervals or on demand, machine nodes will send their lifetime factor f_i as a side information to the respective CH. Then, the current CH will broadcast the updated F to the CMs and they will decide to be the new CH with the updated p^* probability.

IV. SCHEDULING AND POWER CONTROL FOR CHs AND UNCLUSTERED MACHINE NODES

Up to this section, the machine nodes are put into clusters and the CH for each cluster is selected. In this section, we try to investigate lifetime-aware scheduling and power control solutions for the data transmission of CHs and unclustered machine nodes to the BS in LTE networks. The air interface of the 3rd Generation Partnership Project (3GPP) LTE Release 10 is adopted [19]. Based on this standard, SC-FDMA is utilized as the access technique for the uplink transmission. The radio resources for uplink and downlink transmissions are distributed in both time and frequency domains. In the time domain, data transmission is structured in frames where each frame consists of 10 subframes and has 10 ms length. In the frequency domain, the available bandwidth is divided into a number of subcarriers each with 15 KHz bandwidth. Twelve of these subcarriers spanning over 0.5 ms are called a physical resource block [19]. The minimum allocatable resource element in a frame is a physical resource block pair (PRBP), which consists of 12 subcarriers (180 KHz) spanning over one transmission time interval (TTI). The open-loop uplink power control mechanism in LTE enables node i to determine its uplink transmit power by estimating the downlink pathloss, as follows [19]:

$$P_{t_i} = M_i P_0 (\alpha_i P_{loss}^i)(2^{\frac{k_s \text{TBS}(M_i, \delta_i)}{M_i N_s N_{sc}}} - 1) \quad (6)$$

where M_i is the number of assigned PRBPs, P_0 a user specific value due to the required SNR at the receiver, P_{loss}^i is the estimated downlink pathloss, α_i is the compensation factor, k_s is usually set to 1.25, N_s is the number of symbols in a PRBP, N_{sc} is the number of subcarriers in a PRBP. The transport block size (TBS) is found in Table 7.1.7.2.1-1 of [19] as a function of M_i and TBS index, δ_i. Based on the LTE specification in [19], the P_0 in dB is calculated as follows:

$$P_0 = \alpha_i(SNR_{target} + P_n) + (1 - \alpha_i P_{max}^i)$$

where $P_n = -209.26$ dB is the noise power in each resource block. Define the set and the number of machine devices which must be served at once as $\mathcal{L}$ and N respectively. For node i, the remaining energy at time t_0 is denoted by $E_i(t_0)$, the average time between two successive resource allocation to this node is denoted by T_i, the transmit power for reliable data

transmission by P_{t_i}, and the average size of the data packet is denoted by D_i. 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:

$$L_i = \frac{E_i(t_0)T_i}{E_s + TTI(P_c + P_{t_i})}. \quad (7)$$

where $TTI = 1 \ msec$ is the time granularity of resource blocks in LTE. Now, the uplink scheduling of machine nodes is written as an FED network-lifetime maximization problem, as follows:

$$\max \ \min_{i \in \mathcal{L}} \ L_i \quad (8)$$

$$\text{s.t:} \ D_i + D_{oh} \leq \text{TBS}(M_i, \delta_i) \quad \forall i \in \mathcal{L}; \quad (9)$$

$$\sum_{i=1}^{N} M_i \leq M_t \quad (10)$$

$$M_i P_0(\alpha_i P_{loss}^i)(2^{\frac{k_s \text{TBS}(M_i, \delta_i)}{M_i N_s N_{sc}}} - 1) \leq P_{max}^i \quad \forall i \in \mathcal{L} \quad (11)$$

$$\delta_i \in \{0, \cdots, 26\}; M_i \in \{1, \cdots, M_t\} \quad \forall i \in \mathcal{L} \quad (12)$$

$$M_i \leq \frac{D_i + D_{oh}}{16} \quad (13)$$

where M_t is the total available resource blocks, and D_{oh} is the overhead. Also, the constraint in (13) is due to the fact that the minimum number of TBS is 16 bits, which is achieved by inserting $M_i = 1$, $\delta_i = 0$ in Table 7.1.7.2.1-1 of [19]. The optimization problems in (8) with exact values for TBS cannot be solved by convex optimization. We solve these problems by proposing a two-step algorithm. To this end, for each choice of M_i, $\forall i \in \mathcal{L}$, we drive the optimal TBS index as a function of M_i, by looking at M_ith column of Table 7.1.7.2.1-1 in [19] to satisfy the constraint in (9).

The validity of PRBP allocation must be checked in this step by checking the constraint in (11). Then, we insert $\delta_i^*(M_i)$ in (6) and (7) to find the optimal transmit power, $P_{t_i}^*$, and machine lifetime, L_i^*, for each valid PRBP allocation. Now, we are able to calculate the objective function in optimization problem (8) under valid PRBP allocations and select the one which maximizes the objective function, as in Algorithm 1. In this algorithms, we denote each possible PRBP allocation as a 1-by-N vector as $\mathbf{B}$, where its ith element shows the number of assigned resource blocks to node i. Also, P_i^* shows the optimal transmit power for node i and vector $\mathbf{B}^*$ shows the optimal PRBP allocation. Algorithm 1 not only maximizes the shortest lifetime of machine nodes, but in each iteration it assigns optimal number of PRBPs to the most critical node and removes it from the set of nodes. Then in the next iterations, it tries to maximize the shortest lifetime of the remaining machine nodes. This algorithm is an extension of Algorithm 2 in our previous work [16] and the interested reader may refer to that work for discussion on complexity analysis and merits of this algorithm.

A. Low-complexity Scheduling Solution

However Algorithm 1 provide optimal solutions for lifetime-aware resource and power allocation, low-complexity sub-optimal solutions are always of interest. In this section, we

Algorithm 1: Solution to the optimization problem in (8).

1 Define the set of available machine nodes, $S_u = \mathcal{L}$, and the optimal PRBP allocation vector, $\mathbf{B}^* = \mathbf{0}_{1 \times N}$;

2 **while** $|S_u| > 0$ **do**

3   Find the set of possible PRBP allocation vectors, $\mathbf{B}_k$, under constraint in (17) and by considering the already assigned PRBPs in $\mathbf{B}^*$;

4   For each possible PRBP allocation, calculate δ_i^* from (9) and insert it in (11) to check its validity. Then, the set of valid PRBP allocations will be determined as $\mathbf{B}_k$, $\forall k \in \{1, \cdots, K\}$;

5   Calculate P_i^* and $\tilde{L}_i^*(t_0)$, $\forall i \in S_u$, using (7)-(6) for all valid PRBP allocations and denote them for kth possible PRBP allocation as P_i^{*k} and $\tilde{L}_i^{*k}(t_0)$;

6     $l = \arg \max_{k \in \{1, \cdots, K\}} \min_{i \in S_u} L_i^{*k}(t_0)$

7     $m = \arg \min_{S_u} L_i^{*l}(t_0)$. Using m, the index of the corresponding node in $\mathcal{L}$ is found as n;

8     $P_n^* = P_m^{*l}$;

9     $\mathbf{B}^*(n) = \mathbf{B}_l(m)$;

10   Remove node m from S_u;

11 **return** P_i^*, $\forall i \in \mathcal{L}$ and $\mathbf{B}^*$

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derive suboptimal solutions for optimization problems in (8) with much lower complexity. At first, we use linear relaxation to transform the discrete optimization problems in (8) to continuous optimization problems. Also, we use curve fitting and find an approximate expression for transport block size as a function of δ_i and M_i as follows:

$$\widetilde{\text{TBS}}(M_i, \delta_i) = M_i(0.68\delta_i^2 + 8.25\delta_i + 27.95). \quad (14)$$

Then, satisfying the constraint in (9) by equality yields:

$$\delta_i(M_i) = 0.73\sqrt{2.73\ (D_i + D_{oh})/M_i - 8.16} - 6.05 \quad (15)$$

One can see from the approximate expression in (14) that the minimum transport block size is 27.95, then the number of assigned PRBPs to user i must be less than $(D_i + D_{oh})/27.945$ and the derived $\delta_i(M_i)$ in (14) will be always non-negative. By inserting (15) in (14) and (6), the lifetime of node i is found as a function of M_i, where this function is convex and increases in M_i. Now, one can rewrite the optimization problems in (8) as follows:

$$\max \min_{i \in \mathcal{L}} L_i \quad (16)$$

$$\text{s.t:} \sum_{i=1}^{N} M_i \le M_t; \quad (17)$$

$$M_i P_0(\alpha_i P_{loss}^i)\left(2^{\frac{k_s \text{TBS}(M_i, \delta_i(M_i))}{M_i N_s N_{sc}}} - 1\right) \le P_{max}^i$$
$$\forall i \in \mathcal{L}; \quad (18)$$

$$M_i \le (D_i + D_{oh})/27.95 \quad \forall i \in \mathcal{L}. \quad (19)$$

The optimization problems in (16) is convex and can be solved with much lower complexity than Algorithm 1 using conventional convex optimization toolboxes. Solving these optimization problems, the suboptimal PRBP allocation vector will be determined. Then using Table 7.1.7.2.1-1 of [19] and

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TABLE I: Simulation Parameters

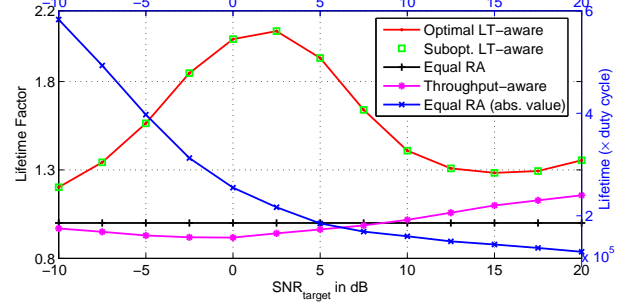| Parameter	Value
Cell radius	500 m
Packet size ($D_i + D_{oh}$)	40+35 Bytes [20]
Circuit power (P_c)	10 mW
α	0.9
E_s	250 μJoule
Full battery Capacity	2500 Joule

Fig. 1: FED Network lifetime evaluation for different scheduling schemes

the constraint in (11) the modulation and coding scheme and consequently, the transmit power will be determined.

V. PERFORMANCE EVALUATION AND DISCUSSION

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 networks [8]. The simulation model is based on the uplink of a single cell, multi-user 3GPP LTE network in which, 2.7 MHz bandwidth is allocated to the nth class of machine nodes in every T_n seconds (duty cycle). Then, 15 physical resource blocks are available, each having a bandwidth of 180 kHz. The number of nodes in class n is assumed to be 10 and the access is granted for all of them each T_n seconds. The other simulation parameters are presented in Table I. We compare the lifetime performance of the proposed protocols with the results of the following schemes: (i) equal resource allocation; and (ii) throughput-aware resource allocation in which machine nodes with better
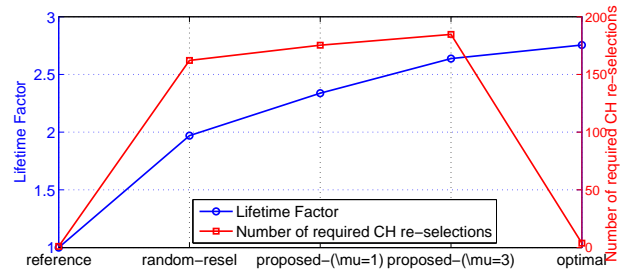

Fig. 2: Network lifetime evaluation for cluster-forming schemes

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 IV-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 the following figures we depict the absolute resulted network-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. 1 shows the FED lifetime performance of the proposed scheduling protocols versus different target SNR values at the base station. One can see that the optimal lifetime-aware scheduling significantly increases the lifetime of the network. Also, the achieved lifetime from low-complexity is in quite match with the results of the optimal solution. The throughput-aware scheme allocates more PRBPs to closer nodes to the BS which results in short lifetimes for far away nodes with high transmit power for pathloss compensation.

Furthermore, we developed another simulation to evaluate the lifetime performance under different cluster-forming schemes. We consider a cluster of 10 nodes with different remaining at the reference time and heterogeneous communication characteristics, i.e. packet length and duty cycle. Fig. 2 compares the FED lifetime for different cluster-forming schemes. In this figure, the x-axis represents the different cluster-forming schemes. The *reference* scheme, where the lifetimes of the other schemes are normalized to its lifetime and represented as lifetime-factor, refers to the random CH selection without CH re-selection. Also, the *random-resel*, *proposed-*(μ), and *optimal* schemes refer to the cluster-forming with random CH re-selection, the proposed protocol in section III-1, and the optimal protocol in section III-2 for CH re-selections, respectively. From the left y-axis of Fig. 2, one can see that the low-complexity distributed scheme, which was developed in section III-2, can provide close to optimal lifetime performance. In the left y-axis of Fig. 2, the average number of required CH re-selections within the network-lifetime is presented, where one can see an interesting tradeoff between optimal centralized and decentralized sub-optimal schemes. The optimal scheme, which performs the CH selection in the BS with global knowledge of the nodes, achieves the best performance, 330 duty cycles of operation, with only 3.7 CH re-selections. The proposed scheme with $\mu = 3$ achieves close to optimal lifetime performance, 268 duty cycles of operation, while it needs 185 CH re-selections.

VI. CONCLUSIONS

In this paper, the uplink scheduling and transmit power control are investigated to maximize the lifetime of battery-driven devices underlying cellular networks. To save energy and simplify the scheduling problem, we present a distributed clustering scheme which utilizes an accurate energy consumption model and forms clusters with the optimal cluster-size. Then by studying the resource allocation and power control strategies in LTE networks, lifetime-aware uplink scheduling

and power control solutions for maximizing the network lifetime are developed. The performance evaluation shows that the network lifetime is significantly extended using the proposed scheduling and power control schemes.

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