Interaction of Clustering Period and Event Sensing Reliability in IEEE 802.15.4 Based WSNs

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***Abstract*—In this paper we evaluate efficiency of our new clustering algorithm (ALEC) by modeling the network behavior during set-up and steady-state phases of the algorithm for CH and non-CH nodes. We investigate the effects of sensing reliability and clustering period on the network lifetime. We also analyze the power consumption and delay overheads of the clustering algorithm. According to the results, energy consumption and delay overheads of ALEC algorithm is very low and acceptable. The results also show that longer network lifetime can be achieved by higher values of clustering periods and lower values of sensing reliability.**

***Index Terms*—Adaptive Low-Energy Clustering, cluster-head election, Clustering overhead, IEEE 802.15.4, network lifetime, wireless sensor networks.**

I. Introduction

With rapid development of Low Rate-Wireless Personal Area Network (LR-WPAN) technology in the field of Wireless Sensor Network (WSN), ZigBee technology becomes one of the most popular technological inventions. ZigBee technology will act as an indispensable role in various fields such as industry, medical care, and intelligent home, by its unique features, including low power consumption, low rate, low cost and high efficiency, and high reliability [16]. It is infeasible to replace batteries of nodes due to the large number of nodes and possibly harsh terrain and hostile environment in which they are deployed. Therefore, the most important problem in these networks is to perform its operations in an efficient manner to prolong their lifetimes. To reduce the transmission overhead for the update of routing tables after topological changes, it was proposed to divide all nodes into clusters [4]. Clustering is the method by which sensor nodes in a network organize themselves into groups according to specific requirements or metrics. As shown in Fig. 1, each group or cluster has a leader node referred to as Cluster-Head (CH) and other ordinary member nodes. A CH node is responsible for conveying any information gathered by nodes in its cluster to BS. Clustering allows intra-cluster and inter-cluster routing which reduces the number of nodes taking part in a long distance communication, thus allowing significant energy saving in addition to smaller dissemination latency. Furthermore, dividing network into clusters reduces number of contending nodes and consequently lowers collisions made by nodes during medium access.

Since added responsibility results in a higher rate of energy drain at CHs, a reasonable solution for prohibiting CH nodes from early dying is to rotate cluster-head roles among nodes. However, cluster-head election and forming new clusters require some message exchanges between nodes. In the other words, periodically changing cluster-heads put some energy consumption overhead and delay on the network. To the best of our knowledge there is no analysis of integrated communication and cluster-head changing functions in wireless sensor network. Furthermore, we believe this paper serves as a useful starting point for the researchers who are interested in conducting research in evaluating clustering algorithms and their effects on network lifetime.

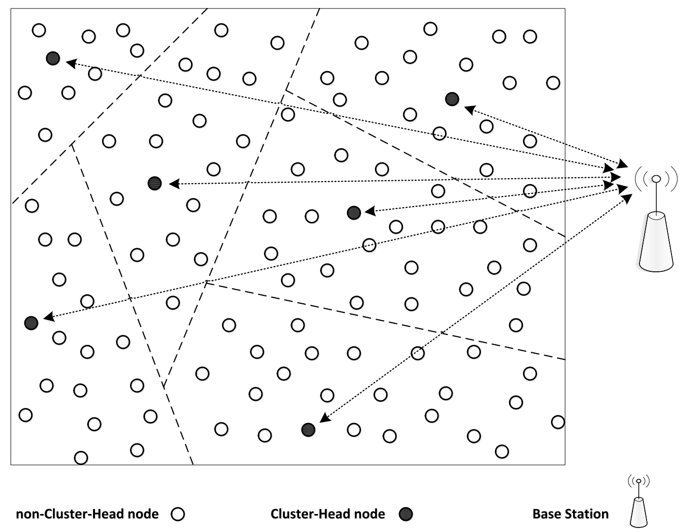

Fig. 1. Topology of the network for round i.

In this paper we present a detailed model of traffic caused by sensing and by clustering algorithm in the network. We also model the energy consumption of message exchanges associated with ALEC algorithm. We assume that individual sensor nodes are battery operated and their transceivers are modeled after the 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver [1]. The paper is organized as follows. Section III gives a brief overview of operation of 802.15.4-compliant networks with star topology, followed by a review of power management and power consumption parameters. An overview of ALEC algorithm is presented in section IV. Sections V and VI present derivation of analytical model for energy consumption for ALEC algorithm. Section VII presents numerical performance results. Finally, Section VIII concludes the paper.

II. Related work

A round of a clustering algorithm composed of two major phases: set-up phase and steady-state phase. Since sensor nodes have limited capabilities in terms of communication range, energy resource and processing power, the clustering algorithms should be compatible with these limitations in either set-up or steady-state phases. There are two major clustering approaches: distributed and centralized. In distributed approaches, the decisions for next CH elections are individually made by ordinary nodes or by CH nodes while in centralized algorithms, there is a central node in the network to elect CH nodes.

Distributed approaches usually consist of probabilistic methods. The selection of a CH node is based on evaluation of an expression composed of some parameters, e.g. round number, number of CHs or amount of energy. One of the most popular probabilistic schemes is Low-Energy Adaptive Clustering Hierarchy (LEACH) [7]. In LEACH, the randomization is used to distribute the energy consumption among all nodes in the network. There are some other distributed algorithms trying to improve threshold value of LEACH algorithm using some other parameters like energy consumption, amount of traffic, number of neighbors and density. Authors in [5] considered the ratio of the current energy level to the initial energy level of the node as a coefficient of the threshold value in LEACH algorithm. The nodes with higher level of remaining energy have more chance to be CHs in future rounds.

Selection of the nodes from denser areas leads to conserving more energy [15]. The algorithms in [2] and [3] consider the factor of number of neighbor nodes to select CHs and lowers the intra-cluster communication. However, detection of neighboring nodes imposes overhead to the network and delays clustering convergence time.

Although distributed algorithms have some advantages, but since a single node does not have a general knowledge of the entire network, distributed schemes cannot result in a good efficiency in clustering of the network. Having more energy resources and processing power makes BS a good choice for shifting the burden of CH selection and cluster formation phases. However, this requires the periodic communication with BS by sensor nodes to update the necessary information about current situation of the network.

There are some centralized methods based on LEACH scheme. In [8] the authors proposed LEACH-Centralized (LEACH-C) to improve placement and number of CHs in LEACH algorithm. The authors in [6] proposed a hybrid method in such a way that the selection of CHs is distributed while controlling the number of CHs is centralized.

Although re-clustering is proposed to increase network lifetime by evenly distributing the heavy load of CH roles among sensor nodes, re-clustering itself is an energy consuming procedure, which imposes extra transmission of control messages on the network [15]. Re-clustering also delays the real-time transmission of data during cluster set-up phases. In the following, the authors propose some solutions to reduce re-clustering overhead.

The paper, [11], proposes an idea that most nodes around the current CH have a high chance of belonging to the same cluster. Therefore, other added nodes should only be considered during exchange control packets. In another method [9], the authors considered a threshold for triggering re-clustering phase. In other words, only those CHs which have energy level below the threshold value participate in CH selection and other CHs will remain as CHs during following round.

III. 802.15.4 Operation and Power Management

All nodes in the network operate in beacon enabled, slotted CSMA-CA mode under the control of their respective cluster (PAN) coordinators. In each cluster, the channel time is divided into superframes bounded by beacon transmissions from the coordinator [10]. All communications in the cluster take place during the active portion of the superframe SD. The duration of the superframe is determined by SO variable according to following relation: $SD = 48 \times 2^{SO}$ unit backoff periods. If clusters operate in the ISM band at 2.4GHz, the duration of the unit backoff period is $320\mu s$ which results in the maximum data rate of 250kbps. In clusters operating in the ISM band at 2.4GHz, the duration of the unit backoff period is $320\mu s$ for a payload of 10 bytes, which results in the maximum data rate of 250kbps. The time interval between successive beacons is $BI = 48 \times 2^{BO}$, where BO can take a value according to following relation [14]: $0 \leq SO \leq BO \leq 15$. Data transfers in the uplink direction use CSMA-CA algorithm aligned to the backoff period boundary. Data transfers in the downlink direction use a more complex protocol in such a way that coordinator announces the presence of a packet, which must be explicitly requested by the target node before being actually sent [12].

Power management consists of adjusting the frequency and ratio of active and inactive periods of sensor nodes [18], [19]. Coordinator periodically broadcasts required event sensing reliability (number of packets per second needed for reliable event detection) and number of nodes which are alive. Based on the above information node can calculate average period of sleep between transmissions [14]. Energy consumptions per backoff period (10 bytes) for a node with a 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver [1] operating under typical conditions in the ISM band are $\omega_s = 18.2 \times 10^{-9}$J, $\omega_r = 17.9 \times 10^{-6}$J and $\omega_t = 15.8 \times 10^{-6}$J, during sleep, receiving and transmitting (at 0dBm), respectively.

IV. Adaptive Low-Energy Clustering (ALEC) algorithm

Here, we explain our new clustering algorithm (ALEC) in more details. As shown in Fig. 2, at the beginning of round r, each node i chooses a random number uniformly between 0 and 1, and compares it with a threshold T(i,r). If the random number is less than the threshold, the node becomes a cluster-head. The threshold is set as:

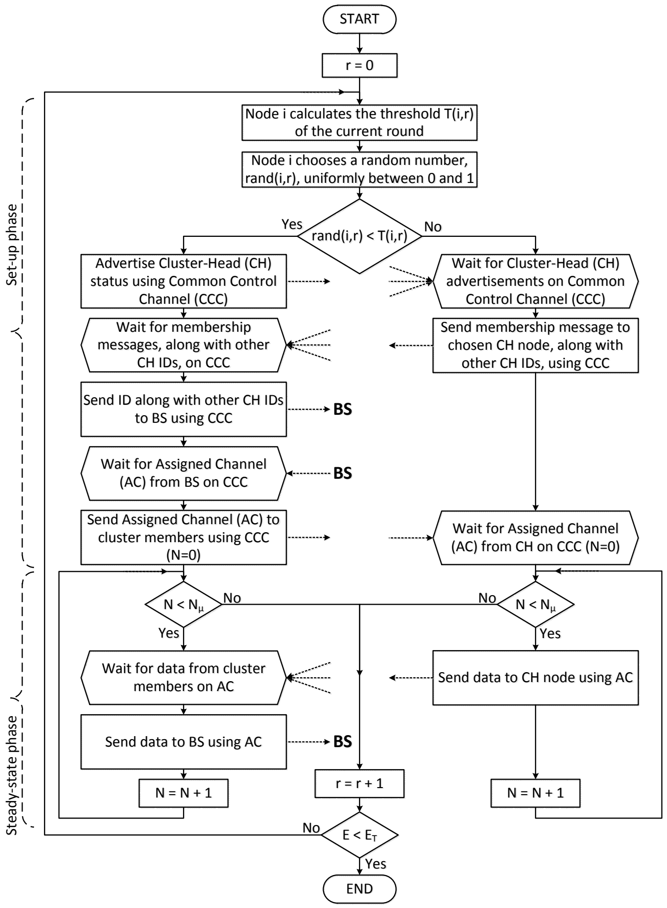

Fig. 2. flowchart of ALEC algorithm.

$$T(i,r) = \begin{cases} \frac{N_c}{N - N_c \times (r \mod \frac{N}{N_c})} \;, & i \in G \\ 0 \;, & otherwise \end{cases} \qquad (1)$$

Where N_c is desired number of cluster-heads, N is number of nodes and G is the set of nodes that have not been cluster-heads in most recent rounds ($r \mod \frac{N}{N_c}$).

If all clusters use the same frequency channel during steady-state phase, some of nodes in each cluster, especially those near the borders, can hear signals related to adjacent clusters. This means that for each cluster, there may be some interfering signals related to its neighbor clusters. Therefore, there may be some nodes in each cluster that cannot communicate with their CHs. Since the 802.15.4 standard uses 16 channels in the ISM band, interference between the clusters can be resolved by proper channel assignment to each cluster. In the other words, all CHs have to receive proper frequency channel from BS in set-up phases. Channel assignment can be carried out by BS using frequency planning concept from cellular networks [17] with channel reuse factors of $\frac{1}{7}$ or $\frac{1}{12}$. According to previous discussion, each set-up phase can be divided into five sub-phases as follows:

- Advertisement: After electing as a CH, new CH node starts broadcasting its status to other nodes.
- Membership: Each non-CH node determines to which cluster it wants to belong by choosing the CH that requires the minimum communication energy. The non-CH node transmits a join-request message along with all CH IDs it could hear during advertisement phase.
- Channel Request: All CHs have to inform BS about their neighbor clusters. Therefore, all CHs have to send their IDs along with other CH IDs they received in membership phase to BS.
- Channel Assignment: BS informs all CH nodes about their appropriate frequency channels.
- Channel Declaration: Each CH node informs all its members about new assigned channel.

For communication with each other during set-up phases, all nodes can only use an initially dedicated frequency channel known as Common Control Channel (CCC). Each steady-state phase is composed of a number of (N_μ) packet transmissions. We denote this parameter (N_μ) as $clustering\ period$. Cluster-head nodes are awake during the steady-state phases. However, non cluster-head nodes sleep between transmissions.

V. Modeling of Clustering

In order to model performance of the clustering we integrate power managed sensing function with clustering algorithm. All packet transmissions use slotted CSMA-CA determined by the standard [10]. A general Markov sub-chain for a single CSMA-CA transmission is shown in Fig. 3. The delay line from Fig. 3 models the requirement from the standard that a transmission has to be delayed to the beginning of the next superframe. This probability is denoted as $P_d = \overline{D_d}/SD$ where $\overline{D_d} = 2 + \overline{G_p} + 1 + \overline{G_a}$ denotes total packet transmission time including two clear channel assessments, transmission time $\overline{G_p}$, waiting time for the acknowledgement and acknowledgement transmission time $\overline{G_a}$. The block labeled T_r denotes $\overline{D_d}$ linearly connected backoff periods needed for actual transmission.

Synchronization time, i.e. the duration from the moment when node wakes up till the next beacon, is uniformly distributed between 0 and $BI-1$ backoff periods. Its Probability Generating Function (PGF) is $D(z) = \frac{1-z^{BI}}{BI(1-z)}$.

Probability that the packet will not be affected by noise is $\delta = 1 - PER = (1 - BER)^{\overline{G_p}+\overline{G_a}}$ where BER represents the Bit Error Rate of the medium.

We assume that the input probability to a transmission block is $\tau_0\gamma\delta$ where $\tau_0 = \sum_{i=0}^{m} x_{i,0,0}$ is medium access probability. We also assume that medium access control layer is reliable and that it will repeat transmission until the packet is acknowledged. Therefore, the probability of finishing the first backoff phase in transmission block is equal to $x_{0,2,0} = \tau_0\gamma\delta + \tau_0(1-\gamma\delta) = \tau_0$. Using the transition probabilities indicated in Fig. 3, we adopt the method in [13] and [12] and derive the relationships between different states and solve the Markov chain. The total access probability (τ) by a node in each round is equal to the sum of access probabilities

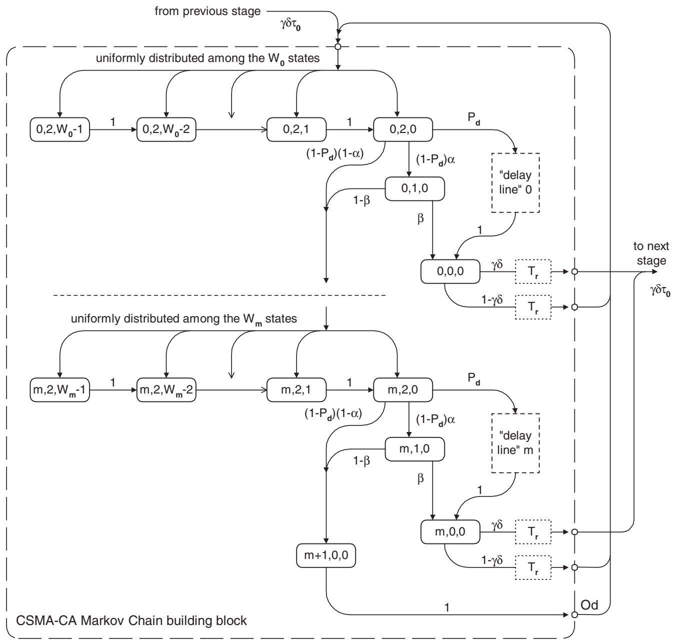

Fig. 3. General Markov sub-chain for a single CSMA-CA transmission [12].

in a round. Considering N_μ as clustering period, we have: $\tau = (6 + N_\mu)\tau_0$.

A. Modeling of sleep period

In order to model sleep period, we assume that sleep period is geometrically distributed with parameter P_{sleep}. We also consider buffer of a node as M/G/1/K queuing model with vacations. After waking up, if there are any packets in the node's buffer, the node transmits only one packet and goes to sleep again which is known as 1-limited service policy [20].

The PGF for one geometrically distributed sleep period is $V(z) = \sum_{k=1}^{\infty} (1 - P_{sleep}) P_{sleep}^{k-1} z^k = \frac{(1-P_{sleep})z}{1-P_{sleep}z}$. The average value of one sleep period is $\overline{V} = \frac{d}{dz}V(z)|_{z=1} = \frac{1}{1-P_{sleep}}$. If we assume arriving packets to each node follow the Poisson process with the rate λ, then the PGF of the number of packets arrive to the buffer during the sleep period of a node is equal to $F(z) = V^*(\lambda - \lambda z)$ where $V^*(s) = \frac{(1-P_{sleep})e^{-s}}{1-P_{sleep}e^{-s}}$ denotes the Laplace-Stieltjes transform (LST) of the sleep period which can be obtained by substituting the variable z with e^{-s}.

After waking up, if there is no packet in the buffer, the node starts immediately another sleep period. We are able to derive approximate value of successive sleep periods for small buffer sizes of 1-2 packets which is a reasonable assumption for sensor networks. Since the packet service period is much smaller than the sleep period, new sleep will be started only if there were zero packet arrivals during the current sleep period, i.e., with probability $F(0) = V^*(\lambda)$. Therefore, the PGF of duration of consecutive sleep periods is $I(z) = \frac{(1-V^*(\lambda))V(z)}{1-V^*(\lambda)V(z)}$ with the average value of $\overline{I} = \frac{1}{(1-P_{sleep})(1-V^*(\lambda))}$. In the following sections we determine relation between R and $\overline{I}$.

B. Success probabilities

Here we want to determine success probabilities; i.e. the probabilities that the medium is idle on first (α) and second CCA (β) and also the probability that the transmission is successful γ).

We focus on a single target node and model aggregate packet arrival rates of the remaining ($n_c - 1$) nodes as background traffic. This approximation is possible when event sensing reliability per cluster ($\frac{R}{N_c}$) is not high, i.e., when the cluster operates below the saturation regime. We estimate the arrival rate for background traffic as: $\lambda_c = (n_c - 1)\tau SD/8$.

The first CCA may fail because a packet transmission from another node is in progress; this particular backoff period may be at any position with respect to that packet. Thus $\alpha = \frac{1}{8}\sum_{i=1}^{7} e^{-i\lambda_c}$. Note that the first medium access will happen within the first 8 backoff periods of the superframe. The second CCA, however, will fail only if some other node has just started its transmission. Thus $\beta = e^{-\lambda_c}$. The probability of success of a transmission attempt is $\gamma = e^{-\lambda_c \overline{D_d}}$.

Access probability for CHs (bridges) can be modeled as $\tau_{bri} = n_c\tau$. The success probability for bridge transmissions depends on all other bridges, hence $\gamma_{bri} = (1-\tau_{bri})^{\overline{D_d}(N_c-1)}$.

VI. Node lifetime

If we assume that the length of a packet is k backoff periods, then the PGF of packet length is $G_p(z) = z^k$. The PGF of the time interval between the data and subsequent ACK packet is $t_{ack}(z) = z^2$. We also denote the PGF for packet transmission time and receipt of acknowledgement as $T_d(z) = G_p(z)t_{ack}(z)G_a(z)$. We can also determine the PGF for the time needed for one complete transmission attempt, including backoffs [12], as: $\mathcal{A}(z) = \frac{\sum_{i=0}^{m}\left(\prod_{j=0}^{i} B_j(z)\right)(1-\alpha\beta)^i z^{2(i+1)}(\alpha\beta T_d(z))}{\alpha\beta\sum_{i=0}^{m}(1-\alpha\beta)^i}$. The LST for the energy consumption during j-th backoff time prior to transmission is $E^*_{B_j}(s) = \frac{e^{-s\omega_r W_j}-1}{W_j(e^{-s\omega_r}-1)}$.

The LSTs for the energy consumption during pure packet transmission time, during two CCAs, and during wait and reception of the acknowledgment are respectively: $e^{-sk\omega_t}$, $e^{-s2\omega_r}$ and $e^{-s3\omega_r}$ [14]. The LST of energy consumption for receiving Beacon containing information about the number of live nodes and requested event sensing reliability is $e^{-s3\omega_r}$. Then, the LST for energy consumption during transmission time of the data packet and reception of acknowledgement will be denoted with $T^*_d(s) = e^{-sk\omega_t}e^{-s2\omega_r}e^{-s\omega_r}$. The LST for energy consumption for one transmission attempt becomes $\mathcal{E}^*_{\mathcal{A}}(s) = \frac{\sum_{i=0}^{m}\left(\prod_{j=0}^{i} E^*_{B_j}(s)\right)(1-\alpha\beta)^i e^{-s2\omega_r(i+1)}\alpha\beta T^*_d(s)}{\alpha\beta\sum_{i=0}^{m}(1-\alpha\beta)^i}$. By taking packet collisions into account [13], the PGF of probability distribution of the packet service time becomes $T(z) = \sum_{k=0}^{\infty}(\mathcal{A}(z)(1-\gamma\delta))^k\mathcal{A}(z)\gamma\delta = \frac{\gamma\delta\mathcal{A}(z)}{1-\mathcal{A}(z)+\gamma\delta\mathcal{A}(z)}$ and the LST for the energy spent on a packet service time is $E^*_T(s) = \frac{\gamma\delta\mathcal{E}^*_{\mathcal{A}}(s)}{1-\mathcal{E}^*_{\mathcal{A}}(s)+\gamma\delta\mathcal{E}^*_{\mathcal{A}}(s)}$. Average value of energy consumed for packet service is [13]: $\overline{E_T} = -\frac{d}{ds}E^*_T(s)|_{s=0}$.

CH nodes send packets during advertisement, channel request, uplink request for channel assignment and channel declaration sub-phases of a set-up phase and receive packets during membership and downlink data for channel assignment sub-phases of a set-up phase. There also are four synchronization times during a set-up phase, i.e. synchronization for advertisement, membership, channel request and uplink request for channel assignment. Non-CH nodes only send packets during membership sub-phase and they are in receiving mode during other sub-phases. According to above discussion, average energy consumption during one set-up phase for a CH node is $\overline{E_{su,CH}} = 4\overline{E_T} + 2\overline{T}\omega_r + 4(\overline{D} + 3)$, and for a non-CH node is $\overline{E_{su,nCH}} = \overline{E_T} + 5\overline{T}\omega_r + 4(\overline{D} + 3)$. If we assume $\omega_r \approx \omega_t$, then we have $\overline{E_{su,CH}} \approx \overline{E_{su,nCH}}$.

For non-CH nodes, each steady-state phase is composed of a number (N_μ) of microcycles which is composed of three steps: sleep, beacon synchronization and data transmission (CSMA uplink). However, during one round all CH nodes are awake. Average energy consumption for CH nodes during one microcycle is $\overline{E_{mi,CH}} = (\overline{D} + 3 + \overline{I} + \overline{T})\omega_r$, and for non-CH nodes is $\overline{E_{mi,nCH}} = \overline{D}\omega_r + 3\omega_r + \overline{I}\omega_s + \overline{T}\omega_r$. Average energy consumption during one round for CH nodes is $\overline{E_{rd,CH}} = \overline{E_{su,CH}} + N_\mu \overline{E_{mi,CH}}$, and for non-CH nodes is $\overline{E_{rd,nCH}} = \overline{E_{su,nCH}} + N_\mu \overline{E_{mi,nCH}}$.

A macrocycle composed of n_c rounds. Each node has to be CH only once during a macrocycle. Therefore, the energy consumed during one macrocycle is $\overline{E_{ma}} = \overline{E_{rd,CH}} + (n_c - 1)\overline{E_{rd,nCH}}$. If the battery budget is E_{bat} Joules, the average number of macrocycles during lifetime of a node is $\frac{E_{bat}}{E_{ma}}$. Therefore, lifetime of the network is $\overline{L} = \overline{T_{ma}} \times \frac{E_{bat}}{E_{ma}}$ where $\overline{T_{ma}}$ is duration of a macrocycle in backoff periods.

VII. Performance evaluation

In this section we present numerical results obtained by solving the system of equations presented in sections V and VI and obtain system parameters τ_0, τ, α, β, γ and P_{sleep}. There are 400 nodes in the network. We assumed that each node is powered with two AA batteries which supply voltage between 2.1 and 3.6 V and 1000 mA h with total energy $E_{bat} = 10260J$. We have assumed that the network operates in the ISM band at 2.45 GHz, with raw data rate 250 kbps and $BER = 10^{-4}$. Superframe size is controlled with $SO = 0$ and $BO = 1$; i.e. SD=48 and BI=96 backoff periods. The packet size has been set to $\overline{G_p} = 12$ backoff periods, while the device buffer has a constant size of L=2 packets.

We want to investigate the performance of the ALEC algorithm according to sensing reliability (R) and number of microcycles (N_μ). Number of microcycles (clustering period) is determined by the algorithm, while sensing reliability is determined by user of data. In Fig. 4 number of clusters is 16. Thus the number of nodes in each cluster is $n_c = \frac{N}{N_c} = 25$. Sensing reliability is variable in the range 10 to 50 packets per second in steps of 10. Number of microcycles is variable in the range 100 to 1000 in steps of 200. While sensing reliability for each node is $r = \frac{R}{N}$, average duration of a microcycle is $\overline{T_{mi}} = \overline{I} + \overline{D} + 3 + \overline{T}$ which is equal to $\frac{1}{r}$.

According to figures 4(a) and 4(b), we can compare energy consumptions of CH and non-CH nodes. As can be seen in these figures, energy consumption will increase if we increase clustering period or decrease sensing reliability. In Fig. 4(c), power consumption of a node during all set-up phases is shown. Energy consumption during set-up phases is the overhead of the algorithm because the nodes contribute this amount of energy to the network to create new clusters and the nodes cannot send data to BS during set-up phases. Higher values of N_μ (800 or larger) should be used to reduce set-up phase overhead and extend network lifetime. We can get the same results from Fig. 4(d) because lower values of power consumption per second means longer network lifetimes. As can be seen in figures 4(e) and 4(f), higher values of N_μ result in lower number of macrocyles during lifetime of the network because this makes clustering overhead minimum. Therefore, for a specified value of sensing reliability, longest lifetimes can be achieved by making duration of one macrocycle equal to network lifetime; i.e. number of macrocycles during lifetime of the network should be near one. Considering the number of nodes is 400 and number of clusters is 16, then a macrocycle is $\frac{400}{16} = 25$ rounds. According to above discussion, longer lifetimes can be achieved if lifetime consists of 25 rounds (one macrocycle).

VIII. Conclusion

In this paper, we consider our new Adaptive Low-Energy Clustering (ALEC) algorithm operating with IEEE 802.15.4 beacon enabled mode. We evaluate the impact of clustering period and event sensing reliability on the network lifetime. According to ALEC, rotating the role of CHs and forming new clusters require message exchanges between nodes and impose power consumption and delay overheads on the network. The results show that overheads of ALEC algorithm are very low and acceptable. Longer network lifetimes can be reached by choosing higher values of clustering periods and lower values of sensing reliability. Our method can also be easily scaled to any other clustering algorithms.

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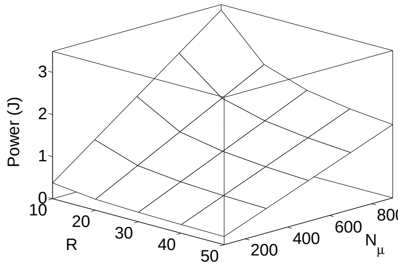
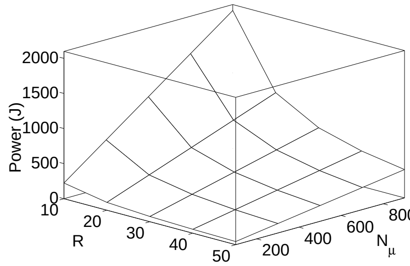
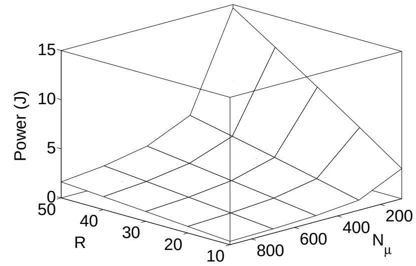


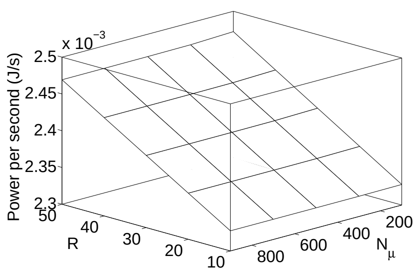
(a) Power consumption (in Joules) during steady-state phase of a non-CH node according to different values of sensing reliability (R) and number of microcycles (N_μ).



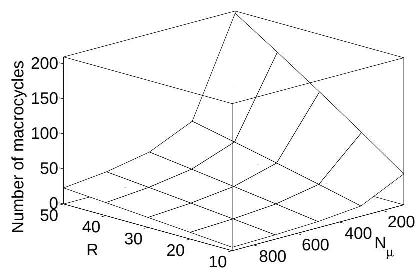
(b) Power consumption (in Joules) of a CH node during one round according to different values of sensing reliability (R) and number of microcycles (N_μ).



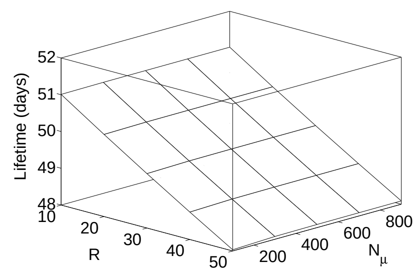
(c) Total power consumption (in Joules) of a node during total set-up phases of the protocol according to different values of sensing reliability (R) and number of microcycles (N_μ).



(d) Power consumption per second of a node according to different values of sensing reliability (R) and number of microcycles (N_μ).



(e) Number of macrocycles during lifetime of a node according to different values of sensing reliability (R) and number of microcycles (N_μ).



(f) Lifetime of a node (in days) according to different values of sensing reliability (R) and number of microcycles (N_μ).

Fig. 4. Lifetime and Power consumptions of a node operating according to ALEC algorithm.

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