Lifetime Properties in Cluster-Based IEEE 802.15.4 WSNs

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***Abstract*—In this paper we discuss probabilistic node lifetime properties under our new clustering algorithm. We investigate the effects of event sensing reliability and number of clusters on the network lifetime. Our model compares effects of physical layer and MAC layer through bit error rate and packet collision probability. In our analysis, closed-form expressions are obtained for the probability generating functions of different intervals of the algorithm, from which other relevant statistics, such as mean, coefficient of variation and skewness, can be derived. The results show that higher values of mean lifetime can be achieved by either lower values of sensing reliability or lower values of number of clusters. Our results confirm that all nodes will die almost at the same time.**

***Index Terms*—Adaptive Low-Energy Clustering, cluster-head election, IEEE 802.15.4, sensing reliability, coefficient of variation, skewness, network lifetime, wireless sensor networks.**

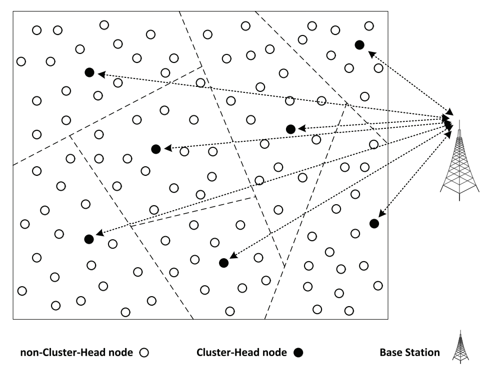


Fig. 1. Topology of the network for round i.

I. Introduction

Recently rapid development of Low Rate-Wireless Personal Area Network (LR-WPAN) technology in the field of Wireless Sensor Network (WSN) makes ZigBee technology one of the most popular technologies [11]. Replacing batteries of nodes is infeasible because of the large number of nodes and possibly harsh terrain 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. One of the most famous methods for reducing energy consumption in a network is clustering. According to clustering, sensor nodes in a network divided into groups based on specific requirements or metrics. As shown in Fig. 1, in each group or cluster a sensor node is chosen as a leader referred to as Cluster-Head (CH). A CH node is responsible for conveying any information gathered by nodes in its cluster.

Since added responsibility results in a higher rate of depleting energy at CHs, an effective solution for prohibiting CH nodes from early dying is to rotate cluster-head roles among nodes.

There are two major clustering approaches: distributed and centralized. In distributed approaches, the decisions for next CH elections are individually made by ordinary nodes while in centralized algorithms, there is a central node in the network that is responsible of electing new CH nodes.

Distributed approaches usually consist of probabilistic methods in which selections of CH nodes are based on evaluation of expressions like energy consumption [4], amount of traffic, number of neighbors [2] and density of sensor nodes [10].

In this paper we evaluate node lifetime for Adaptive Low-Energy Clustering (ALEC) algorithm. ALEC changes cluster-heads based on the number of packets transmitted in the cluster. ALEC is based on IEEE 802.15.4 MAC and physical layer.

Lacking general knowledge of the entire network by a single node results in poor clustering efficiency. Having more energy resources and more processing power makes BS a good choice for shifting the burden of CH selection and cluster formation phases. In centralized clustering approaches, selection of future CHs is decided by a node. However, these approaches require the periodic communication between BS and sensor nodes to update the necessary information about current situation of the network [5].

Although distributed algorithms have some advantages from energy consumption overhead and delay overhead viewpoints, there is randomness with respect to lifetime of node. Given the impact of bit error rate and packet collisions, time to reliability transmit single packet is random variable which results in randomness in time between two consecutive elections of cluster-heads and also in time between two consecutive elections of the same node as cluster-head.

In this paper, we evaluate lifetime of a node and its estimation considering all above effects. 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 II gives a brief overview of operation of 802.15.4-compliant networks with star topology, followed by a review of power consumption parameters. An overview of ALEC algorithm is presented in section III. Sections IV and V present derivation of analytical model for energy consumption of ALEC algorithm. Section VI presents numerical performance results. Finally, Section VII concludes the paper.

II. 802.15.4 Operation and Power Management

In each cluster, the channel time is divided into superframes bounded by beacons transmitted by coordinators [6]. All communications in clusters take place during active portions of their superframes SDs. The duration of the superframe is determined by SO variable according to following relation: $SD = 48 \times 2^{SO}$ unit backoff periods [9]. If clusters operate in the ISM band at 2.4GHz, the duration of unit backoff period is $0.32 \times 10^{-3} s$ which results in maximum data rate of 0.25Mbps. 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 [7].

Power management consists of adjusting the frequency and ratio of active and inactive periods of sensor nodes [13], [14]. Every node should compute average duration of sleep between transmissions Based on the information received from its coordinator [9]. Energy consumptions 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 during a backoff period, i.e. 10 bytes, are $\omega_s = 18.2nJ$, $\omega_r = 17.9\mu J$ and $\omega_t = 15.8\mu J$, for sleep, receiving and transmitting (at 0dBm), respectively.

III. Adaptive Low-Energy Clustering algorithm

Here, we explain our new clustering algorithm (ALEC) in more details. As shown in Fig. 2, in the beginning of round r, a random number is chosen uniformly between 0 and 1 by node i, and compared 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:

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

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 $r \mod \frac{N}{N_c}$ previous rounds.

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 transmissions related to adjacent clusters. Therefore, there may be some nodes in each cluster that cannot communicate with their own CHs. Since 802.15.4 standard uses 16 channels in the ISM band, interference between 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

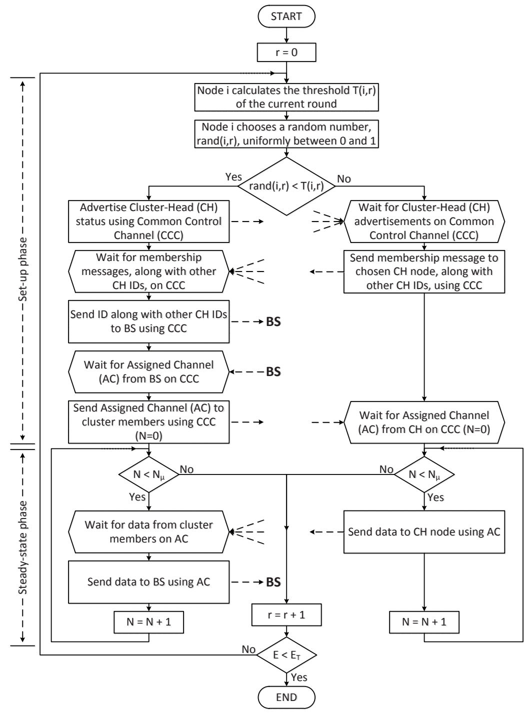


Fig. 2. flowchart of ALEC algorithm.

concept from cellular networks [12] 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 composing of all IDs related to other CHs that 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 IDs they received in membership phase to BS.
- Channel Assignment: During this sub-phase, appropriate frequency channels are sent by BS to all CH nodes.
- 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 steady-state phases. However, non cluster-head nodes sleep between transmissions.

IV. Modeling of Clustering

In order to model performance of the clustering, we integrate power managed sensing function with clustering al-

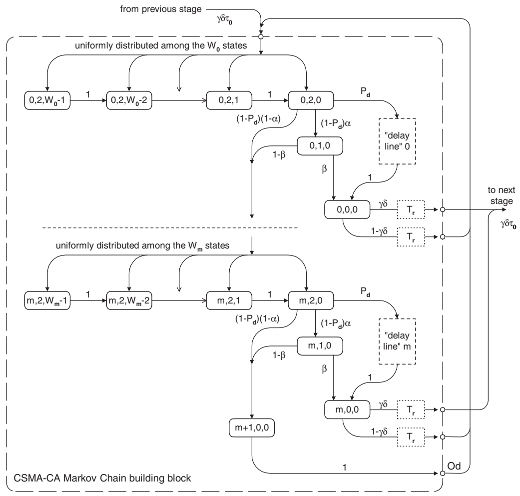


Fig. 3. Markov sub-chain for one CSMA-CA transmission [7].

gorithm. Both uplink and downlink packet transmissions use slotted CSMA-CA determined by the standard [6]. A general Markov sub-chain for a single CSMA-CA transmission is shown in Fig. 3. 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 $P_d = \frac{\overline{D}_d}{SD}$ where $\overline{D}_d = 2 + \overline{G}_p + 1 + \overline{G}_a$ denotes average 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 $D(z) = \frac{1-z^{BI}}{BI(1-z)}$.

Assuming that PER represents the Packet Error Rate, the 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.

As shown in Fig. 3, 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. Considering that medium access control layer is reliable, i.e. it will repeat transmission until the packet is acknowledged, 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 transition probabilities indicated in Fig. 3, we adopt the method in [8] and [7] and derive the relationships between different states and solve the Markov chain. Total access probability (τ) by a node in each round is equal to the sum of access probabilities in a set-up phase and in a steady-state phase.

A. Modeling of inactive time

In order to model inactive time, we assume that sleep period is geometrically distributed with parameter P_{sleep}. The PGF for one sleep period is $V(z) = \sum_{k=1}^{\infty}(1-P_{sleep})P_{sleep}^{k-1}z^k$ which has the following average value $\frac{1}{1-P_{sleep}}$.

We assume arriving packets to each node follow the Poisson process with the rate λ. Therefore, the PGF of the number of packets arrive to the buffer during a sleep period of a node is equal to $F(z) = V^*(\lambda - \lambda z)$ where $V^*()$ is LST of the sleep period.

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 and if there is no packet in the buffer, the node starts immediately another sleep period. This policy is known as 1-limited service policy [15]. 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 consecutive sleep time 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).

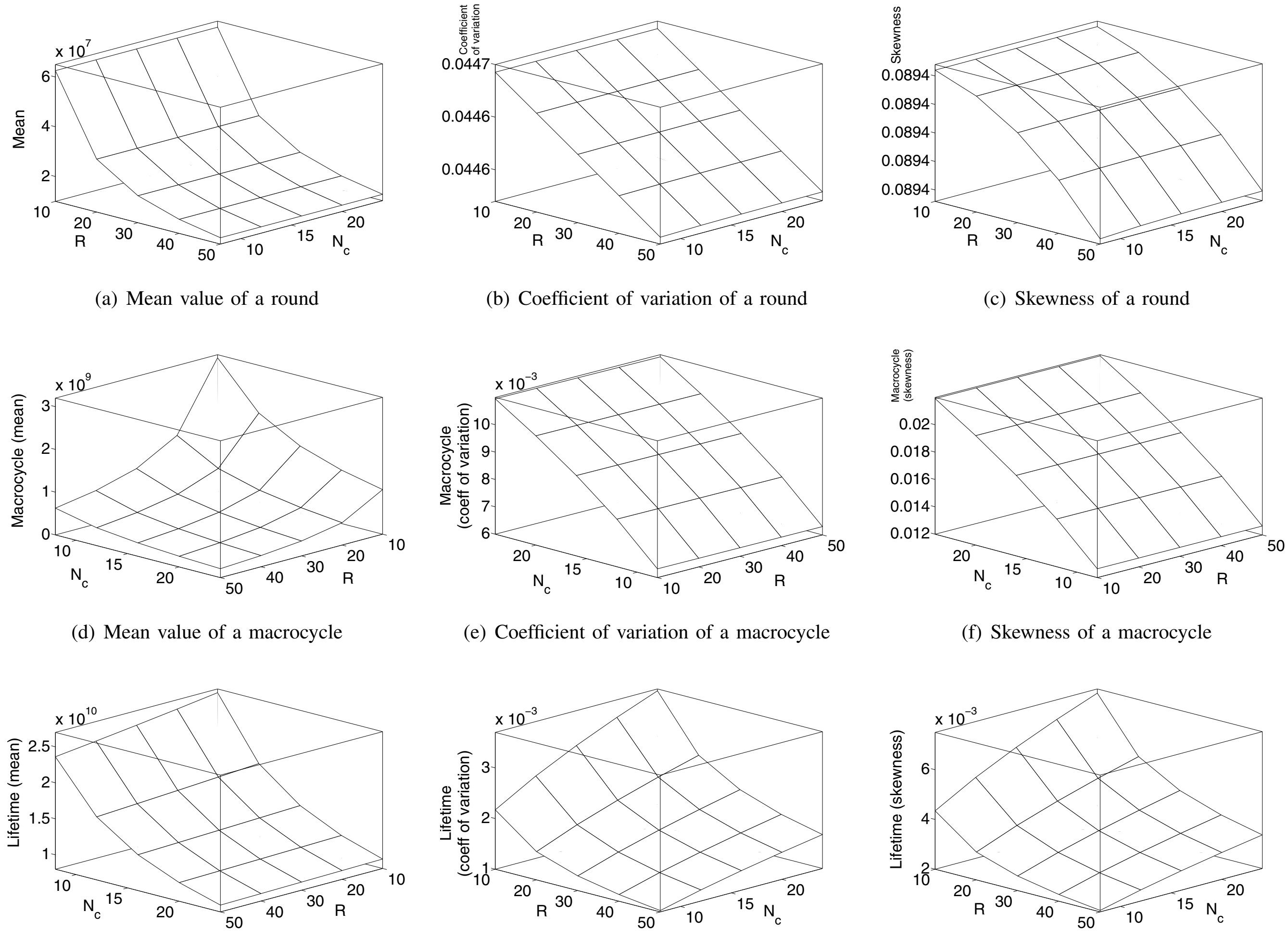
We focus on a single target node and model aggregate packet arrival rates of the remaining $(n_c - 1)$ nodes as background traffic. This approximation is possible when event sensing reliability per cluster ($\frac{R}{N_c}$) is not high, i.e., when the cluster operates below the saturation regime. We 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 $\gamma = \beta^{\overline{D}_d}$.

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 $\gamma_{bri} = (1-\tau_{bri})^{\overline{D}_d(N_c-1)}$.

V. Analyzing Lifetime of a Node

Assuming length of a packet is k backoff periods, 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 [7], as: $\mathcal{A}(z) = \frac{\sum_{i=0}^{m}\left(\prod_{j=0}^{i} B_j(z)\right)(1-\alpha\beta)^i z^{2(i+1)}(\alpha\beta T_d(z))}{\alpha\beta\sum_{i=0}^{m}(1-\alpha\beta)^i}$ in which $B_j(z)$ is the PGF for duration of j-th backoff time prior to transmission and is equal to $B_j(z) = \frac{z^{W_j}-1}{W_j(z-1)}$.



(a) Mean value of a round (b) Coefficient of variation of a round (c) Skewness of a round

(d) Mean value of a macrocycle (e) Coefficient of variation of a macrocycle (f) Skewness of a macrocycle

(g) Mean value of lifetime (h) Coefficient of variation of lifetime (i) Skewness of lifetime

Fig. 4. Mean value, Coefficient of variation and Skewness of different intervals of the algorithm according to different values of sensing reliability (R) and number of clusters (N_c).

The LSTs for energy consumption during pure packet transmission time, two CCAs and wait and reception of the acknowledgment are respectively $e^{-sk\omega_t}$, $e^{-s2\omega_r}$ and $e^{-s3\omega_r}$ [9]. The LST of energy consumption for receiving beacon containing information about the number of alive nodes and requested event sensing reliability is $e^{-s3\omega_r}$. The LST for energy consumption for one transmission attempt is $\mathcal{E}^*_{\mathcal{A}}(s) = \frac{\sum_{i=0}^{m}\left(\prod_{j=0}^{i} E^*_{B_j}(s)\right)(1-\alpha\beta)^i e^{-s2\omega_r(i+1)}\alpha\beta T^*_d(s)}{\alpha\beta\sum_{i=0}^{m}(1-\alpha\beta)^i}$. By taking packet collisions into account [8], 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 $E^*_T(s) = \frac{\gamma\delta\mathcal{E}^*_{\mathcal{A}}(s)}{1-\mathcal{E}^*_{\mathcal{A}}(s)+\gamma\delta\mathcal{E}^*_{\mathcal{A}}(s)}$.

According to above discussion, the PGF of duration of one set-up phase is $T_s(z) = T(z)^6$ and LST of energy consumption during one set-up phase for a CH node is $E^*_{s,C}(s) = E^*_T(s)^4 T(e^{-s\omega_r})^2$ and for a non-CH node is $E^*_{s,nC}(s) = E^*_T(s)T(e^{-s\omega_r})^5$.

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, all CH nodes are awake during a round. Average energy consumption for CH nodes during a microcycle is $E^*_{m,C}(s) = D(e^{-s\omega_r})e^{-s3\omega_r}I(e^{-s\omega_r})T(e^{-s\omega_r})$, and for non-CH nodes is $E^*_{m,nC}(s) = D(e^{-s\omega_r})e^{-s3\omega_r}I(e^{-s\omega_s})T(e^{-s\omega_r})$. The LST for energy consumption during one round for CH nodes is $E^*_{r,C}(s) = E^*_{s,C}(s)(E^*_{m,C}(s))^{N_\mu}$, and for non-CH nodes is $E^*_{r,nC}(s) = E^*_{s,nC}(s)(E^*_{m,nC}(s))^{N_\mu}$.

A macrocycle is composed of n_c rounds. Each node has to be CH only for one round during a macrocycle. Therefore, the LST for energy consumed during one macrocycle is $E^*_M(s) = E^*_{r,C}(s)(E^*_{r,nC}(s))^{n_c-1}$ with the average value of $\overline{E}_M$. If the battery budget is E_{bat} Joules, the average number of macrocycles during lifetime of a node is $\frac{E_{bat}}{\overline{E}_M}$. Therefore, lifetime of the network is $\overline{L} = \overline{T}_M \times \frac{E_{bat}}{\overline{E}_M}$ where $\overline{T}_M$ is average duration of a macrocycle.

Assuming $F^*(s)$ is LST of a random variable, the mean value of the random variable is $\mu = -\frac{d}{ds}F^*(s)|_{s=0}$, Coefficient of variation is $CV = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{d^2}{ds^2}F^*(s)|_{s=0} - \mu^2}}{\mu}$ and skewness is $\gamma = \frac{-\frac{d^3}{ds^3}F^*(s)|_{s=0} - 3\mu\sigma^2 - \mu^3}{\sigma^3}$.

VI. Performance evaluation

Number of nodes in the network is 400. We assumed that each node is powered with two AA batteries which supply voltage between 2.1 and 3.6 V with total energy $E_{bat} = 2 \times 5130J = 10260J$. We have assumed that $BER = 10^{-4}$ and network operates in the ISM band at 2.4 GHz, with raw data rate 0.25Mbps. Superframe size (SD) and beacon interval (BI) are respectively adjusted at 48 and 96 backoff periods.

According to expressions for δ and γ, increasing length of packet results in decreasing δ and γ which means more retransmissions and consequently consuming more energy. In order to consider the worst case, the longest packet size according to IEEE 802.15.4 standard is considered (k=12). We also assume that each node has a buffer size of 2 packets.

We want to investigate the performance of the ALEC algorithm according to event sensing reliability (R), i.e. number of packets per second needed for reliable event detection, and number of clusters (N_c). R and N_c are set by application and cannot be changed by network administrator. In Fig. 4 number of microcycles during a steady-state phase is constant at 500 ($N_\mu = 500$). Number of clusters is variable in the range 8 to 24 in steps of 4. Event sensing reliability (R) is variable in the range 10 to 50 packets per second in steps of 10. This means that number of packets should be sent during a second by a node ($r = \frac{R}{N}$) is variable in the range 0.025 to 0.125. Therefore, average duration of a microcycle can be determined as $\overline{T}_m = \frac{1}{r} = \overline{I} + \overline{D} + 3 + \overline{T}$.

According to Fig. 4(a), a round has a higher mean value when sensing reliability has a lower value around 10 packets per second. Since a macrocycle is sum of a number of (n_c) independent and identically distributed (i.i.d.) random variables representing duration of rounds, the mean of a macrocycle (Fig. 4(d)) is sum of averages of rounds. The lifetime of the network (Fig. 4(g)) is also sum of a number of i.i.d. random variables representing duration of macrocycles. The coefficient of variation of a round is shown in Fig. 4(b). As can be seen, for values of sensing reliability close to 50, we have lower values of coefficient of variation and this means lower dispersion around mean value. Since coefficient of variation of sum of a number of i.i.d. random variables is less than coefficient of variation of each random variable with increasing number of random variables, the dispersion around mean value decreases. Since lifetime is composed of macrocycles, we have the same discussion for coefficient of variation of lifetime. For values of sensing reliability around 50 and values of number of clusters around 8, there is lower dispersion around mean value. With increasing number of clusters, the number of rounds in a macrocycle decreases and this results in higher values of coefficient of variation and more dispersion around mean value. Skewness of a round is shown in Fig. 4(c). As can be seen in Fig. 4(f), skewness of a macrocycle is less than skewness of a round. According to central limit theorem [3], sum of a number of i.i.d. random variables converges to a normal distribution which has zero skewness. Since lifetime is composed of a number of macrocycles, the skewness of lifetime (Fig. 4(i)) is lower than skewness of a macrocycle.

VII. 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 event sensing reliability and number of clusters on the network lifetime. In our analysis, statistical measures such as mean, coefficient of variation and skewness are obtained. We consider the strongest effects of packet collisions and noise on the lifetime. The results show that higher values of mean can be achieved by either lower values of sensing reliability or lower values of number of clusters; while lower values of coefficient of variation and skewness can be achieved by either higher values of sensing reliability or lower values of number of clusters.

References

[1] Chipcon CC2420 Datasheet: 2.4 GHz IEEE 802.15.4 / ZigBee-Ready RF Transceiver (Rev. B), 2012.

[2] X. Bian, X. Liu, and H. Cho. Study on a cluster-chain routing protocol in wireless sensor networks. In *Communications and Networking in China, 2008. ChinaCom 2008. Third International Conference on*, pages 964–968, Aug. 2008.

[3] G. R. Grimmett and D. R. Stirzaker. *Probability and Random Processes*. Clarendon Press, Oxford, second edition, 1992.

[4] M. Handy, M. Haase, and D. Timmermann. Low energy adaptive clustering hierarchy with deterministic cluster-head selection. In *Mobile and Wireless Communications Network, 2002. 4th International Workshop on*, pages 368–372, 2002.

[5] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. An application-specific protocol architecture for wireless microsensor networks. *Wireless Communications, IEEE Transactions on*, 1(4):660–670, Oct. 2002.

[6] IEEE. Wireless MAC and PHY specifications for low rate WPAN. IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003), IEEE, New York, NY, 2006.

[7] J. Mišić. Traffic and energy consumption of an IEEE 802.15.4 network in the presence of authenticated, ECC Diffie-Hellman ephemeral key exchange. *Computer Networks*, 52(11):2227–2236, 2008.

[8] J. Mišić. Cost of secure sensing in IEEE 802.15.4 networks. *Wireless Communications, IEEE Transactions on*, 8(5):2494–2504, may 2009.

[9] J. Mišić and V. Mišić. *Wireless Personal Area Networks Performance, Interconnections and Security with IEEE 802.15.4*. Wiley Publishing, Inc., first edition, 2008.

[10] S. Naeimi, H. Ghafghazi, C.-O. Chow, and H. Ishii. A Survey on the Taxonomy of Cluster-Based Routing Protocols for Homogeneous Wireless Sensor Networks. *Sensors*, 12(6):7350–7409, 2012.

[11] Z. Qian, C. Cheng, X. Zhang, Y. Wang, and I. Stojmenovic. Cluster Label-Based Routing Strategy for Saving Energy in ZigBee Mesh Network. In *Recent Advances in Computer Science and Information Engineering*, volume 127 of *Lecture Notes in Electrical Engineering*, pages 339–345. Springer Berlin Heidelberg, 2012.

[12] T. Rappaport. *Wireless communications: Principles & Paractice*. Prentice Hall, Upper Saddle River, NJ 07458, 1996.

[13] Y. Sankarasubramaniam, Ö. B. Akan, and I. F. Akyildiz. ESRT: event-to-sink reliable transport in wireless sensor networks. In *Proc. 4th ACM MobiHoc*, pages 177–188, Annapolis, MD, June 2003.

[14] I. Stojmenović, editor. *Handbook of Sensor Networks: Algorithms and Architectures*. John Wiley & Sons, 2005.

[15] H. Takagi. *Queueing Analysis*, volume 1: Vacation and Priority Systems. North-Holland, Amsterdam, The Netherlands, 1991.