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# Evaluation of Single Dimensional Sensor Network Implemented Using Slave-Slave Bridging in IEEE 802.15.4 Technology

Hamidreza Tavakoli[1], Jelena Mišić[2], Majid Naderi[1] and Vojislav B. Mišić[2]

[1]*Department of Electrical Engineering, Iran University of Science and Technology, Tehran, Iran 16846*
*E-mail: tavakoli@iust.ac.ir, m_naderi@iust.ac.ir*
[2]*Department of Computer Science, Ryerson University, Toronto ON, Canada M5B 2K3*
*E-mail: jmisic@scs.ryerson.ca, vmisic@scs.ryerson.ca*

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In this paper, we analyze CSMA-CA access for interconnection of IEEE 802.15.4 beacon enabled network clusters using ordinary network nodes as bridge nodes. Bridge design involves uplink transmission to the coordinator and downlink transmission to the bridge. Bridge periodically visits upper and lower clusters and exchanges data using CSMA-CA access. We develop the queuing model for bridging algorithm and present numerically obtained performance results. The effects of different parameters of the bridging algorithm, i.e. event sensing reliability, number of clusters and bridging period, are investigated. Our analysis shows how parameters of clustering algorithm should be tuned in order to prolong the lifetime. Our results demonstrate fair distribution of lifetime of nodes which means that all nodes of a cluster will deplete their energy within short window of time.

*Keywords:* IEEE 802.15.4 beacon-enabled mode, slave-slave Bridge, sensing reliability, coefficient of variation, skewness, network lifetime, wireless sensor networks.

## 1 INTRODUCTION

Wireless Sensor Networks (WSNs) will act as an indispensable role in various fields such as industry, medical care, and intelligent home, by their unique features, including low power consumption, low rate, low cost and high efficiency [8,15,16]. IEEE 802.15.4 is a widespread technology for low data rate wireless personal area networks and supports small, cheap, energy-efficient devices operating on battery power that require little infrastructure to operate [2, 1] which makes it as an enabling technology for wireless sensor networks [3, 4].

The standard supports both peer-to-peer topology and cluster based topology in which all communications from the nodes have to be directed to the PAN coordinator. PAN coordinator has larger power resources than the ordinary nodes. In this work we choose star based (or equivalently cluster based) topology for coverage of the unit sensing area. The reason for this choice is longer lifetime of the network. Namely, if large area is covered by the peer-to-peer topology, nodes close to the sink will exhaust their batteries first [4] and their death will block the operation of the whole network. On the contrary if network has some nodes which have more power resources (and potentially higher bandwidth link resources) they can take over packet relaying and as the result whole network will live longer [7].

In theory, the number of devices in an 802.15.4 cluster can be large, but the performance of a single sensor cluster rapidly deteriorates when the number of devices and/or their individual packet arrival rates increase. In order to cover larger physical areas and still obtain satisfactory network performance in terms of delay, throughput and energy consumption, many sensing applications will require that several smaller 802.15.4 clusters be interconnected in a hierarchical manner to form a single, large network. This means that some devices must function as bridges which share their time between two or more clusters in order to carry inter-cluster traffic. Performance analysis of such topologies is complicated by the fact that quite a few parameters can be tuned, from the size of individual clusters to the duration of the time for a node performing as a bridge role [12].

There are a number of studies about increasing coverage and lifetime. In [13], the authors propose a method to increase coverage using redeployment nodes. This means that after randomly initial deployment of sensor nodes, increasing coverage can be achieved by changing the places of individual sensor nodes. This method is infeasible in sensor networks due to the large number of nodes and possibly harsh terrain and hostile environment in which they are deployed.

In [6, 14], the authors propose a method to increase efficiency in coverage and increasing lifetime but they don't consider the MAC and physical layers in their analysis. In [2], the authors propose a method to form clusters using data which is read by sensor nodes.

The aim of this work is to use ordinary nodes as bridges in which case multiple bridges can collect data in the source lower cluster and visit multiple foreign clusters simultaneously. This approach has the potential to remove the bottleneck of operation from the PAN coordinator. It can also improve

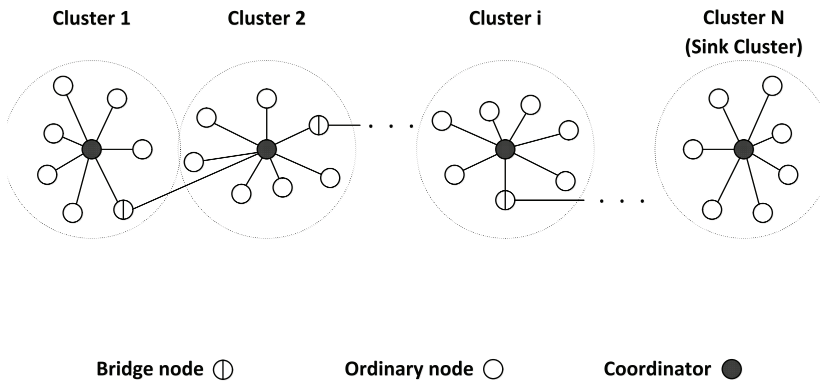



FIGURE 1
Topology of the network for round $i$.

the scalability since multiple bridges can concurrently collect the data and deliver the data to different neighboring clusters which might be the result of different queries sent from the sink or load balancing options of the routing algorithm.

In this paper, we investigate the performance of the network formed by a number of 802.15.4 clusters operating in beacon enabled, slotted CSMA-CA access mode, as shown in Figure 1. The clusters are interconnected in a slave-slave fashion, with one ordinary node acting as the bridge in each cluster. This approach is attractive from the aspects of reliability and scalability since multiple bridges can concurrently operate in one cluster.

The bridge periodically visits the sink cluster in order to deliver the data gathered from the sensor nodes in the source (lower) cluster. Bridge visits are made possible by the existence of active and inactive parts of the superframe, i.e., the bridge visits the sink cluster during the inactive period of the source cluster superframe and delivers its data by competing with other nodes in the sink (upper) cluster using the CSMA-CA access mode [11].

Our analysis focuses on the performance of such networks, in particular with the existence of bridge and the duration of the bridging period. To the best of our knowledge, this problem has not been addressed as yet in the context of 802.15.4 networks and the results presented here might provide useful insights and stimulate further research.

Based on analytical model, we evaluate lifetime of a node using following parameters: mean, coefficient of variation and skewness (ratio of the third central moment to the variance raised to the power of $\frac{3}{2}$.). 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 rest of the paper is organized as follows. In Section 2, we present the operation of slave-slave bridge. Analytical model which combines queuing analysis of all involved queues and Markov chain modeling of nodes activities are discussed in Section 3 and 4. In Section 5 we present performance results for interconnected clusters. Finally, Section 6 concludes the paper.

## 2 OPERATION OF THE SLAVE-SLAVE BRIDGE

Consider the network shown in Figure 1. All clusters 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 [7]. All communications in the cluster take place during the active portion of the superframe, the duration of which is referred to as the superframe duration *SD*. The superframe is divided into 16 slots of equal size, each of which consists of $3 \times 2^{SO}$ unit backoff periods. 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 0.25Mbps. The variable $SO$ determines the duration of the superframe, and its default value of $SO = 0$ corresponds to the shortest active superframe duration of *aBaseSuperframeDuration*=48 unit backoff periods. The time interval between successive beacons is $BI = aBaseSuperframeDuration \times 2^{BO}$, where *BO* can take a value between 1 and 14. Data transfers in the uplink direction use CSMA-CA algorithm aligned to the backoff period boundary. Data transfer in the downlink direction uses a more complex protocol in such a way that the coordinator announces the presence of a packet, which must be explicitly requested by the target node before being actually sent [10].

Activity management consists of adjusting the frequency and ratio of active and inactive periods of sensor nodes [18, 19]. For individual nodes it can be accomplished through scheduling of their active and inactive periods. Coordinator periodically broadcasts the required event sensing reliability *R* and the number of nodes which are alive. Based on that information, individual nodes calculate average period of sleep between transmissions. In order to prevent packet collisions due to synchronous node awakening, sleep periods are randomized around the calculated average value. When a node wakes up with a packet to transmit, it turns its receiver on to synchronize with the beacon, and subsequently transmits the packet. Upon successful transmission (as indicated by the appropriate acknowledgment), the node immediately goes to sleep. Also, if a node has no packet to send upon wake-up, it will immediately start a new sleep period. We refer to sequence of sleep time, beacon finding and packet transmission as a microcycle which is shown in Figure 2.

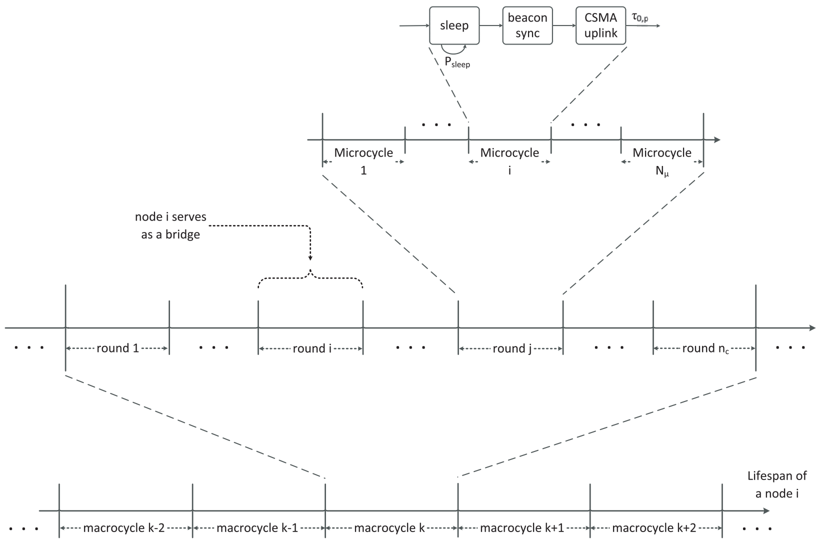



FIGURE 2
Diagram indicating different intervals of lifetime of a node including functionality as a bridge and ordinary node.

After $N_\mu$ microcycles, new bridges are elected by corresponding coordinators. The coordinators elect bridges using round-robin method.

The time interval during which a given node acts as a bridge is referred to as a round. Each round starts with bridge election and is composed of $N_\mu$ packet transmissions. We denote the duration of $N_\mu$ microcycles as $bridging$ $period$.

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. Channel assignment can be carried out by BS (sink coordinator) using frequency planning concept from cellular networks [17] with channel reuse factors of $\frac{1}{7}$ or $\frac{1}{12}$. However, at the beginning, all coordinators have to receive proper frequency channel from BS.

The time interval between two consecutive selections of the same node is denoted as $macrocycle$. As shown in Figure 2, a node during its lifetime spends a number of macrocycles. During a macrocycle, each node will be elected as a bridge exactly for one round.

Although distributed algorithms have some advantages from energy consumption overhead and delay overhead viewpoints, they introduce randomness with respect to lifetime of node. Different aspects of randomness of bridging algorithm are as follows:

There is some randomness with respect to lifetime of a node which is caused by following reasons: 1) random sleep time by individual ordinary nodes, 2) random time to transmit the packet due to CSMA-CA backoff time and 3) possibility of packet collision and packet corruption due to noise.

Considering the above discussion, we analyze efficiency of bridging algorithm in the following sections.

## 3 BRIDGING MODEL

In order to model node's activities in the clusters connected by SS bridges, we will use Discrete Time Markov Chain (DTMC) which has hierarchical and layered structure. As shown in Figure 2, a microcycle covers the period of a sequence of random sleep period (Mean duration of node's sleep period is related with event sensing reliability in the cluster) followed by packet transmission. Period of operating of a single bridge is denoted as a round, and in each round, each node has to transmit exactly $N_\mu$ packets. As can be seen in the figure, a macrocycle is composed of $n_c$ rounds where each node has served as bridge exactly once.

Since transition between successive macrocycles occurs with probability of 1, and within macrocycles, transition between rounds occurs with probability 1, and within a round, transition between microcycles occurs with probability 1, whole DTMC is irreducible, recurrent and apperiodic, therefore it is ergodic and has stationary distribution.

We assume that battery capacity is sufficiently large, so that steady-state of DTMC lasts sufficiently long time.

All packet transmissions use slotted CSMA-CA specified by the standard [7]. A general Markov sub-chain for a single CSMA-CA transmission is shown in Figure 3. Block $x$ from Figure 3 models the situation when packet transmission starts immediately after the beacon. Packet transmission may start immediately after the current beacon or it can be deferred to beginning of the next superframe. Deferring the transmission to the next superframe is stipulated by the standard in cases where a transmission can't be fully completed within the current superframe [7]. The probability that the packet will be transmitted immediately after the beacon, in current or next superframe, is denoted as $P_x$, where index $x$ serves to distinguish between sensing packets ($x$=$p$), downlink request packets ($x$=$dr$) and downlink packets ($x$=$d$). The total general packet transmission time will be denoted as $\overline{D}_x = 2 + \overline{G}_x + 1 + \overline{G}_a$, which includes two clear channel assessments, transmission time $\overline{G}_x$, waiting time for the acknowledgement, and acknowledgement transmission time $\overline{G}_a$. We assume that each packet type has a constant length. The block labeled $T_r$ denotes $\overline{D}_x$ linearly connected backoff periods needed

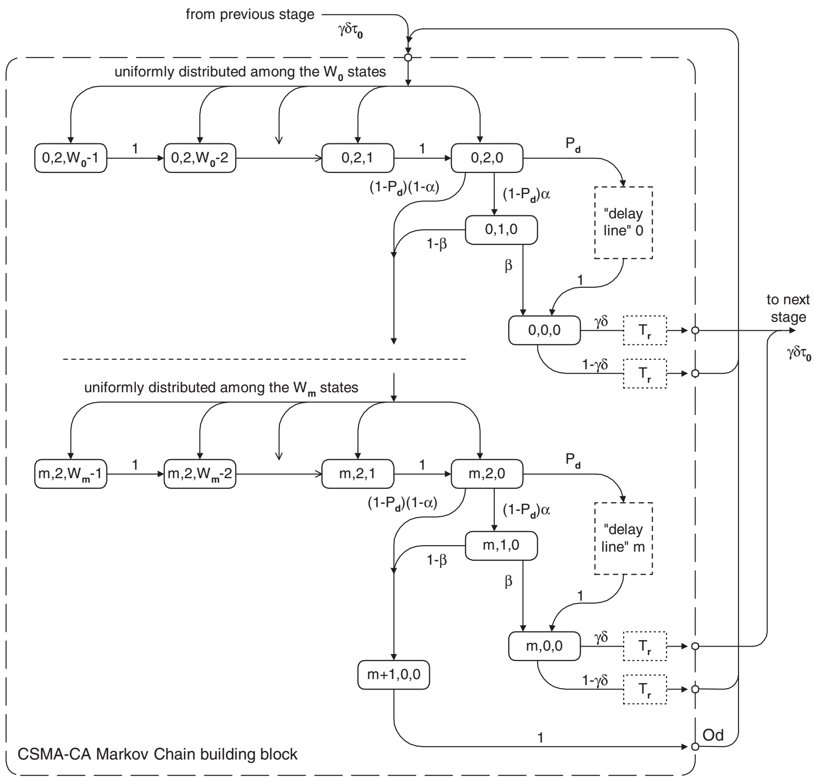



FIGURE 3
General Markov sub-chain for a single CSMA-CA transmission.

for actual transmission. Impact of noise from the physical layer i.e. Packet Error Rate (PER), is modeled through the Bit Error Rate (BER) as the probability $\delta_x = 1 - PER = (1 - BER)^{\overline{G_x} + \overline{G_a}}$. Probabilities that first CCA, second CCA and transmission will be successful for a packet of type $x$ will be denoted as $\alpha_x$, $\beta_x$ and $\gamma_x$ respectively. We also assume that Medium Access Control layer is reliable and that it will repeat the transmission until the packet is acknowledged.

Within the transmission sub-chain, the process $\{i, c, k, d\}$ indicates the state of the device at backoff unit boundaries where $0 \leq i \leq m$ is the index of current backoff attempt ($m$ is a MAC-defined constant with the default value of 4); $0 \leq c \leq 2$ is the index of the current Clear Channel Assessment (CCA) phase (two successful CCAs after the backoff countdown are required for a transmission to start); $0 \leq k < W_i$ is the value of backoff counter, with $W_i = W_0 2^{min(i,\, 5-macMinBE)}$ being the size of backoff window in $i$-th backoff attempt ($W_0 = 2^{macMinBE}$ is the minimum window size, and *macMinBE*=3); $0 \leq d < \overline{D}_x$ denotes the index of the state within the delay line in the case when packet transmission has to be deferred to the next superframe (to reduce notational complexity, it will be shown only within the delay line and omitted in other cases); finally, access probability of the general CSMA-CA block will be denoted as $\tau_{0,x}$. However, there are differences among transmissions of packets with downlink request, downlink and uplink sensing information which we need to point out.

**Packets with sensing information** When a node wakes up, if there is any packet in its buffer, it will wait for the beacon. After that, the node will start its backoff countdown. Since the size of the first backoff window is between 0 and 7 backoff periods, $P_x = P_p = \frac{1}{8}$ denotes the probability that a packet transmission will occur immediately after the beacon with successful first and second CCAs. Packets with sensing information have total length of $\overline{D}_p = 12$ backoff periods.

During a macrocycle, a node is in bridging state exactly once. Therefore, the probability of finishing the first backoff phase in the transmission block is

$$x_{0,2,0}^{(p)} = \tau_{0,p}\gamma_p\delta_p + \tau_{0,p}(1 - \gamma_p\delta_p) = \tau_{0,p} \tag{1}$$

Using the transition probabilities indicated in Figure 3, we can derive the relationships between the state probabilities and solve the Markov chain. For brevity, we will omit detailed derivation and present sum of probabilities for one transmission sub-chain as

$$\begin{aligned} s_p = {} & \tau_0 C_4 \left( C_3(\overline{D}_p - 2) + \alpha(1 - P_p) + \tfrac{P_p(\overline{D}_p - 1)}{2} \right) \\ & + \tau_0 \left( \textstyle\sum_{i=0}^{m} \tfrac{C_2^i(W_i+1)}{2} + C_2^{m+1} \right), \end{aligned} \tag{2}$$

where $C_2 = (1 - P_d)(1 - \alpha\beta)$, $C_3 = (1 - P_d)\alpha\beta$ and $1 - C_4 = \frac{C_2^{m+1}}{1 - C_2}$.

**Synchronization times** We also need the synchronization time from the moment when a node wakes up till the next beacon. This synchronization time is uniformly distributed between 0 and $BI - 1$ backoff periods, and its Probability Generating Function (PGF) is $D(z) = \frac{1-z^{BI}}{BI(1-z)}$.

The sum of probabilities within the beacon synchronization time during steady-state phase is $s_b = \tau_0\gamma\delta\sum_{i=0}^{BI}\frac{i}{BI}$. In order to model the node's sleep time, we assume that this sleep time is geometrically distributed with parameter $P_{sleep}$. Then, the sum of probabilities of being in single sleep is equal to $s_{s1} = \frac{\tau_0\gamma\delta}{(1-P_{sleep})}$.

However, if the node wakes up from sleep and finds its buffer empty, it will start the new sleep. Let us denote the probability of this event as $P_c$; its exact value will be derived later. The sum of probabilities of being in consecutive sleep periods then becomes $s_s = \frac{s_{s1}}{(1-P_c)}$.

The normalization condition for the whole Markov chain becomes

$$N_\mu(n_c - 1)(s_s + s_b + s_p) = 1 \tag{3}$$

The total access probabilities for particular packet type are equal to the sum of access probabilities in a macrocycle

$$\tau_p = N_\mu(n_c - 1)\tau_{0,p} \tag{4}$$

### 3.1 Analysis of the node's packet queue

We need to consider the MAC layer of a node as a $M/G/1/K$ queuing model with a number of Markov points which model the sleep time, synchronization time to the beacon, bridging time and packet service time. We assume that a node transmits a single packet before going to sleep, which is known as 1-limited scheduling [20]. We also assume that packets arriving to each node follow the Poisson process with the rate λ. A node's buffer can accommodate $L$ packets. The PGF for the packet service time will be denoted as $T_{t,x}(z)$, where $x \in \{dr, d, p\}$. The exact value of this PGF will be derived in Section 4. We need to select Markov points in which we will model the state of the node's buffer. We can identify the following moments:

**Departure time of a packet with sensing information** The PGF for the number of packets arriving to the node's buffer during packet service time is $B(z) = \sum_{k=0}^{\infty} b_k z^k = T^*_{t,p}(\lambda - z\lambda)$ where $T^*_{t,p}()$ denotes the Laplace-Stieltjes Transform (LST) of the service time of sensing packet [20]; since service time is a discrete random variable, the LST is obtained by replacing the variable $z$ with $e^{-s}$ in the expression for $T_{t,x}(z)$. We denote $\nu_k$, $0 \le k < L$, as probability of having $k$ packets in the node's buffer after packet departure.

**End of the sleep time** After a packet transmission (if the number of microcycles is less than $N_\mu$), the node goes to sleep; the sleep time is geometrically distributed with the parameter $P_{sleep}$. If the node's buffer is empty upon return from sleep, a new sleep will start immediately. The PGF for a single sleep period is $V(z) = \sum_{k=1}^{\infty}(1 - P_{sleep})P_{sleep}^{k-1}z^k = \frac{(1-P_{sleep})z}{1-zP_{sleep}}$. We also note that the PGF for the number of packet arrivals to the node buffer during the sleep time [20] is $E(z) = \sum_{k=0}^{\infty} e_k z^k = V^*(\lambda - z\lambda)$. The probability of having $k$ packets in the node's buffer after sleep is denoted with $\omega_k$, $0 \le k \le L$.

**End of bridging phase** From Figure 2, after every $N$ rounds the node will enter a bridging phase, during which ordinary sensing packets are not transmitted. The duration of bridging phase may be considered as a single server vacation period for the node's data packet queue. The duration of bridging phase has the PGF of $T_b(z)$ and the number of packet arrivals to the node's buffer during bridging phase has the PGF of $H(z) = \sum_{k=0}^{\infty} h_k z^k = T_b^*(\lambda - z\lambda)$. We will denote the probability of having $k$ packets in the node's buffer after the cluster set-up phase as $\epsilon_k$, $0 \le k \le L$.

**End of synchronization time** A node returning from sleep (i.e., with non-empty buffer) has to synchronize with the next beacon; the synchronization time is uniformly distributed between 0 and $BI - 1$ backoff periods, and its PGF $D(z)$ is given in 3. The PGF for the number of packet arrivals to the node's buffer during the synchronization time is $F(z) = \sum_{k=0}^{\infty} f_k z^k = D^*(\lambda - z\lambda)$. We will denote the probability of having $k$ packets in the node's buffer after the synchronization phase as $\delta_k$, $0 \le k \le L$.

**Node's buffer behavior in Markov points** By modeling the node's buffer state in Markov points of different types, the steady-state equations for state transitions are

$$\omega_0 = (\omega_0 + p\nu_0 + \epsilon_0)e_0, \tag{5-a}$$

$$\omega_k = (\omega_0 + p\nu_0 + \epsilon_0)e_k + \sum_{j=1}^{k} p\nu_j e_{k-j} + \sum_{j=1}^{k} \epsilon_j e_{k-j}, \quad \text{for } 1 \le k \le L-1 \tag{5-b}$$

$$\omega_L = (\omega_0 + p\nu_0 + \epsilon_0)\sum_{k=L}^{\infty} e_k + \sum_{j=1}^{L-1} p\nu_j \sum_{k=L-j}^{\infty} e_k + \sum_{j=1}^{L-1} \epsilon_j \sum_{k=L-j}^{\infty} e_k \tag{5-c}$$

$$\delta_k = \sum_{j=1}^{k} \omega_j f_{k-j} \qquad \text{for} \quad 1 \le k \le L-1 \tag{5-d}$$

$$\delta_L = \sum_{j=1}^{k} \omega_j \sum_{k=L-j}^{\infty} f_k \tag{5-e}$$

$$\nu_k = \sum_{j=1}^{k+1} w_j b_{k-j+1}, \qquad \text{for} \quad 0 \le k \le L-2 \tag{5-f}$$

$$\nu_{L-1} = \sum_{j=1}^{L} w_j \sum_{k=L-j}^{\infty} b_k \tag{5-g}$$

$$\epsilon_k = \sum_{j=0}^{k} (1-p)\nu_j h_{k-j} \quad \text{for} \quad 1 \le k \le L-1 \tag{5-h}$$

$$\epsilon_L = \sum_{j=0}^{k} (1-p)\nu_j \sum_{k=L-j}^{\infty} h_k \tag{5-i}$$

$$1 = \sum_{k=0}^{L} (\omega_k + \epsilon_k) + \sum_{k=1}^{L} \delta_k + \sum_{k=0}^{L-1} \nu_k \tag{5-j}$$

where $p = \frac{N_\mu(n_c-1)-1}{N_\mu(n_c-1)}$ denotes the probability that a packet departure is followed by a sleep, and $1-p = \frac{1}{N_\mu(n_c-1)}$ denotes the probability that it is followed by a bridging phase. The probability distribution of the device queue length at Markov points can be found by solving the system of linear equations (5). In this manner, we obtain the probability that a Markov point corresponds to a return from the vacation and the queue is empty at that moment, as $P_c = \omega_0 / \sum_{i=0}^{L} \omega_i$

The average value of total inactive time of a node, including possible multiple consecutive sleeps, is $\overline{I} = \frac{1}{(1-P_{sleep})(1-P_c)}$.

### 3.2 Transmission success probabilities

We assume that number of clusters in the network is N. The number of nodes in each cluster is $n_c = \frac{n}{N}$ nodes. We model the arrival processes of medium access events for sensing packet as Poisson processes. 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 $(\frac{R}{N})$ is not high, i.e., when the cluster operates below the saturation regime.

*Packet arrival rates for background traffic*

During active portions of the superframes in any clusters, there are three kinds of packets: sensing packets, downlink request packets and downlink packets. According to the place of clusters in the network, there are three different types of clusters: first cluster which is the farthest cluster from the sink. Sink cluster (last cluster) which is the nearest cluster to the sink and sink (BS) is the coordinator of the cluster. Middle clusters which are any of the clusters between first and sink cluster.

**First cluster:** In the first cluster, there is no bridge coming from other clusters. Transmission of the packets with sensing information can commence within eight backoff periods starting from third backoff period after the beacon; the background packet arrival rate for the sensing packets is $\lambda_p = (n_c - 1)\tau_p \frac{SD}{8}$.

Like sensing packets, transmission of downlink request packets can commence within eight backoff periods starting from the third backoff period after the beacon. Since every sensing packet should be requested individually by a downlink request packet, the background packet arrival rate of downlink request packets is $\lambda_r = n_c \tau_p \frac{SD}{8}$.

Transmission of downlink packets can start after the acknowledgment of request packets; in this case, the background downlink packet arrival rate is $\lambda_d = n_c \tau_p \frac{SD}{SD - \overline{D_r} - 0.5(W_0 - 1)}$.

**Middle clusters:** In the middle clusters, we must account for the presence of the bridges. For the $i^{th}$ cluster, the bridge access probability can be modeled as $\tau_{b_i} = \sum_{i=1}^{i-1} n_i \tau_{p,i}$. The background packet arrival rate for the sensing packets in the $i^{th}$ cluster is $\lambda_{p,i} = ((n_i - 1)\tau_{p,i} + \tau_{b_i})\frac{SD}{8}$. The background packet arrival rate of downlink request packets is $\lambda_r = (\sum_{i=1}^{i} n_i \tau_{p,i})\frac{SD}{8}$. The background downlink packet arrival rate is $\lambda_d = (\sum_{i=1}^{i} n_i \tau_{p,i})\frac{SD}{SD - \overline{D_r} - 0.5(W_0 - 1)}$.

**Sink cluster:** In the sink cluster, there is no bridge node belongs to the cluster. Therefore, there are no downlink request or downlink packets. There is just a bridge of adjacent cluster. The bridge access probability in the sink cluster can be modeled as $\tau_{b_N} = \sum_{i=1}^{N-1} n_i \tau_{p,i}$. The background packet arrival rate for the sensing packets in the sink cluster is $\lambda_{p,N} = ((n_N - 1)\tau_{p,N} + \tau_{b_N})\frac{SD}{8}$.

Note that the first CCA may fail because a packet transmission from another node is in progress. The second CCA, however, will fail only if some other node has *just* started its transmission – i.e., the backoff period in which the second CCA is undertaken must be the *first* backoff period of that packet.

*Medium behavior*
Sensing packets in the $i^{th}$ cluster, $1 \leq i \leq N-1$, will experience the following success probabilities:

$$\begin{aligned} \alpha_i &= \tfrac{1}{8}\textstyle\sum_{k=1}^{7} e^{-k(\lambda_{p,i}+\lambda_{r,i}+\lambda_{d,i})}, \\ \beta_i &= e^{-(\lambda_{p,i}+\lambda_{dr,i}+\lambda_{d,i})}, \\ \gamma_i &= \beta_i^{\max(\overline{D_p},\overline{D_{dr}},\overline{D_d})} \end{aligned} \tag{6}$$

Sensing packets in the sink cluster will experience the following success probabilities:

$$\begin{aligned} \alpha_N &= \tfrac{1}{8}\textstyle\sum_{k=1}^{7} e^{-k\lambda_{p,N}}, \\ \beta_N &= e^{-\lambda_{p,N}}, \\ \gamma_N &= \beta_N^{\overline{D_p}} \end{aligned} \tag{7}$$

## 4 ANALYZING LIFETIME OF A NODE

Let the PGF of the packet length be $G_x(z) = z^{k_x}$ where $k_x$ is a constant representing the length of the packet of type $x$ in backoff periods. Let $G_a(z) = z$ stand for the PGF of the ACK packet duration. Let the PGF of the time interval between the data and subsequent ACK packet be $t_{ack}(z) = z^2$; and PGF for packet transmission time and receipt of acknowledgement as $T_x(z) = G_x(z)t_{ack}(z)G_a(z)$. Then, the PGF for the time needed for one complete transmission attempt of packet of type $x$, including backoffs, becomes [9]:

$$\mathcal{A}_x(z) = \frac{\sum_{i=0}^{m}\left(\prod_{j=0}^{i} B_j(z)\right)(1-\alpha_x\beta_x)^i z^{2(i+1)}(\alpha_x\beta_x T_x(z))}{\alpha_x\beta_x \sum_{i=0}^{m}(1-\alpha_x\beta_x)^i} \tag{8}$$

where $B_j(z)$ is the PGF for duration of $j$-th backoff time prior to transmission and is equal to $B_j(z) = \frac{z^{W_j}-1}{W_j(z-1)}$. The LST for energy consumptions during wait and reception of acknowledgment, two CCAs and packet transmission are $e^{-s3\omega_r}$, $e^{-s2\omega_r}$ and $e^{-sk_x\omega_t}$ respectively. Beacon length sufficient for transmitting information about the number of live nodes and requested event sensing reliability is three backoff periods, and the LST for energy consumption while receiving it is $e^{-s3\omega_r}$. Then, the LST for energy consumption during transmission of the data packet and reception of acknowledgement will be denoted with $T_x^*(s) = e^{-sk_x\omega_t} e^{-s3\omega_r}$. The LST for energy consumption for a single transmission attempt becomes

$$\mathcal{E}^*_{\mathcal{A}x}(s) = \frac{\sum_{i=0}^{m}\left(\prod_{j=0}^{i} E^*_{B_j}(s)\right)(1-\alpha_x\beta_x)^i e^{-s2\omega_r(i+1)}\alpha_x\beta_x T_x^*(s)}{\alpha_x\beta_x\sum_{i=0}^{m}(1-\alpha_x\beta_x)^i} \tag{9}$$

By taking packet collisions into account [9], the PGF of probability distribution of the total packet service time becomes $T_{t,x}(z) = \sum_{k=0}^{\infty}(\mathcal{A}_x(z)(1-\gamma_x\delta_x))^k\mathcal{A}_x(z)\gamma_x\delta_x = \frac{\gamma_x\delta_x\mathcal{A}_x(z)}{1-\mathcal{A}_x(z)+\gamma_x\delta_x\mathcal{A}_x(z)}$ and the LST for the energy spent on a packet service time is $E^*_{T_x}(s) = \frac{\gamma_x\delta_x\mathcal{E}^*_{\mathcal{A}x}(s)}{1-\mathcal{E}^*_{\mathcal{A}x}(s)+\gamma_x\delta_x\mathcal{E}^*_{\mathcal{A}x}(s)}$. Average value of energy consumed for packet transmission is $\overline{E}_{Tx} = -\frac{d}{ds}E^*_{Tx}(s)|_{s=0}$.

As discussed before, each round is composed of a number ($N_\mu$) of microcycles which are composed of three steps: sleep, beacon synchronization and data transmission (CSMA-CA uplink). Assuming $\omega_r \approx \omega_t$, we can conclude that. Therefore, the LSTs for energy consumptions for bridge and ordinary nodes during a microcycle are respectively:

$$\begin{aligned} E^*_{m,B}(s) &= I(e^{-s\omega_r})D(e^{-s\omega_r})e^{-s3\omega_r}T_p(e^{-s\omega_r}) \\ E^*_{m,nB}(s) &= I(e^{-s\omega_s})D(e^{-s\omega_r})e^{-s3\omega_r}E^*_{T\,p}(s) \end{aligned} \tag{10}$$

The LSTs for energy consumptions during one round for bridge and ordinary nodes are respectively:

$$\begin{aligned} E^*_{r,B}(s) &= (E^*_{m,B}(s))^{N_\mu} \\ E^*_{r,nB}(s) &= (E^*_{m,nB}(s))^{N_\mu} \end{aligned} \tag{11}$$

During a macrocycle which is composed of $n_c$ rounds, each node has to be Bridge only for one round. Therefore, the LST for energy consumed during one macrocycle is

$$E^*_M(s) = E^*_{r,B}(s)(E^*_{r,nB}(s))^{n_c-1} \tag{12}$$

If the battery budget is $E_{bat}$ Joules, the average number of macrocycles during lifetime of a node is $\frac{E_{bat}}{\overline{E}_M}$ where $\overline{E}_M$ is the average value of energy consumed during a macrocycle. According to above discussion, lifetime of the network is $\overline{L} = \overline{T}_M\frac{E_{bat}}{\overline{E}_M}$ 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 $\mu = -\frac{d}{ds}F^*(s)|_{s=0}$ and Coefficient of variation is $CV = \frac{\sigma}{\mu} = \frac{(\frac{d^2}{ds^2}F^*(s)|_{s=0} - \mu^2)^{\frac{1}{2}}}{\mu}$. The skewness of random variable characterizes the degree of asymmetry of a distribution around its mean and is obtained according to following relation: $\gamma = \frac{-\frac{d^3}{ds^3}F^*(s)|_{s=0} - 3\mu\sigma^2 - \mu^3}{\sigma^3}$. Higher values of CV and $\gamma$ imply lower percentage of nodes dying at the same time which means less efficiency in energy consumption.

## 5 PERFORMANCE EVALUATION

In this section we present numerical results obtained by solving the system of equations presented in sections 3 and 4 and obtain system parameters which we then use their values to calculate bridging performance. Number of nodes in the network is 400 (n=400) and each node is powered with two AA batteries with total energy $E_{bat} = 10260J$. The effect of noise is modeled with $BER = 10^{-4}$. The network operates in the ISM band at 2.4 GHz, with raw data rate 0.25 Mbps. Superframe size (SD) and beacon interval (BI) are adjusted to 48 and 96 backoff periods; i.e. $SO = 0$ and $BO = 1$ respectively.

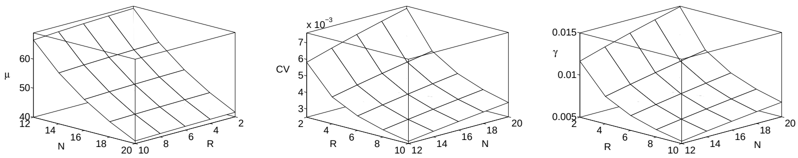
Energy consumptions per backoff period for a node with a 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver [1] operating under typical conditions in the ISM band are $\omega_s = 18.2 \times 10^{-9}$J, $\omega_r = 17.9 \times 10^{-6}$J and $\omega_t = 15.8 \times 10^{-6}$J, during sleep, receiving and transmitting (at 0dBm), respectively.

Increasing length of a packet results in decreasing $\delta_x$ and $\gamma_x$ 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 for sensing packet ($k_p = 12$), downlink request packet ($k_{dr} = 2$) and downlink packet ($k_d = 12$) are considered. We also assume that each node has a buffer size of $L = 2$ packets.

In the following, bridge performance evaluated with respect to three central moments of lifetime is discussed.

### 5.1 Experiment 1

We first investigate bridging performance under variable event sensing reliability ($R$), i.e. number of packets per second needed for reliable event detection, and variable number of clusters ($N$). In Figure 4 number of microcycles in a round is considered as a constant value ($N_\mu = 100$). Number of clusters is variable in the range 12 to 20 in steps of 2. Event sensing reliability (R) is variable in the range 2 to 10 packets per second in steps of 2. This means that number of packets should be sent during a second by a node ($r = \frac{R}{n}$)



(a) Mean value of lifetime (in days) (b) Coefficient of variation of lifetime (c) skewness of lifetime

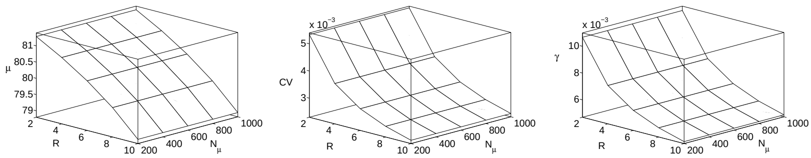
FIGURE 4
Mean value, Coefficient of variation and Skewness of lifetime according to different values of sensing reliability ($R$) and number of clusters ($N$).

is variable in the range 0.005 to 0.025 in step of 0.005. Therefore, we can determine average duration of a microcycle as $\overline{T}_m = \frac{1}{r} = \overline{I} + \overline{D} + 3 + \overline{T}$. According to previous relation, average inactive period ($\overline{I}$) and $P_{sleep}$ can be determined.

Since the nearest cluster to sink cluster relays more traffic than other clusters, it has the lowest cluster lifetime and determines lifetime of the network. As shown in Figure 4(a), with increasing number of clusters, the amount of traffic relayed by the (N-1)-th cluster increases which results in decreasing lifetime of the network.

As can be seen in Figure 2, lifetime of the network is composed of a number of random variable representing duration of macrocycles. Since variance of sum of a number of i.i.d. random variables is sum of their variances, with increasing number of random variables, the numerator of coefficient of variation (standard deviation) decreases more rapidly than denominator which means less values of coefficient of variation. With increasing sensing reliability, the duration of a macrocycle decreases and therefore there are more macrocycles in the lifetime. This results in lower coefficient of variation which means lower dispersion around mean value of lifetime (Figure 4(b)). With decreasing number of clusters, a macrocycle is composed of more rounds which results in lower coefficient of variation of macrocycle and lifetime.

According to central limit theorem [5], sum of a number of i.i.d. random variables converges to a normal distribution which is symmetrical around mean value and has zero skewness. With decreasing sensing reliability, lifetime is composed of more macrocycles which results in less skewness of lifetime (Figure 4(c)) and more symmetrical around mean value of lifetime. Decreasing number of clusters results in increasing number of rounds in a macrocycle. Therefore, lower values of skewness of lifetime can be achieved by lower values of number of clusters.




(a) Mean value of lifetime (in days)

(b) Coefficient of variation of lifetime

(c) skewness of lifetime

FIGURE 5
Mean value, Coefficient of variation and Skewness of lifetime according to different values of sensing reliability ($R$) and number of microcycles ($N_\mu$).

### 5.2 Experiment 2

In this part, we investigate bridging performance under variable event sensing reliability ($R$) and variable bridging period i.e. number of microcycles ($N_\mu$) during a round. In Figure 5, number of clusters is 16 ($N = 10$), thus the number of nodes in each cluster is $n_i = \frac{n}{N} = 40, 1 \leq i \leq N$.

With increasing sensing reliability, the sleep time between two consecutive transmission decreases and therefore the battery energy of sensor nodes depletes more rapidly which results in reducing lifetime of the network (Figure 5(a)).

Lifetime is composed of more macrocycles when sensing reliability increases which results in lower dispersion around mean value (Figure 5(b)).

There are higher numbers of macrocycles during lifetime of a node when sensing reliability decreases. According to central limit theorem, with decreasing sensing reliability, lifetime has lower values of skewness which results in more similarity to normal distribution (Figure 5(c)).

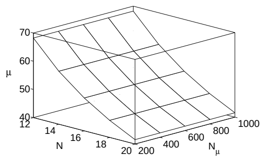
### 5.3 Experiment 3

In this part, we investigate bridging performance under variable number of clusters ($N$) and variable number of microcycles ($N_\mu$). In Figure 6, event sensing reliability is considered as a constant value (R=2). This means that number of packets should be sent to BS by each node ($r = \frac{R}{n}$) is constant at 0.005 packets per second.

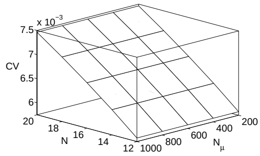
Higher number of clusters results in more traffic relayed by clusters near sink and this causes deceasing in mean value of lifetime (Figure 6(a)).

A macrocyle is composed of more rounds when number of clusters decreases. Therefore, lower number of clusters results in lower coefficient of variation of macrocycles and lifetime (Figure 6(b)).

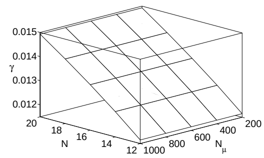
According to central limit theorem, decreasing number of clusters results in decreasing skewness of macrocycle. Therefore, we have more similarity



(a) Mean value of lifetime (in days)



(b) Coefficient of variation of lifetime



(c) skewness of lifetime

FIGURE 6
Mean value, Coefficient of variation and Skewness of different intervals of the algorithm according to different values of number of clusters ($N$) and number of microcycles ($N_\mu$).

to normal distribution when lower values of number of clusters are achieved (Figure 6(c)).

## 6 CONCLUSION

This paper evaluates the solution of developing an 802.15.4 large-scale network formed by clusters, interconnected by slave-slave bridges operating with IEEE 802.15.4 beacon-enabled mode. The impacts of event sensing reliability, number of clusters and number of microcycles are evaluated on network lifetime. In our analysis, using queuing theory and discrete-time Markov chain, statistical measures such as mean, coefficient of variation and skewness are obtained. Higher values of lifetime can be achieved by adjusting network layer parameters i.e. adopting lower values of number of clusters or higher values of number of microcycles. If application allows, lifetime can also be extended by adjusting application layer parameters i.e. adopting lower values of sensing reliability. The results also demonstrate that probability distribution of node lifetime is symmetrical around the mean with low variance which means that all nodes will die at approximately same time.

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