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On the Lifetime of Asynchronous Software Defined Wireless Sensor Networks

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***Abstract*—In this paper, we consider a software-defined wireless sensor network architecture which conserves energy by applying asynchronous duty cycling. In asynchronous sensor networks, the overhearing adversely impacts the energy consumption of the nodes. Using a mathematical model, we compute the maximum lifetime of the network and accordingly propose a multichannel operation and transmit power control to reduce the effect of overhearing in asynchronous networks. Our comprehensive test results confirm that for network with load-aware non-uniform sensor node deployment, the network lifetime is much higher compared to a uniform deployment. We also show that the use of data aggregation software-defined wireless sensor networks can improve the network lifetime as compared to the data gathering networks.**

***Index Terms*—Multi-channel routing, network lifetime, power control, software-defined networking, wireless sensor networks.**

I. Introduction

The rigidity of the traditional networks and their over dependence to proprietary services brought into effect the software defined networking (SDN) that decouples the control plane from the data plane by moving the control logic from the nodes to a central controller [1]. The SDN approach to wireless sensor networks (WSNs) alleviates the challenges in network management by fusing the concepts of SDN and WSN, were the sensor nodes can dynamically change their functionalities and control parameters by loading different programs on-demand according to the real time needs [2]. In software-defined wireless sensor networks (SDWSNs), the control intelligence is alienated from data plane devices (sensors) and is enforced in a logically centralized controller. A SDWSN comprises of tiny sensing nodes along with micro-controllers and software-defined radios for communicating with other nodes. Such networks are self-organized ad-hoc systems competent of sensing, gathering, handling and sending distinctive physical parameters in a multi-hop fashion towards the sink. These nodes are typically powered by batteries, since batteries are troublesome to supplant, diminishing the vitality utilization within the sensor nodes may be a key concern for planning sensor systems. A critical sum of control is devoured by the radio for remote communication; subsequently, maximizing the lifetime of SDWSNs requires that radio transmissions and receptions to be minimized.

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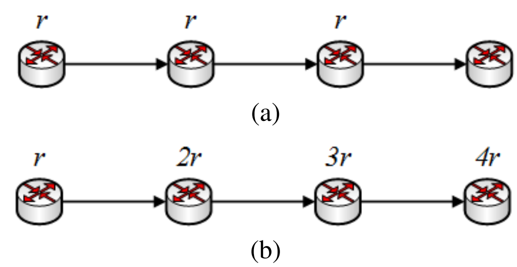


Fig. 1. Illustration of (a) a data aggregation and (b) a data gathering SDWSN.

Duty-cycling between the active and sleep periods is a successful strategy for preserving the vitality devoured by the transceiver and has generally been adopted in numerous MAC conventions in WSNs. However, the key challenge of such approaches is the network-wide time synchronization and the latency of multi-hop transmissions caused by synchronized scheduling standards. Asynchronous duty-cycling is an alternative approach, in which all nodes awaken shortly at recurring intervals of time to examine channel activities and solely stay awake if an activity is detected; otherwise, the nodes come back to their energy-conserving sleep states. In general, a prolonged preamble is employed for every transmitted packet; therefore, the receiving node is able to detect it throughout its transient wake time. This approach offers a good resolution for energy conservation in asynchronous SDWSNs, particularly for underneath low data rates. The study of the past literature [3], [4] show that numerous low power listening and preamble sampling MAC protocols use asynchronous duty cycling.

A key problem in the asynchronous duty-cycling approach is that it wastes energy due to *overhearing*; which happens due to the fact that the unintended neighbors receive an entire packet before knowing the actual destination. A solution to the problem of overhearing could be to provide an additional information in the preamble to enable neighbors to cancel the reception of long packets when not required [5]. Another solution is the use of an adaptive duty-cycling [6]. Despite these solutions, overhearing still remains a major issue for energy consumption in asynchronous SDWSNs, particularly, where the size of network and the node density is large.

To reduce the overhearing problem in asynchronous SDWSNs, we propose the following approaches by utilizing software-definability in the communication layer of the sensor nodes. The first approach reduces the number of co-channel transmissions in a neighborhood of a node by making use of multiple orthogonal channels [7], [8]. Multi-channel operations are supported by typical WSN platforms, such as MICAz [9] and Telos [10], which are usually used for reducing the interference. In addition to control the effect of overhearing, we consider the use of an effective transmit power control mechanism [11]–[13]. Our goal is to adapt the energy consumption of the nodes by applying software-defined channel selection and power control to balance the remaining battery lifetime, and thus can effectively maximize the lifetime of the network [14].

We consider two types of data forwarding schemes: *data aggregation* and *data gathering* SDWSNs. Data gathering is defined as the systematic collection and forwarding of the sensed data to the sink in a multi-hop tree fashion, such as collection tree protocol (CTP) [15], while data aggregation involves data fusion from multiple sensor nodes at the intermediate nodes and the transmission of the aggregated data to the sink. These data forwarding schemes are illustrated in Fig. 1, where we assume that each node is generating packets at r packets/secs. In the data aggregation based forwarding, all nodes are aggregating the packets sent by their downstream nodes along with their own before forwarding, which makes the transmission rate of all the nodes equal to r packets/secs. Whereas, in case of data gathering based forwarding, the nodes forward the packets from their children separately, thus the transmission rates increase as we go upstream. In this paper, our main contribution is to develop a mathematical model to evaluate the network lifetime of SDWSNs under power control for these two types of data forwarding schemes. We also extend the network lifetime calculation to consider multi-channel operation to limit the effects of overhearing.

The outline of this paper is as follows. Related works are discussed in Section II. Sections III and IV develop a statistical model for network lifetime calculation under power adaptation for data aggregation and data gathering SDWSNs. Section V models the network lifetime of a SDWSN in presence of multiple orthogonal channels. Section VI shows the simulation results of the developed analytical models. Finally, the paper is concluded in Section VII.

II. Related Works

There has been extensive research on tree based routing in sensor networks. Xmesh and CTP are two such schemes used in Tinyos 1.x and 2.x respectively. The objective of both Xmesh and CTP is to provide an efficient anycast datagram communication for the collection root nodes of the network. Since these schemes are developed for single channel WSNs, overhearing is an important factor in reducing the network lifetime. In this paper, to reduce the effect of overhearing, we use multiple channels and transmit power adaptation in an energy-efficient manner on top of these tree based routing schemes.

Multi-channel routing in wireless networks is well-studied in the current literature [16]–[19], however, most of the past works either generate high control overheads for channel negotiation or assume multi-radio transceiver at each node. As opposed to these literature, typical sensor nodes such as Micaz [9] and TelosB [10] are equipped with single radio transceivers with limited computational capabilities. Many multi-channel MAC protocols for single-radio transceivers are also studied in the context of WSNs, such as MMSN [20], TMMAC [21] and MMAC [22]. However, these schemes require precise time synchronization. Contrary to these works our focus in this paper is mainly on asynchronous WSNs.

Transmit power control in WSNs is also well-mined, where the key idea is to identify the number of neighbors and then configure the radio transmission power level of each node such that the number of neighbors remains inside a specific bound [23], [24]. These studies have used the channel assignment and transmit power control primarily for interference minimization. However, for low-data rate sensor network applications, the effect of interference is quiet limited. As opposed to these contributions, our primary objective is to explore the capability of SDWSNs for reducing the effect of network overhearing caused due to asynchronous duty-cycling. We focus on developing a mathematical formulation to model the effects of multiple channels and power control on reducing the network-wide effect of overhearing.

III. Network Lifetime with Power Adaptation for Data Aggregation SDWSNs

A. Transmit Power Adaptation

In data aggregation SDWSNs, the intermediate nodes aggregate the packets from multiple sensors, fuse them and transmit. For exchanging different controlling parameters among themselves, nodes broadcast periodic beacons as well. In large scale SDWSNs, where transmission scheduling is not used, it is not easy to implement synchronous sleep and wake cycles. To conserve energy in such networks, a low-power listening (LPL) procedure is used by nodes [25], through which a node periodically polls the wireless channel for incoming packets. The node switches off the radio until the next poll if there is no transmission on the channel; otherwise, it stays on (awake) till it receives the incoming packets. In the LPL procedure, the sender adds a long preamble to the message that spans the complete length of the poll interval, so that the receiving node can observe it regardless of when it awakes. Due to this long preamble length, the effect of *overhearing* is costly, as the nodes overhear every ongoing transmissions in their neighborhood. The effect of such overhearing applies to both data packets and beacons. In such scenarios, transmission power control can significantly reduce the effect of overhearing. The radio transmit power is normally controlled in a dynamic way by most sensor platforms. For instance, the CC2420 radio in Crossbow's MicaZ provides 32 transmission power levels ranging from -25 dBm to 0 dBm [13]. On the other hand, CC1000 radios of Mica2 sensor nodes can also provide 26 power levels from -20 dBm to +5 dBm [26].

Under these assumptions, we came up with an experimentally validated model [8] of the estimated current consumption of a node as

$$\begin{aligned} I &= \frac{I_{Bt}T_{Bt}}{T_B} + M \cdot I_{Dt}T_{Dt} + S \cdot \frac{I_{Br}T_{Br}}{T_B} + O \cdot I_{Dr}T_{Dr} \\ &+ F \cdot I_{Dt}T_{Dt} + R \cdot I_{Dr}T_{Dr} + \frac{I_sT_s}{T_D} + P \cdot I_pT_p, \quad (1) \end{aligned}$$

where T_x and I_x denote the duration and the current drawn, respectively, of the event x. T_B is the beacon interval. B_t/B_r denotes the transmission/reception of beacon packets, D_t/D_r denotes data transmit/receive, whereas p and s represent the processing and sensing, respectively. The overhearing and forwarding rate are denoted by O and F respectively. The rate at which a node transmits its own packets is M and the reception rate is denoted by R. The number of neighbors is denoted by S. The number of times a node wakes up and checks the channel is denoted by P. Accordingly, to minimize the overall power consumption, we first calculate the optimal transmission range for a *linear* network (Fig. 2(a)).

Assume that the receiver electronics draws $I_{Dr} = \alpha_{12}$ current in the receiving mode. In the transmit mode, the amount of the current drawn depends on the power of transmission. If an optimal power control is used to send a packet over a distance d with a path loss exponent of n, then the total consumed current is

$$I_{Dt} \;\; = \;\; \alpha_{11} + \alpha_3 d^n, \tag{2}$$

where α_{11} and α_3 are the current consumed by the transmitter electronics and the current dissipation in the transmit op-amp, respectively. The duration of a packet reception and transmission is proportional to the packet length. Let us assume that both data and beacon packets have equal length. therefore, $T_{Dt} = T_{Dr} = T_{Bt} = T_{Br} = T_l$. The reason behind this assumption is that with low-power operation, nodes send a long preamble before actual transmission, which is much longer than actual packet transmission. The energy consumption of a relay node that receives a packet and transmits it d meters onward is given by

$$\mathcal{E}_{\text{relay}}(d) = (\alpha_{11} + \alpha_3 d^n + \alpha_{12}) \cdot T_l. \tag{3}$$

Also, let us assume that ρ denotes the node density (that is, the number of nodes in a unit area), and $\pi \cdot d^2\rho - 2$ is the expected number of nodes that overhear the transmission. When $\pi \cdot d^2\rho > 2$, the expected number of overhearing is positive; otherwise, it is zero. We deduct 2 because the receiver and the transmitter are not counted as the nodes that overhear. Therefore, the energy used for overhearing while transmitting a packet is $\mathcal{E}_{\text{ov}} = \big(\pi \cdot d^2\rho - 2\big) \cdot \alpha_{12} \cdot T_l$.

We now calculate the total energy consumed to transmit a packet from A to B, with distance D in between, via $K-1$ relay nodes. The situation is illustrated in Fig. 2(a). Thus, the overall energy consumed is given by

$$\mathcal{E}_T(D) = \textstyle\sum_{i=1}^{K} \left(\mathcal{E}_{\text{relay}}(d_i) + \mathcal{E}_{\text{ov}}(d_i)\right) = \sum_{i=1}^{K} \mathcal{E}_R(d_i), \tag{4}$$

where

$$\begin{aligned}\mathcal{E}_R(d_i) &= \mathcal{E}_{\text{relay}}(d_i) + \mathcal{E}_{\text{ov}}(d_i)\\ &= \big(\alpha_{11} - \alpha_{12} + \alpha_3 d_i^n + \pi \cdot d_i^2\rho \cdot \alpha_{12}\big) \cdot T_l\\ &= \big(\alpha_1 + \alpha_2 d_i^2 + \alpha_3 d_i^n\big) \cdot T_l. \end{aligned} \tag{5}$$

Theorem 1: Given D and K, when all hop-distances are made equal to $\frac{D}{K}$, the $\mathcal{E}_T(D)$ is minimized.

Proof: The proof is done in the similar line as done in [27]. Note that $\mathcal{E}_R(d)$ is strictly convex as $\frac{d^2\mathcal{E}_R}{dt^2} > 0$. Therefore, using *Jensen's inequality*, it yields

$$\begin{aligned}&\mathcal{E}_R\left(\tfrac{\sum_{i=1}^{K} d_i}{K}\right) \le \tfrac{\sum_{i=1}^{K} \mathcal{E}_R(d_i)}{K} \Rightarrow K \cdot \mathcal{E}_R\left(\tfrac{D}{K}\right) \le \textstyle\sum_{i=1}^{K} \mathcal{E}_R(d_i)\\ &\qquad\Rightarrow K \cdot \mathcal{E}_R\left(\tfrac{D}{K}\right) \le \mathcal{E}_T(D), \end{aligned} \tag{6}$$

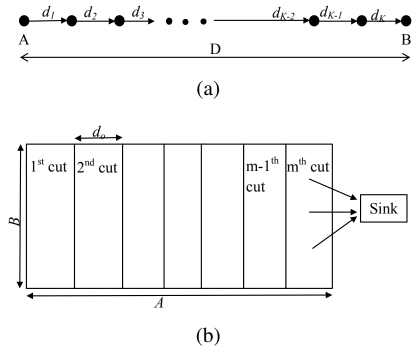


Fig. 2. (a) $K-1$ relays between A and B. (b) A sensor network with N nodes in a field of A×B.

and this completes the proof. ■

Therefore, the minimum consumption of energy for sending a packet to a distance D through K number of hops is

$$\mathcal{E}_T(D) = \left(\alpha_1 K + \alpha_2 \cdot K \cdot \left(\frac{D}{K}\right)^2 + \alpha_3 \cdot K \cdot \left(\frac{D}{K}\right)^n\right) \cdot T_l \tag{7}$$

Differentiating $\mathcal{E}_T(D)$ with respect to K are setting to zero, we get $\alpha_1 - \alpha_2 \cdot \left(\frac{D}{K}\right)^2 + (n-1)\alpha_3 \cdot \left(\frac{D}{K}\right)^n = 0$. If K_{opt} is the optimal value of K, then the characteristic distance $d_m = \frac{D}{K_{\text{opt}}}$. Replacing d_m in the previous equation, we get

$$\alpha_1 - \alpha_2 \cdot d_m^2 + (n-1)\alpha_3 \cdot d_m^n = 0. \tag{8}$$

Solving equation (8) gives d_m in terms of α_1, α_2, α_3, n. More importantly, d_m is independent of D.

B. Network Lifetime Calculation of Data Aggregation SD-WSNs

Using Theorem 1, we compute the the lifetime of a network that has N sensor nodes with uniform distribution in an area of $A \times B$. As shown in Fig. 2(b), we assume that the network area is divided into rectangular areas, namely *cuts*, with width d_o. In any cut, packets are forwarded to immediate right nodes. Let us first consider a single channel operation and compute the energy consumption in each cut under the assumptions that the beacon rate is B beacons/seconds and that each node generates b packets/seconds. Cuts numbered from left to right in an increasing order and the total number of cuts is $m = \frac{A}{d_o}$. We assume that in any cut, the nodes convey the traffic of the nodes from their left cuts. Due to full aggregation, all nodes transmit their traffic, along with their children's traffic, at a rate of b packets/seconds after fusion. Therefore, under our assumptions, in the i-th cut, the expected energy consumed for different actions is

$$\begin{aligned}&\mathcal{E}_{Dt}^i = b\left(\alpha_{11} + \alpha_3 d_o^n\right) \cdot T_l \qquad \mathcal{E}_{Dr}^i = b\alpha_{12} \cdot T_l\\ &\mathcal{E}_{Bt}^i = B\left(\alpha_{11} + \alpha_3 d_o^n\right) \cdot T_l \qquad \mathcal{E}_{Br}^i = \big(\pi \cdot d_o^2\rho - 1\big)\, B\alpha_{12} \cdot T_l\\ &\mathcal{E}_{\text{ov}}^i = \big(\pi \cdot d_o^2\rho - 1\big)\, b\alpha_{12} \cdot T_l \end{aligned} \tag{9}$$

Thus, for the nodes in the i-th cut, the total energy consumption is

$$\mathcal{E}^i \;\; = \;\; \mathcal{E}_{Dt}^i + \mathcal{E}_{Dr}^i + \mathcal{E}_{Bt}^i + \mathcal{E}_{Br}^i + \mathcal{E}_{\text{ov}}^i + \mathcal{E}_S^i + \mathcal{E}_P^i. \tag{10}$$

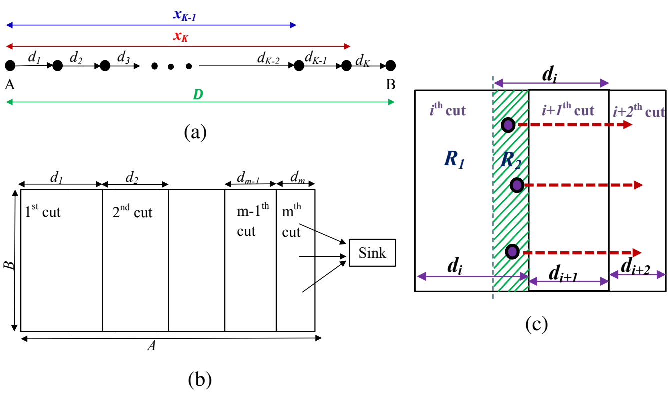


Fig. 3. (a) Introducing $K-1$ relays between A and B for data gathering SDWSNs. (b) A sensor network with N nodes in a field of A×B. (c) An illustration of extra energy consumption due to the assumption that nodes in the i-th cut send their packets only to $(i+1)$-th cut.

In the case of data aggregation SDWSNs, all cuts have same average energy consumption. Now we calculate the network lifetime with different battery capacity distributions as follows:

Expected Lifetime for Identical Battery Capacities: Assume that the initial battery capacity of each node is e_0 and the cut-off capacity is τ is, beyond which the sensor does not work. $L_i = \frac{e_0-\tau}{\mathcal{E}^i}$ denotes the expected lifetime of any node in the i-th cut of L.

Expected Lifetime for Differing Battery Capacities: In real deployment scenarios, few sensor nodes die earlier than others due to different spatio-temporal factors. To resume the network connectivity and coverage, new nodes are used in the low-density areas. Because of all these reasons, the battery capacities of all the nodes at any time instance are different, which can be modeled as a Gaussian distribution. In such a scenario, the lifetime of the network is defined as the time till *a fraction of the network nodes remain alive*. We assume that the battery capacity of any node at any instance is a Gaussian random variable with mean μ and standard deviation σ. We define the remaining capacity of any node k in the i-th cut at time t_j is $e_{ki}(t_j)$. If at a time instance t_0, $e_{ki}(t_0) \sim \mathcal{N}\left(\mu, \sigma^2\right)$, the probability that the remaining capacity of a node in the i-th cut is greater than τ at time t_j (assume $t_j - t_0 = \Delta t$) is

$$\begin{aligned} p_i &= P[e_{ki}(t_j) > \tau] = P[e_{ki}(t_0) - \mathcal{E}^i \cdot \Delta t > \tau] \\ &= P[e_{ki}(t_0) > \tau + \mathcal{E}^i \cdot \Delta t] = Q\left(\tfrac{\tau+\mathcal{E}^i\cdot\Delta t-\mu}{\sigma}\right). \end{aligned} \tag{11}$$

Therefore, the expected number of nodes at time t_j in the i-th cut whose capacity is greater than τ is given by $\sum_{x=1}^{\mathbb{N}} x \cdot \binom{\mathbb{N}}{x} \cdot p_i^x \cdot (1-p_i)^{\mathbb{N}-x}$, where $\mathbb{N} = \frac{N}{m}$ is the number of nodes in each cut. If the lifetime of the cut is the time that f fraction of the nodes remain alive, then the expected lifetime of any cut i is calculated by

$$\textstyle\sum_{x=1}^{\mathbb{N}} x \cdot \binom{\mathbb{N}}{x} \cdot p_i^x \cdot (1-p_i)^{\mathbb{N}-x} = f \cdot \mathbb{N}. \tag{12}$$

Notice that in the case of data aggregation SDWSNs, except the cuts at the two ends (that is, 1st and m-th cut), *the expected lifetime of all the other cuts are identical*. This is due to the fact that in all these cuts the data forwarding rate are identical and so is the overhearing rate, due to data aggregation at every node in the multi-hop topology.

IV. Network Lifetime with Power Adaptation for Data Gathering SDWSNs

A. Transmit Power Adaptation

Now consider the case of data gathering SDWSNs, in which all the nodes sense and transmit their packets periodically in a multihop tree fashion without aggregation. Similar to the previous section, we calculate the total energy consumption, while all nodes in between A to B with $K-1$ relays in between, transmit a packet, as depicted in Fig. 3(a). D denotes the distance between A and B. Hence, the overall energy consumed in this case is given by

$$\mathcal{E}_T(D) = \textstyle\sum_{i=1}^{K} i\left(\mathcal{E}_{\text{relay}}(d_i) + \mathcal{E}_{\text{ov}}(d_i)\right) = \sum_{i=1}^{K} i \cdot \mathcal{E}_R(d_i) \tag{13}$$

where

$$\begin{aligned} \mathcal{E}_R(d_i) &= \mathcal{E}_{\text{relay}}(d_i) + \mathcal{E}_{\text{ov}}(d_i) \\ &= \left(\alpha_{11} - \alpha_{12} + \alpha_3 d_i^n + \pi \cdot d_i^2 \rho \cdot \alpha_{12}\right) \cdot T_l \\ &= \left(\alpha_1 + \alpha_2 d_i^2 + \alpha_3 d_i^n\right) \cdot T_l \\ \therefore \mathcal{E}_T(D) &= \sum_{i=1}^{K} i\big(\alpha_1 + \alpha_2 d_i^2 + \alpha_3 d_i^n\big) \cdot T_l \end{aligned} \tag{14}$$

Theorem 2: Given D and K, $\mathcal{E}_T(D)$ is minimized when d_i's are given by equation (15), where $x_K = \sum_{i=1}^{K-1} d_i$, and $P_{K-1} = \frac{x_{K-1}}{x_K}$.

$$\begin{aligned} &\sum_{l=0}^{i-2} l \cdot \left\{\alpha_2(1-P_l)^2 \prod_{q=l+1}^{i-1} P_q^2 \cdot 2x_i + \alpha_3(1-P_l)^n \prod_{q=l+1}^{i-1} P_q^n \cdot n x_i^{n-1}\right\} + (i-1)\left[2\alpha_2 x_i(1-P_{i-1})^2 + n\alpha_3 x_i^{n-1}(1-P_{i-1})^n\right] \\ &= 2i\alpha_2(x_{i+1}-x_i) + ni\alpha_3(x_{i+1}-x_i)^{n-1}. \end{aligned} \tag{15}$$

Proof: We first assume that $\mathcal{E}_T(D) = f_K T_l$, where

$$\begin{aligned} f_K &= \sum_{i=1}^{K} i\left(\alpha_1 + \alpha_2 d_i^2 + \alpha_3 d_i^n\right) \\ &= K\big(\alpha_1 + \alpha_2 d_K^2 + \alpha_3 d_K^n\big) \\ &+ (K-1)\big(\alpha_1 + \alpha_2 d_{K-1}^2 + \alpha_3 d_{K-1}^n\big) + \cdots \\ &= K\big(\alpha_1 + \alpha_2 d_K^2 + \alpha_3 d_K^n\big) + f_{K-1}. \end{aligned} \tag{16}$$

Now, let us calculate the optimal transmission ranges (d_1, d_2, d_3, …, d_K) to minimize $\mathcal{E}_T(D)$ (or f_K) using *dynamic programming*, similar to [28]. We define a variable x_K =

$\sum_{i=1}^{K-1} d_i$, as shown in Fig. 3(a). Thus, $d_K = D - x_K$, $d_{K-1} = x_K - x_{K-1}$, $d_{K-2} = x_{K-1} - x_{K-2}$ and so on. The optimal solution of the problem with K hops and a given distance D is equivalent to the optimal solution for some distance $x_K < D$ with $K-1$ hops, plus a final hop to the sink as in Fig. 3(a), which is written in Equation (17). Next assume that $P_{K-1} = \frac{x_{K-1}}{x_K}$, then Equation (17) can be written using recursion as in equation (18). Note that $P_K = \frac{x_K}{D}$ and $P_1 = \frac{x_1}{x_2} = 0$. Taking the derivative of Equation (18) and equating it to zero gives Equation (21), which completes the proof. For $n = 2$, we get a closed form solution of x_K as shown in Equation (22), but for general n, the optimal transmissions ranges can be calculated by solving Equation (21). ■

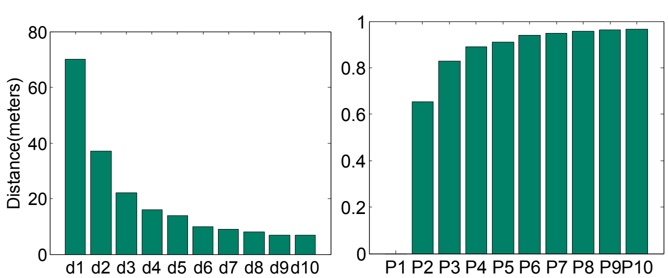
$$
\begin{aligned}
f_K(D) &= \min_{0\le x_K\le D} f_{K-1}(x_K) + K\big[\alpha_1 + \alpha_2(D-x_K)^2 + \alpha_3(D-x_K)^n\big], \qquad (17)\\
\text{and } f_{K-1}(x_K) &= \min_{0\le x_K\le D} f_{K-2}(x_{K-1}) + (K-1)\big[\alpha_1 + \alpha_2(x_K-x_{K-1})^2 + \alpha_3(x_K-x_{K-1})^n\big],\\
\therefore f_K(D) &= \min_{0\le x_K\le D} \sum_{l=0}^{K-2} l\cdot\left\{\alpha_1 + \alpha_2(1-P_l)^2\prod_{q=l+1}^{K-1}P_q^2x_K^2 + \alpha_3(1-P_l)^n\prod_{q=l+1}^{K-1}P_q^nx_K^n\right\}\\
&\quad +(K-1)\left[\alpha_1 + \alpha_2x_K^2(1-P_{K-1})^2 + \alpha_3x_K^n(1-P_{K-1})^n\right] + K\left[\alpha_1+\alpha_2(D-x_K)^2+\alpha_3(D-x_K)^n\right], \qquad (18)
\end{aligned}
$$

$$
\begin{aligned}
&\sum_{l=0}^{K-2} l \cdot\left\{\alpha_2(1-P_l)^2\prod_{q=l+1}^{K-1}P_q^2\cdot 2x_K + \alpha_3(1-P_l)^n\prod_{q=l+1}^{K-1}P_q^n\cdot nx_K^{n-1}\right\}\\
&+(K-1)\left[2\alpha_2x_K(1-P_{K-1})^2 + n\alpha_3x_K^{n-1}(1-P_{K-1})^n\right] = 2K\alpha_2(D-x_K) + nK\alpha_3(D-x_K)^{n-1}. \qquad (19)
\end{aligned}
$$

$$
\text{For } n = 2,\ x_K = \frac{KD(\alpha_2+\alpha_3)}{\sum_{l=0}^{K-2} l\cdot\left\{\alpha_2(1-P_l)^2\prod_{q=l+1}^{K-1}P_q^2 + \alpha_3(1-P_l)^2\prod_{q=l+1}^{K-1}P_q^2\right\} + (K-1)\left[\alpha_2(1-P_{K-1})^2+\alpha_3(1-P_{K-1})^2\right] + K(\alpha_2+\alpha_3)}. \qquad (20)
$$

$$
\begin{aligned}
\text{In general, } \forall i \in \{2,3,\ldots,K\}, &\sum_{l=0}^{i-2} l\cdot\left\{\alpha_2(1-P_l)^2\prod_{q=l+1}^{i-1}P_q^2\cdot 2x_i + \alpha_3(1-P_l)^n\prod_{q=l+1}^{i-1}P_q^n\cdot nx_i^{n-1}\right\}\\
&+(i-1)\left[2\alpha_2x_i(1-P_{i-1})^2 + n\alpha_3x_i^{n-1}(1-P_{i-1})^n\right] = 2i\alpha_2(x_{i+1}-x_i) + ni\alpha_3(x_{i+1}-x_i)^{n-1}. \qquad (21)
\end{aligned}
$$

$$
\text{For } n = 2,\ x_i = \frac{i\cdot x_{i+1}(\alpha_2+\alpha_3)}{\sum_{l=0}^{i-2} l\cdot\left\{\alpha_2(1-P_l)^2\prod_{q=l+1}^{i-1}P_q^2 + \alpha_3(1-P_l)^2\prod_{q=l+1}^{i-1}P_q^2\right\} + (i-1)\left[\alpha_2(1-P_{i-1})^2+\alpha_3(1-P_{i-1})^2\right] + i(\alpha_2+\alpha_3)}. \qquad (22)
$$



(a) (b)

Fig. 4. Variation of (a) d_i and (b) P_i when D = 200 meters, ρ = 0.0125 nodes/meters^2, n = 2.5. α_1, α_3, and α_3 are found to be -0.6877, 0.3925 and 0.00054 respectively.

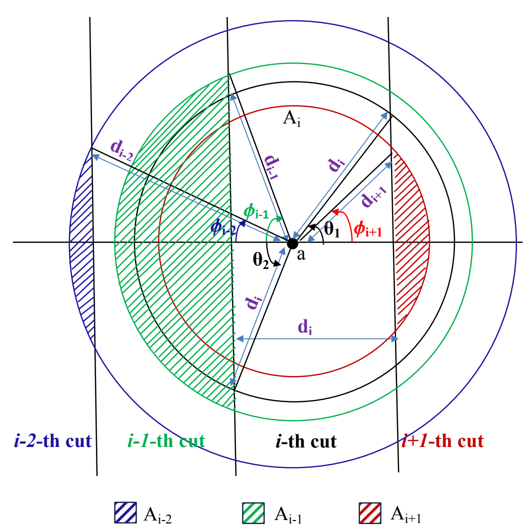


Fig. 5. Calculating overhearing at the i-th cut in tree based SDWSNs.

Fig. 4 shows the variation of hop length and $P_i = \frac{x_i}{x_{i+1}}$, for a ten-hop linear network as in Fig. 3(a). From this figure, it is observed that the nodes that are closer to the sink have lesser transmit power compared to the nodes that are far away. The reason is because the nodes closer to the sink carry more traffic, and so the amount of overhearing and packet forwarding are higher. Thus, to balance this nonuniform distribution of traffic, the hop lengths are lesser in the regions closer to the sink to limit the effect of more overhearing and forwarding. Also from Fig. 4(b), we can see that P_i increases with the increase in i and gradually becomes close to one in the region nearer to the sink.

B. Network Lifetime Calculation of Data Gathering SDWSNs

With this we calculate the network lifetime, where N sensor nodes are distributed in an area of $A\times B$, that forward their packets in a multi-hop tree fashion to the sink. As we have seen in data gathering SDWSNs, the hop-lengths closer to the sink are smaller compared to the nodes that are far away. Thus we divide the network in different cuts, where the cut length nearer to the sink are smaller compared to the cuts that are farther away, as shown in Fig. 3(b). For simplicity, we assume that nodes in any cut forward their packets to the nodes that are in their immediately right cut.[1] When there are not enough number of alive nodes in a cut, the packets sent by the preceding cuts cannot able to cross that cut, thus the network is partitioned. Now we calculate the energy consumption in each cut. Similar to the previous section, we assume that each node generates b packets/seconds and the beacon rate is B beacons/seconds. Based on the distribution of the nodes in the cuts, we consider two different cases as described below:

Uniform node distribution: In uniform distribution of sensor nodes, cuts nearer to the sink forward packets generated by the previous cuts. At any cut, nodes transmit their own b packets/seconds in addition to packets generated by their previous cuts. Therefore, on average, nodes in the i-th cut send $\left(1+\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b$ packets per second. Hence, under our assumptions, the expected energy used for different actions in the i-th cut is given by

$$\begin{aligned}
\mathcal{E}_{Dt}^i &= \left(1+\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b\left(\alpha_{11}+\alpha_3 d_o^n\right)\cdot T_l,\\
\mathcal{E}_{Dr}^i &= \left(\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b\alpha_{12}\cdot T_l,\\
\mathcal{E}_{Bt}^i &= B\left(\alpha_{11}+\alpha_3 d_i^n\right)\cdot T_l. \qquad (23)
\end{aligned}$$

The nodes in the i-th cut are overheard by the nodes from $(i-2)$-th, $(i-1)$-th and $(i+1)$-th cut and also from the nodes in the i-th cut, as shown in Fig 5. The areas of A_{i-2}, A_{i-1}, A_i and A_{i+1} are given by

$$\begin{aligned}
A_{i-2} &= d_{i-2}^2(\phi_{i-2}-\sin\phi_{i-2}\cos\phi_{i-2})\\
A_{i-1} &= d_{i-1}^2(\phi_{i-1}-\sin\phi_{i-1}\cos\phi_{i-1})\\
A_i &= \pi d_i^2 - d_i^2(\theta_1-\sin\theta_1\cos\theta_1) - d_i^2(\theta_2-\sin\theta_2\cos\theta_2)\\
A_{i+1} &= d_{i+1}^2(\phi_{i+1}-\sin\phi_{i+1}\cos\phi_{i+1}) \qquad (24)
\end{aligned}$$

Therefore, the expected number of packets that a node a in the i-th cut overhears is given in Equation (25). Similarly, the number of beacon packet received by a node in the i-th cut is

$$\begin{aligned}
B_i &= E[A_i]B\rho + E[A_{i+1}]B\rho, && \text{for } i=1\\
&= E[A_{i-1}]B\rho + E[A_i]B\rho + E[A_{i+1}]B\rho, && \text{for } i=2\\
&= E[A_{i-2}]B\rho + E[A_{i-1}]B\rho + E[A_i]B\rho\\
&\quad +E[A_{i+1}]B\rho, && \text{for } 3<i<m\\
&= E[A_{i-2}]B\rho + E[A_{i-1}]B\rho + E[A_i]B\rho, && \text{for } i=m \qquad (26)
\end{aligned}$$

[1] We assume this for simplicity, although this assumption results in some waste in current consumption. This is illustrated in Fig. 3(c) where some nodes from region R_2 of the i-th cut can send their packets directly to the $(i+2)$-th cut, instead of going through $(i+1)$-th cut. We assume that nodes in i-th cut sends only to $(i+1)$-th cut for simplicity, but this is valid especially for the cuts closer to the sink as the hop-lengths are almost same to the nodes closer to the sink as shown in Fig. 4(a).

Non-uniform node distribution: In the uniform node distribution, the number of nodes decreases with the increase in the cut number. As the nodes need to forward the packets of their previous cuts, the forwarding rate increases significantly with the increase in cut number, which results in significantly lesser battery lifetime for the nodes that are closer to the sink. To improve the network lifetime, non-uniform node placement is proposed where each cut has $\frac{N}{m}$ nodes that are placed uniformly within the cut. In this type of node distribution, nodes in the i-th cut on average transmit $i\cdot b$ packets/seconds. In that case the energy consumption in the i-th cut due to different actions are given as

$$\begin{aligned}
ov_i &= E[A_i]i\cdot b\rho_i + E[A_{i+1}](i+1)b\rho_{i+1}, && \text{for } i=1\\
&= E[A_{i-1}](i-1)b\rho_{i-1} + E[A_i]i\cdot b\rho_i\\
&\quad +E[A_{i+1}](i+1)b\rho_{i+1}, && \text{for } i=2\\
&= E[A_{i-2}](i-2)b\rho_{i-2} + E[A_{i-1}](i-1)b\rho_{i-1}\\
&\quad +E[A_i]i\cdot b\rho_i + E[A_{i+1}](i+1)b\rho_{i+1}, && \text{for } 3<i<m\\
&= E[A_{i-2}](i-2)b\rho_{i-2} + E[A_{i-1}](i-1)b\rho_{i-1}\\
&\quad +E[A_i]i\cdot b\rho_i, && \text{for } i=m \qquad (27)
\end{aligned}$$

$$\begin{aligned}
B_i &= E[A_i]B\rho_i + E[A_{i+1}]B\rho_{i+1}, && \text{for } i=1\\
&= E[A_{i-1}]B\rho_{i-1} + E[A_i]B\rho_i + E[A_{i+1}]B\rho_{i+1}, && \text{for } i=2\\
&= E[A_{i-2}]B\rho_{i-2} + E[A_{i-1}]B\rho_{i-1} + E[A_i]B\rho_i\\
&\quad +E[A_{i+1}]B\rho_{i+1}, && \text{for } 3<i<m\\
&= E[A_{i-2}]B\rho_{i-2} + E[A_{i-1}]B\rho_{i-1} + E[A_i]B\rho_i, && \text{for } i=m \qquad (28)
\end{aligned}$$

$$\begin{aligned}
\mathcal{E}_{Dt}^i &= i\cdot b\left(\alpha_{11}+\alpha_3 d_i^n\right)\cdot T_l,\\
\mathcal{E}_{Dr}^i &= (i-1)\cdot b\alpha_{12}\cdot T_l,\\
\mathcal{E}_{Bt}^i &= B\left(\alpha_{11}+\alpha_3 d_i^n\right)\cdot T_l, \qquad (29)
\end{aligned}$$

where ρ_i is the node density in the i-th cut, that is, $\rho_i = \frac{N}{m\cdot B\cdot d_i}$. Putting the energy consumption of different events in equation (10), we obtain a new expression of $\mathcal{E}^i$ to calculate the average energy consumption and network lifetime.

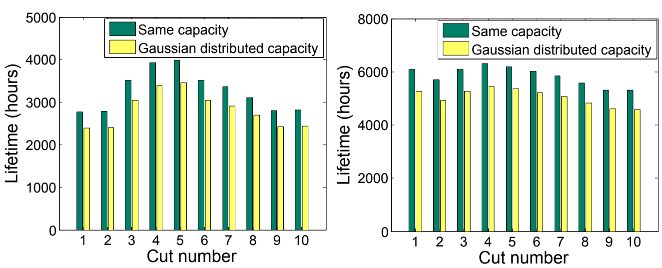
To compare the effects of node placement in data collecting SDWSNs, we place 100 nodes in an area of 200×200 sq. meter. The parameters used for the results are listed in Table I. We consider two scenarios. In the first scenario, all nodes have the same initial battery capacity equal to 5000 mAHr. In the second scenario, battery capacities have a normal distribution with a mean of 5000 mAHr and a standard deviation of 1000 mAHr. In the case of normally distributed battery capacities, the expected lifetime is computed as the time till the 75% of nodes in a cut survive. Every node sends a beacon and a packet in every minute. τ is assumed to be 0. Fig. 6 shows the lifetime comparison between the uniform and nonuniform node deployments, for different cut numbers. From this figure we can observe that for uniform distribution of nodes, the lifetime is poor compared to the nonuniform case. This is because of significant increase in forwarding and overhearing rates, with the increase in cut number. Also we can observe

$$
\begin{aligned}
ov_i &= E[A_i]\left(1+\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b\rho + E[A_{i+1}]\left(1+\frac{\sum_{j=1}^{i} d_j}{d_{i+1}}\right)\cdot b\rho & \text{for } i=1\\
&= E[A_{i-1}]\left(1+\frac{\sum_{j=1}^{i-2} d_j}{d_{i-1}}\right)\cdot b\rho + E[A_i]\left(1+\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b\rho + E[A_{i+1}]\left(1+\frac{\sum_{j=1}^{i} d_j}{d_{i+1}}\right)\cdot b\rho & \text{for } i=2\\
&= E[A_{i-2}]\left(1+\frac{\sum_{j=1}^{i-3} d_j}{d_{i-2}}\right)\cdot b\rho + E[A_{i-1}]\left(1+\frac{\sum_{j=1}^{i-2} d_j}{d_{i-1}}\right)\cdot b\rho + E[A_i]\left(1+\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b\rho + E[A_{i+1}]\left(1+\frac{\sum_{j=1}^{i} d_j}{d_{i+1}}\right)\cdot b\rho & \text{for } 3<i<m\\
&= E[A_{i-2}]\left(1+\frac{\sum_{j=1}^{i-3} d_j}{d_{i-2}}\right)\cdot b\rho + E[A_{i-1}]\left(1+\frac{\sum_{j=1}^{i-2} d_j}{d_{i-1}}\right)\cdot b\rho + E[A_i]\left(1+\frac{\sum_{j=1}^{i-1} d_j}{d_i}\right)\cdot b\rho & \text{for } i=m\\
E[A_{i-2}] &= \frac{1}{\cos^{-1}\left(\frac{d_{i-1}}{d_{i-2}}\right)}\int_0^{\cos^{-1}\left(\frac{d_{i-1}}{d_{i-2}}\right)} d_{i-2}^2\,(\Phi-\sin\Phi\cos\Phi)\cdot d\Phi\\
E[A_{i-1}] &= \frac{1}{\frac{\pi}{2}-\cos^{-1}\left(\frac{d_i}{d_{i-1}}\right)}\int_{\cos^{-1}\left(\frac{d_i}{d_{i-1}}\right)}^{\frac{\pi}{2}} d_{i-1}^2\,(\Phi-\sin\Phi\cos\Phi)\cdot d\Phi\\
E[A_i] &= \pi\cdot d_i^2-\frac{2}{\pi}\int_0^{\frac{\pi}{2}} d_i^2(\Phi-\sin\Phi\cos\Phi)\cdot d\Phi-\frac{2}{\pi}\int_0^{\frac{\pi}{2}} d_i^2(\Phi-\sin\Phi\cos\Phi)\cdot d\Phi\\
E[A_{i+1}] &= \frac{2}{\pi}\int_0^{\frac{\pi}{2}} d_{i+1}^2\,(\Phi-\sin\Phi\cos\Phi)\cdot d\Phi & (25)
\end{aligned}
$$

TABLE I
MICA2 PARAMETERS

Var	Values	Var	Values	Var	Values	Var	Values
I_{Br}	10 mA	T_{Br}	140 ms	I_{Dr}	10 mA	T_{Dr}	140 ms
I_P	10 mA	T_P	3 ms	I_S	7.5 mA	T_S	112 ms

Var	Values	Var	Values
I_{Bt}, I_{Dt}	11.8 mA (1 dBm), 9.7 mA (-2 dBm) 13.8 mA (4 dBm), 12.8 mA (2 dBm) 16.8 mA (7 dBm), 14.8 mA (5 dBm) 26.7 mA (10 dBm), 20 mA (8 dBm)	T_{Bt}, T_{Dt}	140 ms



(a) (b)

Fig. 6. Variation of lifetime of different cuts for (a) uniform and (b) nonuniform deployment of sensor nodes.

that for non-uniform node deployment, the lifetime not only improves, but also becomes more uniform among different cuts. We can also observe that the $(m-1)$-th cut has the lowest lifetime for both cases.

V. Network Lifetime with Multiple Channels

A key challenge of a single channel, asynchronous sensor network is that, a node overhears the traffic sent by all its neighbors, even if they are not destined to it. This problem can be alleviated by using multiple orthogonal channels, where

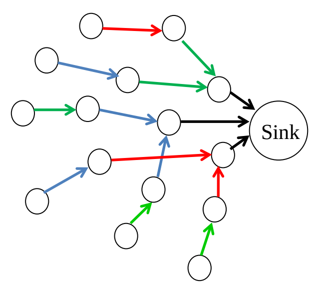


Fig. 7. Illustration of a multi-channel SDWSN. Different channels are represented by different colors.

the network traffic is divided among these channels. Typical WSN sensor nodes, such as TelosB [10] and MICAz [9] use CC2420 radios which provides 16 orthogonal channels with 5MHz spacing in between the center frequencies. On the other hand Mica2 [29] uses CC1000 radios, which can provide 50 channels [30]. Thus the current hardwares can take advantage of such multi-channel radios to reduce the effect of overhearing.

Thus to minimize the overall energy consumption and to extend the network lifetime, we uniformly distribute k orthogonal channels over network nodes, as shown in Fig. 7. We now show that the effect of overhearing in presence of multiple channels is similar to the well-known *vertex coloring problem* [31]. Given a connectivity graph, the objective of the vertex coloring problem is to color the vertices in such a way that no two vertices in the connectivity graph having a link have the same color. In other words, for an undirected graph $G=(V,E)$, a coloring of G is a mapping $\pi: V\rightarrow C$, where $\forall x,y$, $(x,y)\in E \rightarrow \pi(x)\neq\pi(y)$. In our case the connectivity graph G consists of all the sensor nodes. An edge exists in between two nodes if they are inside the overhearing range of each other. By exploiting multiple orthogonal channels, our objective is to color the graph with k colors is such a way

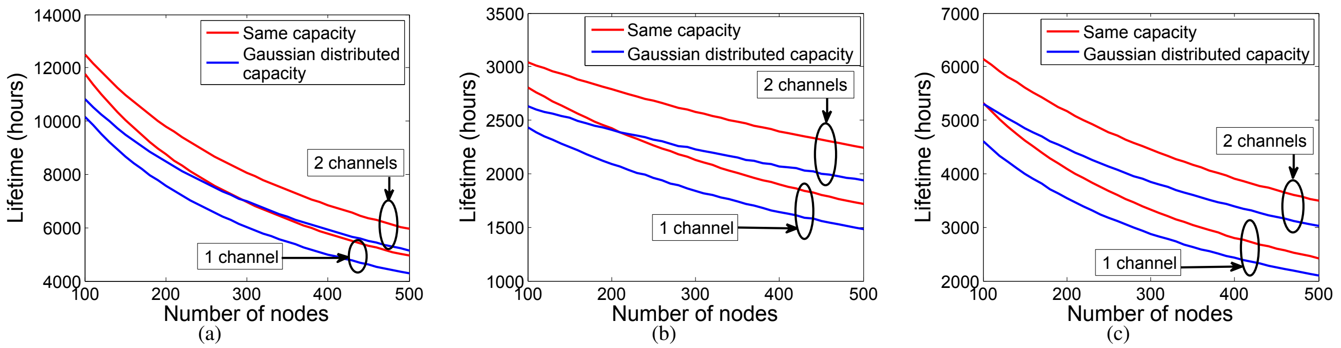


Fig. 8. Expected network lifetime with different number of nodes, for (a) data aggregation SDWSNs, (b) data gathering SDWSNs with uniform node deployment and (c) data gathering SDWSNs with nonuniform node deployment.

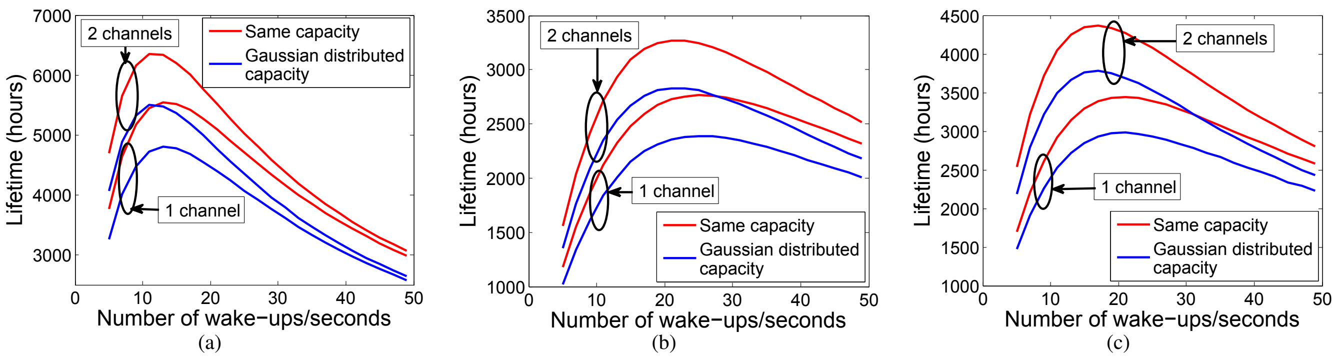


Fig. 9. Expected network lifetime with different wake-up rates, for (a) data aggregation SDWSNs, (b) data gathering SDWSNs with uniform node deployment and (c) data gathering SDWSNs with nonuniform node deployment.

the number of overhearing edges is minimized. Therefore, we define the multi-channel assignment problem as a vertex coloring problem. In this section, we use the words *channel* and *color* interchangeably.

We therefore calculate the expected network lifetime of a multi-channel SDWSN, by making use of the concept of vertex coloring. For simplicity, we assume that a graph is *regular* with degree δ, i.e. all its vertices have the same degree. We uniformly assign k colors to N vertices of this graph, and then group the nodes having the same color. Let us represent the set of nodes colored with the i-th color by the i-th color set S_i, where $i = \{1, \ldots, k\}$. For simplicity, we assume $k|N$; thus, $|S_i| \approx \frac{N}{k}$. Let us denote the probability that an edge $e \in G$ is an overhearing edge by $\text{Prob}_{\text{overhear}}(e)$. Thus $\text{Prob}_{\text{overhear}}(e)$ can be expressed as the probability that nodes at the both ends of e are from the same color set, which is given by

$$\text{Prob}_{\text{overhear}}(e) = \frac{k \cdot \binom{|S_i|}{2}}{\binom{N}{2}}, \tag{30}$$

Then the expected number of overhearing edges is

$$q = \frac{N \cdot \delta}{2} \cdot \frac{k \cdot \binom{|S_i|}{2}}{\binom{N}{2}} = \frac{N \cdot \delta \cdot (N-k)}{2 \cdot k \cdot (N-1)}, \tag{31}$$

where $\frac{N \cdot \delta}{2}$ is the total number of edges in the graph. Thus, each node has $\frac{2 \cdot q}{N} = \frac{\delta \cdot (N-k)}{k \cdot (N-1)}$ overhearers. Therefore, the number of overhearers in a unit area is approximately given by

$$\rho_c = \frac{\delta \cdot (N-k)}{\pi \cdot d_0^2 \cdot k \cdot (N-1)}. \tag{32}$$

Putting ρ_c in place of ρ in overhearing energy consumption in Equation (9) yields a modified $\mathcal{E}^i_{\text{ov}}$. With this modified expression of $\mathcal{E}^i_{\text{ov}}$, we obtain a new expression of $\mathcal{E}^i$ and L_i for network lifetime with multiple channels. Notice that when $N \gg k$, $\rho_c \approx \frac{\rho}{k}$.

VI. Performance Evaluations

In this section, we evaluate the performance of the network lifetime with different control parameters. We use the same setup as done for Fig. 6 for our results. The parameters used for the following results are listed in Table I, unless it is mentioned otherwise. In our experiments, we consider $T_l = \frac{1}{P} + 15$ ms; hence, for P = 8, T_l = 140 ms. We consider the worst case scenario when the nodes overhear the whole preamble, including the control packet or data payload. The beacons and data packets are sent only once per minute. We assume that the mean battery capacity of nodes is 5000 mAHr. For Gaussian distributed battery capacities, the capacities uniformly vary with σ = 1000 mAHr.

A. Effect of number of nodes

For both data aggregation and data gathering SDWSNs, we consider the lifetime of the $(m-1)$-th cut as the representative cut for comparing the worst network lifetime. This is because in data aggregation SDWSNs the lifetime of all the cuts (except 1st and m-th cut) are identical, whereas in data gathering SDWSNs the $(m-1)$-th cut has the lowest lifetime as shown in Fig. 6. The sensor nodes are placed uniformly in area of 200×200 sq. meter. Notice that for nonuniform node distribution, we use the overhearing expression of uniform distribution from equation (32), by considering the fact that the density of the neighboring regions of $(m-1)$-th cut is almost identical.

The variation of lifetime for the $(m-1)$-th cut with different number of nodes is shown in Fig. 8. We assume that a node wakes-up 8 times a second to check the channel activity, which makes T_{Br} = T_{Dr} = T_l = 140 ms as mentioned in Table I. From this figure we observe a good amount of improvement in lifetime using two channels compared to a single channel case. This is obvious since increasing channels results in reduced overhearing, which results in higher network lifetime. We also observe that with data aggregation, the network lifetime is $\sim$2-4 times higher as compared to the data gathering scenario. This is because in case of data aggregation, the forwarding rate is same for all the cuts, which improves the network lifetime significantly. Also, we observe that the network lifetime is higher for non-uniform network deployment compared to the uniform deployment of sensor nodes.

B. Effect of wake-up frequencies

The variation of lifetime for the $(m-1)$-th cut with wake-up frequencies is shown in Fig. 9. For this experiment, we assume 500 nodes. As shown in Fig. 9, with an increase in the wake-up frequency, the lifetime starts increasing because of lesser preamble length. However, the lifetime starts to reduce after a certain point since frequent wake-ups consume more current. The maximum lifetime is achieved when the wake-up frequency is $\sim$10-20 times/seconds. It is also observed that data aggregation SDWSNs improve the network lifetime compared to data gathering SDWSNs, which is consistent with our previous observation in Fig. 6.

VII. Conclusion

The fundamental challenge in designing protocols for SD-WSNs is to maximize the network lifetime. This paper addresses an analytical model of network lifetime calculation of SDWSNs for different battery capacity distributions and compares the effects of different parameters on network lifetime under transmit power adaptations. Other than power control, another important factor for controlling overhearing as well as network lifetime is to consider the effects of multiple channels. We also consider data aggregation as well as data gathering SDWSNs with different node deployment strategies. Comprehensive effects of different parameters on network lifetime is also evaluated. Our comprehensive test results showed that the network lifetime is higher for traffic-aware non-uniform node deployment compared to the uniform deployment of sensor nodes. Also, as compared to data gathering SDWSNs, the use of data aggregation SDWSNs improves the network lifetime.

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