Data Packet Length Optimization for Wireless Sensor Network Lifetime Maximization

Ayhan Akbas (Corresponding author)[1,*], Huseyin Ugur Yildiz[2], and Bulent Tavli[2]
[1]*TOBB University of Economics and Technology, Dept. of Computer Engineering, Ankara, Turkey.*
[2]*TOBB University of Economics and Technology, Dept. of Electrical and Electronics Engineering, Ankara, Turkey.*
[*]Corresponding author (E-mail : aakbas@etu.edu.tr)

***Abstract*—Wireless Sensor Networks (WSNs) comprising of battery-powered sensor nodes are being used in a wide range of applications. The feasibility of such applications is highly influenced by the longevity of these networks. In this work, we present a realistic WSN lifetime optimization framework where transmission power levels for both data and ACK packets are optimally selected (*i.e.*, a complete link-layer handshaking cycle is modeled). Log-normal shadowing path loss model is employed to take into account the effects of path losses. We utilized the developed Mixed Integer Programming (MIP) based optimization framework to investigate the impact of data packet length on WSN lifetime. To quantify the effects of data packet length on network lifetime we explored the parameter space consisting of the number of nodes and node deployment density. Our results show that the optimal data packet length is the maximum allowed length.**

***Keywords* - Wireless Sensor Networks, Network Lifetime, Energy Efficiency, Packet Size Optimization, Mixed Integer Programming.**

I. Introduction

A wireless sensor network (WSN), typically, consists of a base station and a multitude of spatially distributed sensor nodes to monitor real-world phenomena such as temperature, sound, pressure [1]. Sensor nodes are composed of a limited energy source, usually a battery. Hence, WSNs should be designed to prolong the lifetime. To maximize network lifetime, sensor nodes are obliged to cooperate in forwarding data towards the base station and dissipate their energies in a balanced fashion so that premature death of any node due to over-utilization of its energy is avoided, hence, the lifetime of the WSN is maximized [2].

Data packet length optimization is one of the potential areas for lifetime maximization in WSNs and there have been several studies on packet length optimization for WSNs in the literature. A survey of packet length optimization techniques in WSNs is presented in [3]. It is argued that higher rate of packet errors are more likely for longer packets which leads to higher frequency of retransmissions. On the other hand, shorter packet lengths result in lower retransmission rates. Authors propose that in order to develop energy efficient wireless sensor networks, an optimal length of packets must be chosen. Their research also shows that utilizing variable packet length scheme will increase the channel throughput, but on the other hand WSNs will ultimately suffer from the overhead of resource management.

Determination of the fixed optimal packet length for maximization of energy efficiency is studied in [4]. For a set of radio and channel parameters, the effects of error control on the packet length optimization for energy efficiency is also explored. It is shown that forward error correction can improve energy efficiency and retransmission schemes are not energy inefficient.

The effects of shadowing on the optimal transmit power to sustain network connectivity is investigated in [5]. Optimizations are made to increase battery-powered wireless sensor network by reducing internode interference. It is also shown that the use of optimal packet length significantly reduces energy dissipation.

In [6], a packet length control technique using variable sized packets based on channel condition is proposed. If channel is noisy (*i.e.*, the channel is congested due to heavy traffic), shorter packets are generated. While in a quite channel, (*i.e.*, it's almost idle) it will generate larger sized packets. Hence the proposed scheme enhances overall throughput and efficiency.

Though the literature is rich on packet optimization and network lifetime, in these studies, either the packet losses due to bit errors are not taken into account and/or handshaking mechanism is not considered properly. For example, in [5], failure probability of a handshake is taken as a constant for all of the links for a given network node density which is a misleading assumption because even if the distances between all node pairs are constant the path losses will not be the same (*i.e.*, the path loss under the assumption of log-normal shadowing includes a random term which varies from link to link). Furthermore, packer failure rates are not necessarily the same for data and acknowledgement (ACK) packets which is overlooked in [5]. Contrary to other studies, our model studies transmission power level optimized WSNs without ignoring packet losses which vary from link to link due to channel errors that can affect both data and ACK packets and focuses on low interference levels which is the general case for WSNs.

The rest of the paper is organized as follows. Our system model is elaborated, assumptions are stated, a succinct background on mathematical programming is provided, and the developed Mixed Integer Programming (MIP) model is presented in Section II. Numerical analysis to explore the parameter space and to compare the performances of the proposed strategies are provided in Section III. Section IV provides our concluding remarks.

II. System Model

Increasing the packet length decreases the ratio of overhead to the payload, therefore, it can increase the network lifetime. However, longer packets are more likely to be corrupted due to the higher probability of packet error. On the other hand, shorter packets are less prone to failure, yet, the ratio of overhead bits to the payload bits is also lower for shorter packets. Furthermore, the number of data packets to transport the same amount of data bits is higher when the maximum packet length is shorter. Hence, there are multiple mechanisms working in opposite directions, concurrently. To assess the net impact of packet length selection on WSN lifetime, we utilize an MIP framework for our quantitative analysis.

A. Overview

We consider a WSN consisting of a base station and multiple sensor nodes deployed uniformly to cover the WSN deployment domain. Sensor nodes convey collected data to base station directly (single-hop) or act as relay for other nodes (multi-hop). Time is organized into equal timed rounds of duration 60 seconds ($T_{rnd} = 60$ seconds). In each round, node-i generates s_i number of packets. Data exchange between any node is performed with hand-shaking (*i.e.*, each successful transmission is replied with an ACK packet by the receiver). Nodes can select transmission power levels from a finite set for both data and ACK packets. The objective of our problem is to maximize the network lifetime that is the duration between the time network starts operating and the time when the first sensor node in the network exhausts all its energy [2], [7].

B. Assumptions

Following assumptions are valid throughout this work:

1) The network consists of stationary nodes (both sensor nodes and the base station).
2) The base station has the complete topology information (*e.g.*, path losses on each link) and sufficiently high processing and energy resources to perform the necessary computation for data flow planning in a centralized manner.
3) All nodes are roughly time synchronized. There are many synchronization protocols designed specifically for WSNs with virtually no overhead and satisfactory synchronization performance [8].
4) Network reorganization period for a typical WSN is sufficiently long [1], therefore, the energy costs of topology discovery and route creation operations constitute a small fraction (*e.g.*, less than 1.0% [9]) of the total network energy dissipation. Therefore, control overhead can be neglected without leading to significant underestimation of total energy dissipation.
5) A TDMA-based MAC layer is in operation which mitigates interference between active links through a time-slot assignment algorithm which outputs a conflict-free transmission schedule. In fact, in our model, we use the sufficient condition presented in [10]. Furthermore, it is also possible to reduce data packet collisions to negligible levels in practical MAC protocols designed with a dynamic TDMA approach [11].
6) Path loss for each link can be measured by a closed loop power control mechanism and we assume that such a mechanism is in effect for our system.
7) Generated data packets at sensor nodes are treated as atomic data units that cannot be fragmented or aggregated at any relay node.

C. Link Layer Model

We employed Mica2 motes' energy dissipation characteristics to model energy dissipation of sensor nodes. Mica2 motes are equipped with a AtMega 128L processor and a CC1000 transceiver and they are the most heavily utilized sensor nodes in experimental WSN research due to their well-characterized energy dissipation properties. Power consumption of the transceiver and the corresponding output antenna power for Mica2 motes are presented in Table I. In this table, $P_{tx}^{crc}(l)$ and $P_{tx}^{ant}(l)$ refer the power consumption for transmission at power level-l, and the output antenna power at power level-l, respectively. The set of power levels is denoted as S_L. Power consumption for reception is constant ($P_{rx}^{crc} = 35.4$ mW).

At each round energy dissipation for data acquisition is $E_{DA} = 600$ μJ. The size of a data packet and an ACK packet are denoted as M_P and M_A, respectively. The slot time (T_{slot}) is taken as 115 ms.

Link quality between two nodes depends on the radio and channel parameters. The path loss (Υ_{ij}) at a distance d_{ij} is formulated as

$$\Upsilon_{ij}[\text{dB}] = \Upsilon_0[\text{dB}] + 10nlog_{10}(d_{ij}/d_0) + X_\sigma[\text{dB}], \quad (1)$$

where d_{ij} is the distance between transmitter and receiver, d_0 is a reference distance, $\Upsilon_0 = 55$ dB is the path loss at the reference distance, $n = 4$ is the path loss exponent (rate at which signal decays), and X_σ is a zero-mean Gaussian random variable with standard deviation $\sigma = 4$ dB.

Received signal power ($P_{rx,ij}^{ant}(l)$) due to a transmission at power level-l over the link-(i,j) can be expressed as

$$P_{rx,ij}^{ant}(l)[\text{dBm}] = P_{tx}^{ant}(l)[\text{dBm}] - \Upsilon_{ij}[\text{dB}]. \quad (2)$$

In the Mica2 motes NRZ (Non-Return-to-Zero) encoding and non-coherent FSK (Frequency Shift Keying) modulation are used. The noise power (P_n) is -115 dBm at the temperature of 300 Kelvin for Mica2 motes [12]. Hence, SNR (Signal-to-Noise ratio) is obtained as

$$\psi_{ij}(l)[\text{dB}] = P_{rx,ij}^{ant}(l)[\text{dBm}] - P_n[\text{dBm}]. \quad (3)$$

Probability of successful packet reception of φ Byte packet transmitted at power level-l over the link-(i,j) can be calculated as [12]

$$p_{ij}^{s}(l,\varphi) = \left(1 - \frac{1}{2}\exp\left(\frac{-\psi_{ij}(l)}{2}\frac{1}{0.64}\right)\right)^{8\varphi}. \quad (4)$$

Thus, failure probability is

$$p_{ij}^{f}(l,\varphi) = 1 - p_{ij}^{s}(l,\varphi). \quad (5)$$

Table I: Transmission power consumption ($P_{tx}^{crc}(l)$ in mW) and output antenna power ($P_{tx}^{ant}(l)$ in mW) at each power level (l) for the Mica2 motes equipped with CC1000 for different power levels (l) [13].

l	$P_{tx}^{crc}(l)$	$P_{tx}^{ant}(l)$	l	$P_{tx}^{crc}(l)$	$P_{tx}^{ant}(l)$
1 (l_{min})	25.8	0.0100	14	32.4	0.1995
2	26.4	0.0126	15	33.3	0.2512
3	27.0	0.0158	16	41.4	0.3162
4	27.1	0.0200	17	43.5	0.3981
5	27.3	0.0251	18	43.6	0.5012
6	27.8	0.0316	19	45.3	0.6310
7	27.9	0.0398	20	47.4	0.7943
8	28.5	0.0501	21	50.4	1.0000
9	29.1	0.0631	22	51.6	1.2589
10	29.7	0.0794	23	55.5	1.5849
11	30.3	0.1000	24	57.6	1.9953
12	31.2	0.1259	25	63.9	2.5119
13	31.8	0.1585	26 (l_{max})	76.2	3.1623

The probability of a successful handshake when the data packet is transmitted at power level-l and acknowledged at power level-k over the link-(i, j) is

$$p_{ij}^{HS,s}(l,k) = p_{ij}^{s}(l, M_P) \times p_{ji}^{s}(k, M_A). \tag{6}$$

The probability of a failed handshake is given as

$$p_{ij}^{HS,f}(l,k) = 1 - p_{ij}^{HS,s}(l,k). \tag{7}$$

On the average, each packet has to be transmitted

$$\lambda_{ij}(l,k) = \frac{1}{p_{ij}^{HS,s}(l,k)}, \tag{8}$$

times.

Energy dissipation for transmitting M_P Bytes of data from node-i to node-j at power level-l is obtained as

$$E_{tx}^{P}(l, M_P) = P_{tx}^{crc}(l) T_{tx}(M_P), \tag{9}$$

where $T_{tx}(M_P)$ is the duration of a data packet which is obtained by dividing the number of bits to the channel data rate (ξ = 19.2 Kbps) [14].

A node stays in receiving mode when it is not transmitting. So the total energy dissipation of a transmitter in a slot (during a single handshake) is

$$E_{tx}^{HS}(l, M_P) = E_{tx}^{P}(l, M_P) + P_{rx}^{crc}(T_{slot} - T_{tx}(M_P)). \tag{10}$$

Transmitter's energy dissipation including packet failure and packet processing cost ($E_{PP} = 120\ \mu$J) is

$$E_{tx,ij}^{D}(l,k) = E_{PP} + \lambda_{ij}(l,k) E_{tx}^{HS}(l, M_P). \tag{11}$$

Energy dissipation for receiving a data packet and replying with an ACK packet without any packet error (*i.e.*, successful handshake) is

$$E_{rx}^{HS,s}(k, M_A) = P_{rx}^{crc}(T_{slot} - T_{tx}(M_A)) + E_{tx}^{P}(k, M_A), \tag{12}$$

where $T_{tx}(M_A)$ denotes the duration of an ACK packet.

If the handshake failure caused by the bit errors in the received data packet then the energy cost for reception can be expressed as

$$E_{rx}^{HS,f} = P_{rx}^{crc} T_{slot}. \tag{13}$$

Receiver's energy dissipation including the effects of packet failures can be obtained as

$$\begin{aligned} E_{rx,ji}^{D}(l,k) = E_{rx}^{HS,s}(k, M_A) + E_{PP} + \\ \lambda_{ij}(l,k)\left[p_{ij}^{s}(l, M_P) p_{ji}^{f}(k, M_A) E_{rx}^{HS,s}(k, M_A) + p_{ij}^{f}(l, M_P) E_{rx}^{HS,f}\right] \end{aligned} \tag{14}$$

D. Background on Mathematical Programming

Before presenting the MIP model for packet length optimization, in this section we provide a brief background on mathematical programming motivating the use of MIP in our model. As examples of mathematical programming models, both linear programming (LP) and MIP are used to find the best solution considering a given set of constraints, which characterize the set of legitimate decisions [15], [16]. Alternative decisions are compared based on their objective function values and the one with the best value (could be the smallest or the largest depending on the nature of the function) is selected as the optimal. Although they are used for the same reason, LP and MIP models cannot be used in place of each other in many occasions. Hence, they should not be considered as alternatives. Basically, types of decisions to be made determine which type of a mathematical model should be used to model the problem under consideration. Namely, for example in our model introduced shortly, f_{ij}^{lk} variable indicates the number of data packets, therefore, it should take an integer value. As a result, we can say that the type of mathematical model to be used depends on the type of decisions to be made, which leads to an MIP model for our problem.

LP models whose variables take continuous values are relatively easier to solve. This is due to the special geometry of the set of feasible solutions (called the feasible set) of LPs. The vertices of the feasible set are defined by the constraints of the model and it is known that, given a nonempty feasible set, there is always a vertex solution which is optimal. Hence the well-known Simplex Algorithm, which searches the optimal solution among the vertices greedily, is a quite effective solution method for LPs, on the average. Unfortunately, MIP models do not have such a property in general and hence call for more advanced solution algorithms such as branch-and-bound, branch-and-cut, *etc*. These methods guaranteeing an optimal solution are called exact solution methods. At each step of such algorithms, first the problem without the integrality restrictions on variables (*i.e.*, the LP relaxation) is solved. Then, if an integer variable has a fractional value in the current solution, then the problem is divided into two subproblems by setting that variable's value to the closest integer values, respectively. Then the new problems are solved recursively in the same manner until the optimal solution is found. This basic method can be improved and fastened by incorporating problem specific information in the subproblem creation step.

The literature on mathematical programming based optimization, modeling and analysis of WSNs is extensive and has grown rapidly in recent years [2], [17]–[22]. Providing a comprehensive overview of the published research on modeling WSNs through mathematical programming is beyond the scope of our work. We refer interested readers to the recent review papers on this topic [7], [23].

E. MIP Framework

In this section, we present the MIP framework used to maximize WSN lifetime. Our network topology is represented by a directed graph, $G = (V, A)$, where V denotes the set of all nodes including the base station as node-1. We also define set W which includes all nodes except node-1 (*i.e.*, $W = V \setminus \{1\}$). $A = \{(i, j) : i \in W, j \in V - i\}$ is the ordered set of arcs. Note that the definition of A implies that no node sends data to itself. The amount of data (*i.e.*, the number of data packets) flowing from node-i to node-j transmitted at power level-l and acknowledged at power level-k is represented as f_{ij}^{lk}. The objective function to be maximized is the network lifetime which is defined as the product of number of rounds and the round duration. Formally stated, the objective of the optimization problem is:

$$\text{Maximize } N_{rnd}. \tag{15}$$

Note that unitless variable N_{rnd} gives the network lifetime in terms of number of rounds and the actual network lifetime can be expressed by the product $N_{rnd} \times T_{rnd}$. Having stated the objective of the optimization problem in Equation 15, constraints of the MIP model are presented in Equations 16–22.

Non-negative flow constraint is given as

$$f_{ij}^{lk} \geq 0 \ \forall l \in S_L, \ \forall k \in S_L, \ \forall (i, j) \in A. \tag{16}$$

Flow-balancing constraint (data flowing out is equal to data flowing into node plus data generated in the node) is presented as

$$\sum_{l \in S_L} \sum_{k \in S_L} \sum_{(i,j) \in A} f_{ij}^{lk} - \sum_{l \in S_L} \sum_{k \in S_L} \sum_{(j,i) \in A} f_{ji}^{lk} = N_{rnd} s_i \ \forall i \in W. \tag{17}$$

Base station flow constraint (all data should eventually sink into base node) can be expressed as

$$\sum_{l \in S_L} \sum_{k \in S_L} \sum_{(j,1) \in A} f_{j1}^{lk} = N_{rnd} \sum_{j \in W} s_j. \tag{18}$$

Total busy time of a node constraint (if a node is neither in transmitting nor receiving mode, then it is in sleep mode) is

$$\begin{aligned} T_{bsy,i} = T_{slot} \sum_{l \in S_L} \sum_{k \in S_L} \Bigg[\sum_{(i,j) \in A} \lambda_{ij}(l,k) f_{ij}^{lk} \\ + \sum_{(j,i) \in A} \lambda_{ji}(l,k) f_{ji}^{lk} \Bigg] + N_{rnd} T_{DA} \ \forall i \in W. \end{aligned} \tag{19}$$

Energy balance constraint (*i.e.*, total energy dissipated cannot exceed the energy stored in batteries):

$$\begin{aligned} \underbrace{\sum_{l \in S_L} \sum_{k \in S_L} \sum_{(i,j) \in A} E_{tx,ij}^{D}(l,k) f_{ij}^{lk}}_{\textbf{transmission}} + \underbrace{P_{slp}(N_{rnd} T_{rnd} - T_{bsy,i})}_{\textbf{sleep}} \\ + \underbrace{\sum_{l \in S_L} \sum_{k \in S_L} \sum_{(j,i) \in A} E_{rx,ji}^{D}(l,k) f_{ji}^{lk}}_{\textbf{reception}} + \underbrace{N_{rnd} E_{DA}}_{\textbf{acquisiton}} \leq e_i \ \forall i \in W. \end{aligned} \tag{20}$$

Each node is assigned an initial energy of 25KJ (*i.e.*, $e_i =$ 25 KJ $\forall i \in W$ – two AA batteries) at the beginning of the network operation.

Bandwidth constraint (*i.e.*, bandwidth required to transmit and receive at each node is less than or equal to total bandwidth and the duration of all incoming and outgoing flows of all nodes is upper bounded by the total network lifetime) is presented as

$$\begin{aligned} T_{slot} \sum_{l \in S_L} \sum_{k \in S_L} \Bigg[\sum_{(i,j) \in A} \lambda_{ij}(l,k) f_{ij}^{lk} + \sum_{(j,i) \in A} \lambda_{ij}(l,k) f_{ji}^{lk} \\ + \sum_{(j,n) \in A} \lambda_{jn}(l,k) f_{jn}^{lk} I_{jnlk}^{i} \Bigg] \leq N_{rnd} T_{rnd} \ \forall i \in V. \end{aligned} \tag{21}$$

Interference function (*i.e.*, if node-i is interfered by the handshake between the transmitter node-j at power level-l and the receiver node-n ACKing at power level-k then $I_{jnlk}^{i} = 1$) is

$$I_{jnlk}^{i} = \begin{cases} 1 \text{ if } \overline{P_{rx,ji}^{ant}(l)} \geq \overline{P_{sns}} \text{ or } \overline{P_{rx,ni}^{ant}(k)} \geq \overline{P_{sns}} \\ 0 \text{ o.w.} \end{cases}, \tag{22}$$

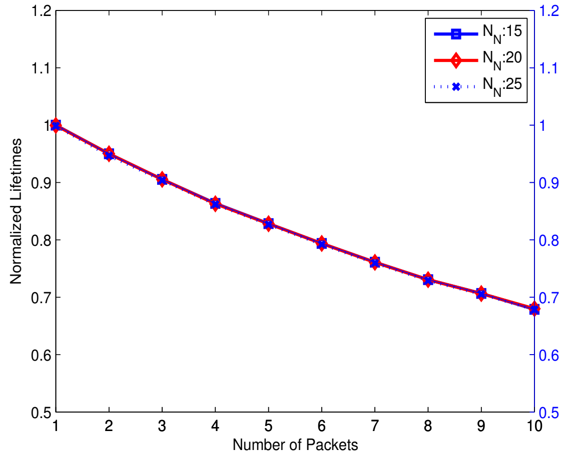
where P_{sns} denotes the reception sensitivity of the Mica2 motes ($P_{sns} =$ -102 dBm) [13].

III. Analysis

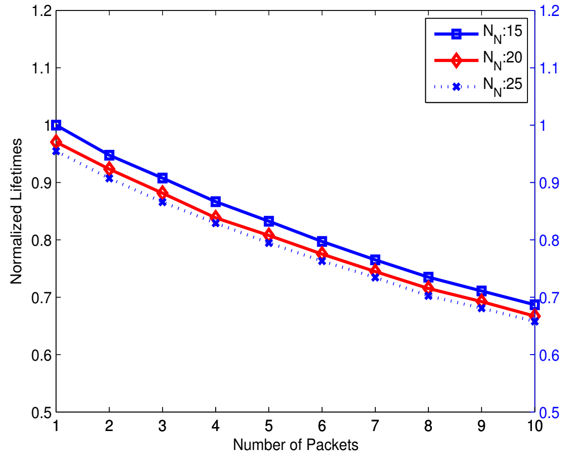
In this section we explore the parameters space by numerical evaluations of the developed MIP model. We use a disk shaped network and the base station is at the center of the disk. Nodes are deployed uniformly by using the best known disk packing geometries reported in [24]. MATLAB is used to construct the data link layer (Section II-C) and General Algebraic Modeling System (GAMS) [25] with CPLEX solver for the optimization problems (Section II-E).

The results presented in Figure 1 and 2 are the averages of 100 random runs (*i.e.*, at each run path loss values of all links are regenerated). Each sensor node generates 1024 Bytes of raw data at each round to be conveyed to the base station. Information bits are embedded into data packets. Each data packet has an overhead of 20 Bytes and ACK packets size is also chosen as 20 Bytes (M_A = 20 Bytes) unless otherwise stated. Generated data is divided into several packets to observe the effects of packet length on network lifetime. For example, if a single data packet size is employed then at each round only a 1044 Bytes data packet (M_P = 1044 Bytes) is send by each sensor node. However, if two packets are utilized then each sensor node send two 532 Bytes (M_P = 532 Bytes) data packets at each round.

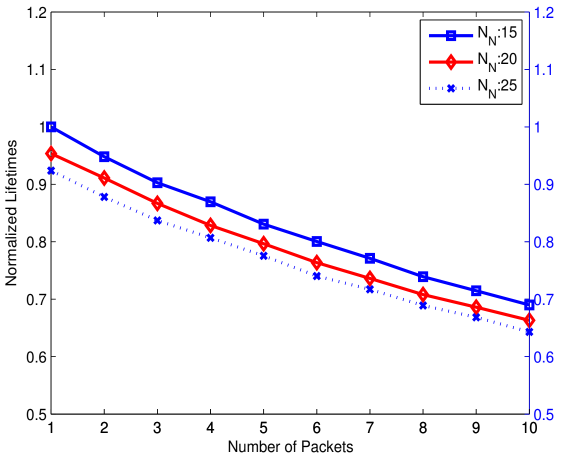
In Figure 1 we investigate the effects of data packet size on network lifetime for various number of nodes (N_N) and Area per Node (ApN) values. Network lifetime normalization is achieved by dividing each value in each figure with the largest value in the corresponding figure. As the node density gets lower (*i.e.*, higher ApN), normalized lifetime difference between networks with higher N_N gets larger. The reason for such behavior is that the impact of transmission difference is higher for sparser networks. Nevertheless, the main observation is that the network lifetime decreases as the data packet length decreases for all figures which shows that the



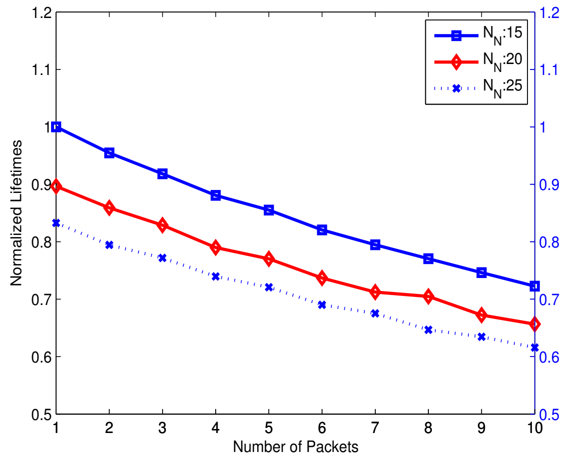
(a) ApN= 1 m^2



(b) ApN= 4 m^2

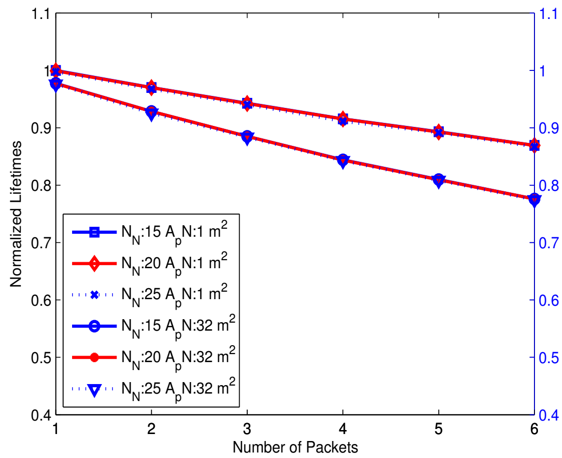


(c) ApN= 16 m^2

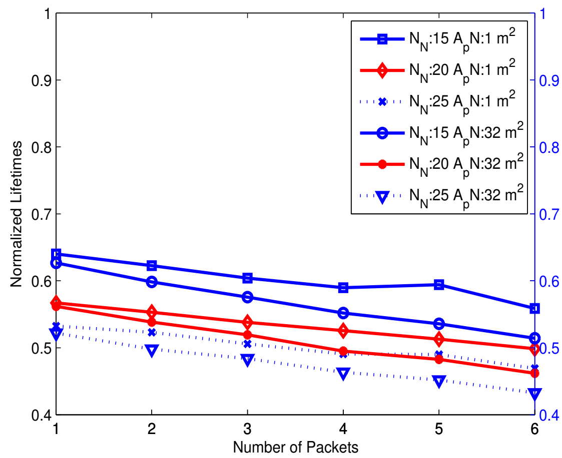


(d) ApN= 32 m^2

Figure 1: Network lifetimes wrt. number of packets generated at each round (s) for various N_N and ApN values.



(a) M_A = 1 Byte



(b) M_A = 20 Bytes

Figure 2: Network lifetimes wrt. number of packets generated at each round (s) for two different ACK packet sizes with various N_N and ApN values.

dominant term in data packet length optimization is the energy dissipation for overhead.

We also investigate the effects of energy dissipation for ACK packet transmission. Actually, the question we seek the answer for is what the impact of energy dissipation on ACK packets on energy dissipation is. (*i.e.*, if there is only one data packet then only one ACK packet is transmitted in reply, however, if there are ten data packets which has one tenth of the payload of a single packet then there will be ten ACK packets in reply). In Figure 2, ACK packet sizes are chosen as 1 Byte (a hypothetical case) and 20 Bytes, respectively. For these figures normalization is achieved by dividing the values in both figures with the largest value in Figure 2a. The general trend in both figures is that the network lifetime decreases as the packet size gets larger. There are some data points that violate the monotonic decrease of the normalized network lifetime as a function of decreasing data packet length due to insufficient statistical averaging, however, these anomalies are rare. Therefore, we ruled out the fact that ACK packet energy dissipation is the dominant term in energy overhead because otherwise the trend in network lifetime decrease for decreasing data packet length would manifest itself in other form (*i.e.*, the fact that normalized network lifetime decreases as the data packet length decreases is evident for both short and long ACK packet lengths scenarios).

In our model which is based on actual measurements with Mica2 motes, the only way to increase the bit error rate (BER) is to increase the distance between nodes. By utilizing a wide range of ApN values we explored the effects of BER. Yet, we do not employ very sparse WSN deployments (*i.e.*, $ApN > 36$ m^2) in our analysis because WSN lifetime decreases sharply (*e.g.*, network lifetimes with $M_P = 1044$ Bytes, $M_A = 20$ Bytes, and $N_N = 25$ are 2.0×10^6 and 1.1×10^6 for $ApN = 1$ m^2 and $ApN = 36$ m^2, respectively) as the network gates very sparse and the main philosophy in WSN design is against highly sparse deployment of sensor nodes.

IV. Conclusion

We investigate the tradeoff in determining the data packet length for WSN lifetime maximization by considering the whole link layer handshake cycle. In fact, we developed an MIP framework that accounts for almost all major sources energy dissipation in practical WSN platforms to assess the data packet optimization problem under realistic assumptions. The main conclusion of this study is that for maximizing WSN lifetime it is preferable to utilize the maximum allowable packet length because otherwise maximum possible network lifetime is not achievable (*e.g.*, using ten packets to transport 1024 Bytes of data results in more than 30 % lifetime decrease when compared to using a single packet).

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