Transmission Power Control for Link Level Handshaking in Wireless Sensor Networks

Huseyin Ugur Yildiz, *Student Member, IEEE,* Bulent Tavli, *Member, IEEE,* and Halim Yanikomeroglu, *Senior Member, IEEE*

***Abstract*—In practical Wireless Sensor Networks (WSNs) the main mechanism for link level data exchange is through handshaking. To maximize the network lifetime, transmission power levels for both data and acknowledgement (ACK) packets should be selected optimally. If the highest transmission power level is selected then handshake failure is minimized, however, minimizing handshake failure does not necessarily result in the maximized lifetime due to the fact that for some links selection of the maximum transmission power may not be necessary. In this study we investigate the impact of optimal transmission power assignment for data and ACK packets on network lifetime in WSNs. We built a novel family of mathematical programming formulations to accurately model the energy dissipation in WSNs under practical assumptions by considering a wide range of energy dissipation mechanisms. We also investigate the validity of a commonly made assumption in wireless communication and networking research: lossless feedback channel (*i.e.*, ACK packets never fail). Our results show that the global optimal assignment of data and ACK packets can be replaced with link scope power level assignment strategies without any significant deterioration of network lifetime. The assumption that ACK packets do not fail is shown to be misleading.**

***Index Terms*—wireless sensor networks, mathematical programming, network lifetime, log-normal shadowing, transmission power control, discrete power levels, energy efficiency.**

I. Introduction

WIRELESS Sensor Networks (WSNs) is envisioned to be a major enabling technology for Internet of Things (IoT) paradigm [1]. In WSNs, to maximize network lifetime, sensor nodes are required to cooperate in forwarding data towards the base station. Indeed, sensor nodes should dissipate their energy in a balanced fashion so that premature death of any sensor due to over-utilization of its battery energy is avoided, hence, the lifetime of the WSN is maximized [2]–[5]. To achieve energy balancing several decisions should be made optimally which include the amount of data flow and transmission power levels employed on each link.

In many studies on lifetime maximization of WSNs, several simplifying assumptions (*e.g.*, a capability for performing power adjustments on a continuous range, lossless channel, perfect feedback channel, unlimited bandwidth) are made to abstract the actual phenomena without creating too complicated models [5]–[7]. However, it is known that in practical settings power level assignment is limited to a discrete set of values, the channel used in WSNs is prone to packet errors, the acknowledgement (ACK) packets are also subject to bit errors, and channel bandwidth is finite. Therefore, incorporating aforementioned mechanisms into network models and investigating their effects on network lifetime are necessary for better understanding the trade-offs involved.

Acknowledgement packets are used over end-to-end paths in the transport layer [8]. For example, well-known Transmission Control Protocol (TCP) uses various forms of acknowledgements (*e.g.*, selective ACK, cumulative ACK) [9]. However, in this paper, we do not investigate transport layer handshaking. Our focus is on link layer handshaking. All widely used wireless link layer communication standards (*e.g.*, IEEE 802.11 [10], IEEE 802.15.4 [11]) define link level handshaking mechanisms (*i.e.*, data packets are replied with ACK packets) for information exchange. For example, IEEE 802.15.4 is a widely utilized standard for WSN link layer which uses link layer ACK packets for reliable information exchange between sensor nodes [12]. It is worth mentioning that transport layer ACK packets and link layer ACK packets have complementary functionalities. Link layer ACKs enable faster reaction to link layer packet losses when compared to transport layer ACKs. On the other hand transport layer ACKs are instrumental in congestion control while link layer ACKs are not generally used for this purpose. Nevertheless, existence of handshaking mechanisms in different layers of the network stack is not a redundancy, instead, it is a design decision made for overall system optimization [13].

In this paper, we present a novel family of mathematical programming formulations to maximize WSN lifetime by employing accurate and realistic energy dissipation models. Each of these formulations is created to model a specific data/ACK transmission strategy for maximizing WSN lifetime. In fact, most of the strategies are based on the fundamental ideas used to design prominent transmission control approaches proposed in the literature.

Our work presents a framework which enables us to quantify the impact and to make a systematic comparison of various joint data and ACK packet transmission power assignment strategies. More precisely stated, our objective is to seek answers to the following research questions:

1) How can we incorporate data and ACK packet errors into a mathematical programming framework with an objective of lifetime maximization?
2) Is it possible to solve such a mathematical program in polynomial time without creating significant approxima-

Huseyin Ugur Yildiz and Bulent Tavli are with the Department of Electrical and Electronics Engineering, TOBB University of Economics and Technology, 06520, Ankara, Turkey (e-mail: {huyildiz, btavli}@etu.edu.tr).

Halim Yanikomeroglu is with the Department of Systems and Computer Engineering at Carleton University, Ottawa, Ontario, Canada (e-mail: halim@sce.carleton.ca).

tion errors?
3) Should we consider data and ACK packet transmission levels as global decision variables?
4) What is the extent of lifetime decrease if data and ACK transmission decisions are made considering only each link at a time?
5) Can we use the same optimized transmission power level for both data and ACK packets on each link?
6) Is it a good strategy to utilize only the highest transmission power level for ACK packets?
7) What are the effects of the assumption that ACK packets are always error-free?

The rest of the paper is organized as follows. An overview of the related work is presented in Section II. Our system model is elaborated in Section III. We construct and describe the mathematical programming framework in Section IV. Numerical analysis to explore the parameter space and to compare the performance of the proposed strategies are given in Section V. A discussion on the assumptions, strategies, practical aspects, and implications of our results is presented in Section VI. Section VII provides our concluding remarks.

II. Related Work

Transmission power control in WSNs is a topic that has been studied extensively in the literature [14], [15]. In [15], an overview on power management and classification of transmission power control approaches in WSNs is presented. Transmission power control approaches in WSNs can be categorized into three major groups: network level [16], node level [17], [18], and link level [14], [19]–[22] strategies. In network level strategies, the whole network uses a single transmission power level. In node level strategies, each node uses a single optimal transmission power level for transmitting to its neighbors. In link level strategies, transmission power level for each link is optimized. In fact, most of the recent studies on WSN lifetime maximization through transmission power control employ link level strategies. Referring the audience for the wide scope literature review on transmission power control in WSNs to [15], we will present an overview of recent developments on network lifetime maximization in WSNs through link level transmission power control strategies.

One of the earliest and most prominent studies on link level transmission power control in WSNs is [14], where a transmission power control algorithm that monitors individual link quality through close loop feedback is developed. It is shown that the overhead created by the algorithm is low through extensive testbed experiments. Furthermore, the superiority of link level transmission power control approach over node level and network level approaches is shown in terms of energy efficiency. In [19], a transmission power control scheme for improving the energy efficiency of WSNs is proposed. In this scheme, the minimum transmission power level is used for data transmission on each link that ensures a predetermined target packet error probability whereas control packets (*i.e.*, ACK packets) are transmitted using the maximum power level. A theoretical analysis of transmission power control employing the channel feedback obtained from the ACK and NACK (Negative ACK) packets only is presented in [20]. The channel is modeled as a finite state Markov channel and a dynamic programming solution for the finite horizon transmission power control problem is proposed. In [21], joint design of routing and transmission power assignment is investigated for increasing both end-to-end reliability and energy efficiency. Nodes adjust their transmission power levels to ensure that end-to-end packet delivery ratio is above a predetermined threshold. In [22], an approach to continuously monitor link quality for multiple transmission power levels is proposed which enables the selection of lowest transmission power level that achieves the target reliability level.

Although, various transmission power assignment strategies have been proposed for prolonging WSN lifetime, the net impact of the joint data and ACK packet transmission power assignment on WSN lifetime remains unclear. To facilitate such an analysis, utilization of a detailed and accurate link layer model is necessary. There have been many link layer models proposed in the literature for WSNs. Among all these models Heinzelman-Chandrakasan-Balakrishnan (HCB) energy model for data transmission and reception has been the most widely utilized model and it has affected almost all aspects of WSN research for more than a decade in a profound manner [2]. In the HCB model, transmission power can be adjusted in a continuum depending on the distance between the transmitter and the receiver. Note that in the HCB model, the energy cost of electronics is also accounted for both in transmission and reception. The HCB model is an excellent abstraction to hide the complexity of MAC (Medium Access Control) and physical layers for researchers interested in higher layer systems aspects of WSNs. Yet, more detailed radio propagation and transmission energy models are needed when investigating MAC and physical layer mechanisms of WSNs for lifetime maximization. There have been several studies to improve the HCB model to obtain more accurate energy dissipation characteristics [23], [24].

In quest for more accurate radio propagation and communication energy dissipation models, abstractions based on empirical data obtained by using WSN testbeds as opposed to analytical models have attracted wide attention in the literature [25]–[27]. A review of radio propagation models proposed specifically for WSNs is presented in [28].

The literature on mathematical programming based modeling and analysis of WSNs is extensive and has grown rapidly in recent years. 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 reviews on this topic [29], [30]. However, we will provide a brief overview of literature on mathematical programming based analysis of WSNs which are most related to our study. Indeed, studies on transmission power optimization in WSNs through mathematical programming can be categorized into two broad groups: (i) studies with continuous transmission power assumption and (ii) studies with discrete transmission power levels assumption. In the first group, WSN lifetime maximization problem is investigated by considering variable transmission power assignment to each link in the network and transmission power levels are assumed to be adjusted in a continuum [5], [7], [31]–[33]. In the second group, transmission power optimization for WSN lifetime maximization is investigated by using discrete transmission power levels [24], [34], [35]. However, all of the aforementioned studies failed to model the complete handshaking mechanism. Therefore, the effects of energy dissipation on ACK packets and the effects of ACK transmission power optimization have not been investigated in the literature on mathematical programming based modeling and analysis of WSNs.

When compared to the existing body of work on WSN network lifetime maximization in literature, one of the novel aspects of our study is that we created a mathematical programming framework by using an experimentally verified accurate radio propagation and channel model whereas most of the studies investigating WSN lifetime maximization are based on idealized models (*e.g.*, unit disc model). The abstractions we incorporate into our framework encompass a large set of factors affecting the network lifetime as opposed to the minimalist models based on over simplified assumptions. Furthermore, we analyze the effects of transmission power control strategies for data and ACK packet exchange (*i.e.*, two-way handshake) mechanism on WSN lifetime which has not been systematically investigated in the literature before. Our results show that for maximization of WSN lifetime, optimizing the transmission power levels of both data and ACK packets are of utmost importance, hence, the research questions we posed in Section I are important. Since these research questions have not been investigated in the WSN literature, the answers we provide to them are our novel contributions. The presented optimization framework can be reused with minor modifications for investigating many other WSN related research questions.

We also made theoretical contributions to the WSN literature. We determined an upper bound on the maximum difference between the exact and LP-relaxed solutions of the optimization problem we constructed and provided the proof of the bound. Furthermore, we investigated the validity of the perfect feedback assumption in link level handshaking which is a commonly made assumption in many theoretical papers on transmission power control in WSNs.

III. System Model

In this section, we present an overview of our system model, state our assumptions, and present the link layer model used in constructing the mathematical programming framework.

A. Overview

We consider a WSN consisting of a base station and multiple sensor nodes (*i.e.*, N_N sensor nodes) deployed over a sensing area to collect data from the environment. Sensor nodes convey their generated data to the base station either directly or via other sensor nodes acting as relays. Time is organized into rounds ($T_{rnd} = 60$ s) and any sensor node-i generates s_i number of data packets at each round.

Data exchange between any two node pair is achieved through a two-way handshake mechanism. For a successful handshake operation both data and ACK packets should be received error free by the intended recipients. Transmission power levels for both data and ACK packets can be chosen from a finite set of discrete power levels (*i.e.*, $l_{max} = 26$ power levels are available).

Adopting a suitable definition of the lifetime in a WSN lifetime optimization problem is of utmost importance. The most commonly utilized lifetime definition in WSN lifetime optimization studies [5], [29], [30] is that the network lifetime is the duration between the time network starts operating and the time when the first sensor node in the network exhausts all its energy. If the aforementioned lifetime definition is employed naively then some of the sensor nodes can run out of their energies while the others are left with high levels of battery energy. Therefore, this definition of lifetime cannot capture the energy efficiency of a particular strategy. However, if the optimization problem is cast as a *MaXMiN* problem as we do in this study (*i.e.*, maximize the lifetime of the minimum lifetime node), then all nodes collaborate to avoid the premature death of any individual node by network-wide sharing of the data forwarding burden in a balanced fashion. Therefore, the lifetime definition we adopted in this study is a metric that sufficiently characterizes the energy efficiency of the investigated strategies. To maximize the network lifetime the variables that are to be optimized are data and ACK packet transmission power levels on each link and the amount of data flowing for the particular selection of data and ACK packet transmission levels.

B. Assumptions

In our framework, we make the following assumptions:

- The network consists of stationary nodes (both sensor nodes and the base station).
- In our framework, the amount of data flowing on each link is optimized in a centralized manner. Furthermore, TDMA time slots allocation is also assumed to be done in a centralized manner. Therefore, we assume that the base station has the complete topology information. However, except for two power level assignment strategies (Global Power Level Decisions strategy and Global Power Level Decisions with Single Power Level Assignment strategy), power level assignments are determined by the nodes themselves. 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.
- All nodes are roughly time synchronized. There are many synchronization protocols designed specifically for WSNs with virtually no overhead and satisfactory synchronization performance [36].
- Network reorganization period for a typical WSN is sufficiently long [3], therefore, the energy costs of topology discovery and route creation operations constitute a small fraction (*e.g.*, less than 1.0% [37]) of the total network energy dissipation. Therefore, control overhead can be neglected without leading to significant underestimation of total energy dissipation.

- 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. A combinatorial interference model can be used to model interference, and the scheduling constraints can then be modeled by a conflict graph. In [38], it is shown that such an algorithm is possible hence collision free communication is achieved if sufficient bandwidth requirements are satisfied. In fact, in our model, we use the sufficient condition presented in [38]. Furthermore, it is also possible to reduce data packet collisions to negligible levels in practical MAC protocols designed with a dynamic TDMA approach [39]. TDMA-based channel access is also necessary to avoid overhearing.
- Path loss for each link can be measured by a closed loop power control mechanism [14] and we assume that such a mechanism is in effect for our system.
- 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 utilize Mica2 motes' energy dissipation characteristics in constructing our energy model. Mica2 motes [19], which have arguably been the most heavily utilized workhorse of the experimental WSN research, consist of an Atmel Atmega 128L processor and Chipcon CC1000 radio. Power consumption of the transceiver and the corresponding output antenna power for Mica2 motes are presented in Table I. Power consumption for transmission at power level-l is denoted as $P_{tx}^{crc}(l)$ and the output antenna power at power level-l is denoted as $P_{tx}^{ant}(l)$ (varies between -20 dBm and 5 dBm). The set of power levels is denoted as S_L. Power consumption for reception is constant and denoted as $P_{rx}^{crc} = 35.4$ mW.

At each round every node dissipates a certain amount of energy for data acquisition ($E_{DA} = 600\ \mu$J) and generates the same amount of processed data to be conveyed to the base station (*e.g.*, each sensor node generates one 256 Byte data packet at each 60 s round). Energy dissipation for data acquisition is obtained by multiplying the power for running the processor and the sensor board in active mode ($P_{DA} = 30$ mW) [40] and the total data acquisition and processing time ($T_{DA} = 20$ ms).

Data and ACK packet lengths are denoted as M_P and M_A, respectively. Data transmission between a transmitter and receiver pair takes place at a single time slot which has a predetermined time. Perfect synchronization between any transmitter/receiver pair is not achievable, thus, in practical protocol implementations guard times are used at the start and end of a data slot [41]. There are many synchronization protocols designed specifically for WSNs with virtually no overhead and satisfactory synchronization performance [36]. For example, timing-sync protocol uses piggybacking for synchronization [42], which is reported to have an average synchronization error of 16.9 μs and a worst case error of 44 μs. Thus, we choose the guard time to be $T_{grd} = 100\ \mu$s, which is roughly twice the maximum synchronization error.

The time interval between the completion of the data packet transmission at the source node and the beginning of the ACK packet receipt which includes various delay terms (*e.g.*, propagation delay) is modeled by T_{rsp} (500 μs). To account for all of the aforementioned terms, the slot time is found as $T_{slot} = [2 \times T_{grd} + T_{tx}(M_P) + T_{rsp} + T_{tx}(M_A)] = 115$ ms for $M_P = 256$ Bytes and $M_A = 20$ Bytes, where $T_{tx}(M_P)$ and $T_{tx}(M_A)$ are the durations of data and ACK packets, respectively, which are obtained by dividing the number of bits to the channel data rate ($\xi = 19.2$ Kbps) [43].

In wireless communications, the reliability of a link depends on the quality of the channel (including the severity of path loss) as well as the physical layer parameters (such as modulation and encoding types). In WSNs, the path loss model with a distance dependent attenuation and log-normal shadowing is shown to provide a realistic assessment of communication characteristics of WSN nodes in practice [26]. Therefore, we adopt this model and utilize the parameters presented in [26] to incorporate the propagation effects.

The path loss in a link-(i,j), Υ_{ij}, is given as [28]

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

where d_{ij} is the distance between transmitter and receiver, d_0 is a reference distance, Υ_0 is the path loss at the reference distance, n is the path loss exponent (rate at which signal decays), and X_σ is a Gaussian random variable with mean 0 dB standard deviation σ dB capturing the shadowing effects. We adopt the parameter values provided for Mica2 motes as n = 4, σ = 4 dB, d_0 = 1 m, and Υ_0 = 55 dB [26]. Antenna gains are assumed to be included in the model as part of the Υ_0 (a quarter wave monopole antenna with an antenna gain of 5.19 dBi [44] is assumed to be employed). The received signal power due to a transmission at power level-l over the link-(i,j) is denoted as $P_{rx,ij}^{ant}(l)$ and it can be obtained as

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

In Mica2 motes, NRZ (Non-Return-to-Zero) encoding and non-coherent FSK (Frequency Shift Keying) modulation is used. The noise power (P_n) is -115 dBm at the temperature of

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) [19].

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

300 Kelvin for Mica2 motes [26]. The expression for signal-to-noise ratio (SNR) is given as follows:

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

Hence, the probability of a successful packet reception [26] of a φ-Byte packet transmitted at power level-l over the link-(i,j) is

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

and failure probability is

$$p^f_{ij}(l,\varphi) = 1 - p^s_{ij}(l,\varphi). \quad (5)$$

A successful handshake is performed if both data and ACK packets are received without errors by the intended recipients. There are two possible cases for an unsuccessful handshake. First, the data packet can be received without any errors but the ACK packet may fail. Second, the data packet may not be received error-free in which case no ACK packet is sent to the transmitter. In such cases, the handshake must be repeated which leads to extra energy dissipation.

Even if the transmitted data packet cannot be received by the destination due to bit errors, the amount of energy dissipated by the transmitter is the same with the case of a successful reception because the transmitter has to listen to the ACK packet. Note that in CC1000 radios there is no difference in energy dissipation for actual data reception or idle listening. The lack of an ACK packet in response to the data packet transmission indicates a packet loss.

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

$$p^{HS,s}_{ij}(l,k) = p^s_{ij}(l,M_P) \times p^s_{ji}(k,M_A), \quad (6)$$

provided that $P^{ant}_{rx,ij}(l) \geq P_{sns}$ and $P^{ant}_{rx,ji}(k) \geq P_{sns}$. Otherwise (*i.e.*, $P^{ant}_{rx,ij}(l) < P_{sns}$ and $P^{ant}_{rx,ji}(k) < P_{sns}$), $p^{HS,s}_{ij}(l,k) = 0$ where P_{sns} denotes the reception sensitivity of the Mica2 motes (P_{sns} = -102 dBm) [19]. The probability of a failed handshake is given as

$$p^{HS,f}_{ij}(l,k) = 1 - p^{HS,s}_{ij}(l,k). \quad (7)$$

On the average, each data packet has to be transmitted

$$\lambda_{ij}(l,k) = 1 + \sum_{n=1}^{N_{rtr}} [p^{HS,f}_{ij}(l,k)]^n \quad (8)$$

times, where N_{rtr} is the maximum retransmission limit. Note that for $N_{rtr} \to \infty$, $\lambda_{ij}(l,k) = \frac{1}{p^{HS,s}_{ij}(l,k)}$. In the IEEE 802.15.4 standard default maximum number of retransmissions (macMaxFrameRetries) is 3 (*i.e.*, $N_{rtr} = 3$) [45], however, N_{rtr} can be set to a much larger value. Energy dissipation for transmitting M_P Bytes of data from node-i to node-j at power level-l is

$$E^P_{tx}(l,M_P) = P^{crc}_{tx}(l)T_{tx}(M_P). \quad (9)$$

A transmitting node stays in the receive mode during an active slot except the time it transmits the data packet. The total energy dissipation of a transmitter in a slot (during a single handshake) is given in as

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

Transmitter's energy dissipation including the effects of packet failures and packet processing energy dissipation can be expressed as

$$E^D_{tx,ij}(l,k) = E_{PP} + \lambda_{ij}(l,k)E^{HS}_{tx}(l,M_P). \quad (11)$$

Packet processing energy is dissipated only once and subsequent retransmissions do not incur additional packet processing energy dissipation. If a transmitted data packet is not acknowledged in the corresponding slot, then the data packet should be retransmitted again. Packet processing energy (E_{PP}) is obtained by using the power consumption of Mica2 platform in active mode (24 mW) [4] and the total utilization time of the CPU for each packet (*e.g.*, E_{PP} = 120 μJ for M_P = 256 Bytes).

Energy dissipation for receiving a data packet and replying with an ACK without any packet error can be expressed as

$$E^{HS,s}_{rx}(k,M_A) = P^{crc}_{rx}(T_{slot} - T_{tx}(M_A)) + E^P_{tx}(k,M_A). \quad (12)$$

The handshake can fail due to bit errors in the ACK packet, however, such a failure has the same energy cost on the receiver's side. If the handshake failure is because of the bit errors in the received data packet then the energy cost is

$$E^{HS,f}_{rx} = P^{crc}_{rx}T_{slot}. \quad (13)$$

If a data packet is not successfully received, the receiving node switches to the sleep mode upon expiration of the maximum amount of time to receive a data packet. Receiver's energy dissipation including the effects of packet failures can be expressed as

$$\begin{aligned} E^D_{rx,ji}(l,k) = E_{PP} + \lambda_{ij}(l,k)\Big[p^{HS,s}_{ij}(l,k)E^{HS,s}_{rx}(k,M_A) + \\ p^s_{ij}(l,M_P)p^f_{ji}(k,M_A)E^{HS,s}_{rx}(k,M_A) + p^f_{ij}(l,M_P)E^{HS,f}_{rx}\Big]. \end{aligned} \quad (14)$$

IV. Mathematical Programming Framework

In this section, we present a family of mathematical programming formulations to model eight handshake transmission power optimization strategies for WSN lifetime maximization. The 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^{lk}_{ij}. In all strategies we propose, the objective function to be maximized is the network lifetime which is defined as the product of number of rounds (N_{rnd}) and the round duration (T_{rnd}). Formally stated, the objective is

$$\text{Maximize } N_{rnd} \times T_{rnd}. \quad (15)$$

A. Global Power Level Decisions (GPLD) Strategy

In GPLD strategy both data and ACK packet transmission power levels on each link are optimized. We do not impose any constraints on the ACK packet transmission level assignment. The constraints defining GPLD strategy are presented in Equations 16–24.

Non-negativity constraint for flows can be expressed as

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

where S_L is the set of power levels (Table I).

Data flowing into node-i plus data generated by node-i is equal to the data flowing out of node-i (*i.e.*, flow balancing constraint) which is stated as

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

where $\theta_{ji}(l,k)$ is the loss rate due to the finite number of retransmission limit and expressed as

$$\theta_{ij}(l,k) = 1 - \left[p_{ij}^{HS,f}(l,k)\right]^{(N_{rtr}+1)}. \quad (18)$$

If a node is not a receiver or a transmitter at any slot, or if it is not acquiring data, then it is in the sleep mode. Hence the total sleep time can be obtained from the total busy time ($T_{bsy,i}$) which is calculated as

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

Total energy dissipation at each node (e_i) is limited by the amount of energy stored in batteries. Four terms on the left side of inequality in Equation 20 accounts for transmission, sleep (power consumption in the sleep mode is $P_{slp} = 3\ \mu$W), reception, and data acquisition energies, respectively:

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

Each sensor node is assigned equal initial energy ($battery = 3000$ J) at the beginning of the network operation which is stated as

$$e_i = battery,\ \forall i \in W. \quad (21)$$

In a broadcast medium, we need to make sure that the bandwidth required to transmit and receive at each node is lower than or equal to the total bandwidth. Such a constraint should take the shared capacity into consideration. We refer to the flows around node-i which are not flowing into or flowing out of node-i, however, affect the available bandwidth of node-i as interfering flows. The total amount of bandwidth utilized during the entire network lifetime for node-i, $\varsigma(i)$, is presented as

$$T_{slot} \sum_{l \in S_L} \sum_{k \in S_L} \left[\sum_{(i,j) \in A} \lambda_{ij}(l,k) f_{ij}^{lk} + \sum_{(j,i) \in A} \lambda_{ij}(l,k) f_{ji}^{lk} + \sum_{(j,n) \in A} \lambda_{jn}(l,k) f_{jn}^{lk} I_{jnlk}^{i} \right] = \varsigma(i),\ \forall i \in V. \quad (22)$$

The maximum bandwidth requirement is upper bounded as

$$\varsigma(i) \leq N_{rnd} T_{rnd},\ \forall i \in V. \quad (23)$$

For all nodes including the base station the aggregate duration of incoming flows, outgoing flows, and interfering flows is upper bounded by the total network lifetime. This constraint is a modified version of the sufficient condition given in [38], [46].

Interference function (I_{jnlk}^{i}) is formulated as

$$I_{jnlk}^{i} = \begin{cases} 1, & \text{if } P_{rx,ji}^{ant}(l) \geq P_{sns} \text{ or } P_{rx,ni}^{ant}(k) \geq P_{sns} \\ 0, & \text{o.w.} \end{cases}. \quad (24)$$

If node-i is in the interference region of the transmission from node-j to node-n at power level-l (data transmission) or node-n to node-j at power level-k (ACK transmission), then the value of interference function for node-i is unity ($i \neq j \neq n$), otherwise it is zero.

B. Local Power Level Decisions (LPLD) Strategy

In LPLD strategy, data and ACK transmission power levels are determined for each link considering the energy dissipation of node-i and node-j, only. Therefore, we should determine a single optimal power level for data packet transmission (l_{ij}^{opt}) and a single optimal power level for ACK packet transmission (k_{ji}^{opt}) for each link-(i,j) (*i.e.*, on link-(i,j) data packets are transmitted at power level-l_{ij}^{opt} by node-i and ACK packets are transmitted at power level-k_{ji}^{opt} by node-j). The power levels are determined by using the following local optimization scheme

$$\{l_{ij}^{opt}, k_{ji}^{opt}\} = \underset{l \in S_L k \in S_L}{\operatorname{argmin}} \left(E_{tx,ij}^{D}(l,k) + E_{rx,ji}^{D}(l,k) \right). \quad (25)$$

While in GPLD strategy the variables of the optimization problem are f_{ij}^{lk}, in LPLD strategy the variables are f_{ij}, therefore, the computational complexity of LPLD is lower than the computational complexity of GPLD. Once the optimum power levels for LPLD strategy $\{l_{ij}^{opt}, k_{ji}^{opt}\}$ are computed, we can use the mathematical programming formulation defining GPLD strategy for modeling LPLD strategy by replacing (l,k) with their optimal values for each link (as given in Equation 25) and removing the summations $\sum_{l \in S_L}$ and $\sum_{k \in S_L}$ in equations involving these summations.

C. Local Power Level Decisions with Equal Power Level Assignment (LPLD-EPL) Strategy

Although in LPLD strategy power level assignment for data and ACK packets are determined locally, transmission power levels for data and ACK packets for each link are not forced to be the same. However, it is possible to assign equal power levels for both data and ACK packets on each link which will simplify the local power level assignment computations. Furthermore, it may not be necessary to assign different power levels for data and ACK packet transmissions to maximize network lifetime. Therefore, in LPLD-EPL strategy, we assume that only a single optimal power level (m_{ij}^{opt}) is used for both data packet and ACK transmission over the link-(i,j) which is defined as

$$m_{ij}^{opt} = k_{ji}^{opt} = l_{ij}^{opt},\ \forall (i,j) \in A, \tag{26}$$

and can be obtained by

$$m_{ij}^{opt} = \underset{l \in S_L}{\operatorname{argmin}} \left(E_{tx,ij}^{D}(l,l) + E_{rx,ji}^{D}(l,l) \right). \tag{27}$$

Mathematical programming model for LPLD-EPL strategy is the same with LPLD strategy, however, the only difference in LPLD-EPL is that the power levels $\{l_{ij}^{opt}, k_{ji}^{opt}\}$ are replaced with m_{ij}^{opt}.

D. Local Power Level Decisions with Maximum ACK Power Level Assignment (LPLD-MAPL) Strategy

Failure of an ACK packet necessitates the execution of a whole data exchange cycle (*i.e.*, the handshake). Therefore, it is plausible to transmit ACK packets with the maximum transmission power level available. If such an assumption is made then transmission power level of only the data packet on each link is to be determined. In LPLD-MAPL strategy a single optimal power level is used for packet transmission (n_{ij}^{opt}) at each link and all ACK packets are sent at maximum power level ($l_{max} = 26$). The link scope optimization problem for LPLD-MAPL is defined as

$$n_{ij}^{opt} = \underset{l \in S_L}{\operatorname{argmin}} \left(E_{tx,ij}^{D}(l,l_{max}) + E_{rx,ji}^{D}(l,l_{max}) \right). \tag{28}$$

The difference between the formulations of LPLD strategy and LPLD-MAPL strategy is that in LPLD-MAPL l_{ij}^{opt} is replaced with n_{ij}^{opt} and $k_{ij}^{opt} = l_{max}$.

E. Local Power Level Decisions with Maximum Power Level Assignment (LPLD-MPL) Strategy

Increasing transmission power levels for both data and ACK packets, decreases the handshake failure probability. Therefore, if the maximum available transmission power levels are utilized in both data and ACK packet transmissions then energy dissipation due to retransmissions will be minimized. However, such an approach will also increase the transmission energy dissipation for both data and ACK packets. Hence, utilizing the maximum transmission power for both data and ACK packets is a strategy to be investigated for comparison with other strategies and to uncover the trade-off involved in minimizing retransmission and increasing transmission power for maximizing the network lifetime. In LPLD-MPL strategy, both data and ACK packets for all links are sent by using the highest transmission power available (*i.e.*, $l_{max} = 26$). LPLD-MPL strategy is modeled by using the LPLD-EPL strategy, however, the only difference is that the transmission power levels are set to the maximum which can be expressed as

$$m_{ij}^{opt} = l_{max} = 26,\ \forall (i,j) \in A. \tag{29}$$

F. Local Power Level Decisions with Perfect Feedback (LPLD-PF) Strategy

In LPLD-PF strategy, we model the network lifetime optimization problem by setting the probability of error for ACK packets to zero (*i.e.*, handshake success probability is determined by only the data packet success probability). We modify the LPLD-EPL strategy to construct LPLD-PF (*i.e.*, both data and ACK packets are transmitted by using the same power level at each link). Although the ACK packets are assumed to be received with zero failure probability, transmission of ACK packets have non-zero energy dissipation because we do not assume the ACK packets are non-existent in LPLD-PF strategy (*i.e.*, ACK packet size is still $M_A = 20$ Bytes).

G. Local Power Level Decisions with Perfect Feedback and Zero ACK Length (LPLD-PFZA) Strategy

In LPLD-PFZA strategy, ACK packets are ignored completely (*i.e.*, unlike in LPLD-PF strategy, in LPLD-PFZA strategy ACK packet size is taken as zero). Mathematically speaking, we assume that ACK packet transmissions are performed over hypothetic lossless links (*i.e.*, $p_{ij}^{s}(k, M_A) = 1$) and $M_A = 0$ Bytes. Therefore, we assume that data packet failures are monitored by a hypothetical omniscient observer and the sending nodes are informed of data packet failures without any ACK packets which is a common assumption in wireless communications and networking research.

H. Global Power Level Decisions with Single Power Level Assignment (GPLD-SPLA) Strategy

In GPLD-SPLA strategy, only a single optimal data (l^{opt}) and ACK (k^{opt}) transmission power level pair is used by all nodes for all their links. We utilized the LPLD strategy to determine l^{opt} and k^{opt}. First we obtained the network lifetime values by solving the LPLD problem for all combinations of (l,k) pairs (*i.e.*, only a single predetermined (l,k) pair can be used at all links). The pair that gives the highest network lifetime is the optimal network layer transmission power level pair.

I. Error bounds for LP-relaxation

In this subsection, we will prove that the maximum difference between the exact integer solution and LP-relaxation solution is bounded by $l_{max}^{2}(N_N - 1)$ and $(N_N - 1)$ for GPLD and LPLD strategies, respectively.

Definition 1: Let the feasible solutions of a particular network lifetime optimization problem given in Subsection IV-A obtained by treating the variables as integer and continuous variables be $\{[f_{ij}^{lk}]_{IP}, N_{rnd-IP}\}$ and $\{[f_{ij}^{lk}]_{LP}, N_{rnd-LP}\}$, respectively. Furthermore, the MIP solution (possibly infeasible) obtained by rounding the flow values, given by the LP solution, down to the nearest integer and keeping the lifetime as it is be given as $\{[f_{ij}^{lk}]_{LP\rightarrow IP}, N_{rnd-LP}\}$. For the ease of exposition we assume that $\theta_{ji}(l,k) = 1$ (*i.e.*, $N_{rtr} \rightarrow \infty$) and $s_i = 1$.

Lemma 1: The MIP solution $\{[f_{ij}^{lk}]_{LP\rightarrow MIP}, N_{rnd-LP}\}$ does not violate any constraints except the flow balance constraint.

Proof: The constraints defining GPLD strategy are presented in Equations (16)–(24).

1) The non-negativity constraint (defined by Equation 16) holds for the LP solution and rounding does not create negative values, hence, $[f_{ij}^{lk}]_{LP\rightarrow IP} \geq 0$.
2) The flow balance constraint (defined by Equations 17 and 18) does not necessarily hold for the mixed integer solution.
3) Energy constraint (defined by Equations 19, 20,and 21) holds for the mixed integer solution. Since $[f_{ij}^{lk}]_{LP\rightarrow IP}$ values are lower than or equal to $[f_{ij}^{lk}]_{LP}$ values, transmission and reception energy terms in Equation 20 are lower for the MIP case than the LP case. Acquisition energy term do not change. Sleep energy term in MIP case is larger than or equal to the sleep energy term for the LP case because $[f_{ij}^{lk}]_{LP\rightarrow IP}$ values are lower than or equal to $[f_{ij}^{lk}]_{LP}$ values (see Equation 19). When compared to the LP solution, MIP solution gives lower (or equal) transmission and reception energy terms and higher (or equal) sleep energy term. Since the lifetime (N_{rnd}) is the same for the LP and MIP solutions, the increase of the sleep time is in the expense of the transmission and reception terms. However, sleep energy term is the lowest possible energy dissipation state, hence, a solution with higher sleep time dissipates less energy energy than a solution with a lower sleep time.
4) The bandwidth constraint (defined by Equations 22, 23, and 24) holds for the MIP case because $[f_{ij}^{lk}]_{LP\rightarrow IP}$ values are lower than or equal to $[f_{ij}^{lk}]_{LP}$ values (see Equation 22). ■

Definition 2: Let's construct an alternative MIP problem (Auxillary 1 problem – A1 problem) by modifying the optimization problem presented in Subsection IV-A. In A1 problem the flow balance constraint (Equation 17) is modified as follows

$$\sum_{l\in S_L}\sum_{k\in S_L}\sum_{(i,j)\in A} f_{ij}^{lk} - \sum_{l\in S_L}\sum_{k\in S_L}\sum_{(j,i)\in A} \theta_{ji}(l,k) f_{ji}^{lk} = N_{rnd}^1 s_i + s_i^2, \ \forall i \in W, \tag{30}$$

where N_{rnd}^1 is a non-negative continuous variable and s_i^2 is a continuous variable with no constraints on its positivity or negativity. In the rest of the equations of the original problem N_{rnd} is replaced with N_{rnd}^1.

Lemma 2: The MIP solution $[f_{ij}^{lk}]_{LP\rightarrow MIP}, N_{rnd-LP}$ plus an appropriate selection of s_i^2 constitutes a feasible solution for the A1 problem.

Proof: Since the only difference between the original and the modified optimization problems is the flow balance equation, all of the other constraints of modified problem are satisfied by the MIP solution as proved in Lemma 1. The flow balance constraint of A1 problem enables the satisfaction of the flow balance equation by the introduction of s_i^2 variables which fill the gaps created by the rounding of the continuous flow variables because s_i^2 values can be chosen appropriately to satisfy the modified flow balance equation. ■

Remark 1: $N_{rnd-LP} = N_{rnd}^1$.

Remark 2: In A1 problem, the network lifetime is N_{rnd}^1. Each node creates s_i packets at each round. The flows have non-negative integer values. Each node inserts or deletes s_i^2 packets to/from the total sum of $N_{rnd}^1 s_i$ packets.

Lemma 3: We can find non-negative integer values $\widehat{N_{rnd}^1}$ and $\widehat{s_i^2}$ that satisfy $N_{rnd}^1 s_i + s_i^2 = \widehat{N_{rnd}^1} s_i + \widehat{s_i^2}$ by using s_i^2 variables that satisfy $|s_i^2| \leq l_{max}^2(N_N - 1)$ provided that $N_{rnd}^1 s_i \geq 2|l_{max}^2(N_N - 1)|$.

Proof: Any sensor node has at most $(N_N - 1)$ incoming or outgoing links with at most l_{max}^2 power level combinations. Therefore, the mismatch between the incoming and outgoing links due to the rounding of flows can at most be $|l_{max}^2(N_N - 1)|$. $N_{rnd}^1 s_i + s_i^2$ is an integer because it is the difference of two integers. Since $|s_i^2| \leq l_{max}^2(N_N - 1)$ and $N_{rnd}^1 s_i \geq 0$, $(N_{rnd}^1 s_i + s_i^2) \geq 0$ if $N_{rnd}^1 s_i \geq 2|l_{max}^2(N_N - 1)|$. ■

Lemma 4: We can construct a feasible solution for the A1 problem with non-negative integer variables $\widehat{[f_{ij}^{lk}]_{LP\rightarrow MIP}}, \widehat{N_{rnd}^1}$ and $\widehat{s_i^2} = 0$, provided that $\frac{\widehat{N_{rnd}^1}}{N_{rnd-LP}} \geq \frac{\varsigma(i)}{\widehat{N_{rnd}^1} T_{rnd}}$, $\forall i \in V$.

Proof:

1) Due to the linearity of the problems, we can decompose flows into per packet flows. Furthermore, we can form paths for each generated packet from the source to the sink. However, the sum of flows on each link should satisfy the modified flow balance equation. Again, due to the linearity of the problems, we can remove remove any number of packets from each source provided that the number of removed packets from each source do not exceed $\widehat{N_{rnd}^1} s_i + \widehat{s_i^2}$, hence, we can remove $\widehat{s_i^2}$ packets from each node-i without violating the modified flow balance Equation (*i.e.*, while preserving the non-negativity of the flows $\widehat{s_i^2} = 0$ can be achieved by preserving the modified flow balance constraint).
2) Non-negativity of $\widehat{N_{rnd}^1}$ is proved in Lemma 3.
3) Since $\widehat{[f_{ij}^{lk}]_{LP\rightarrow MIP}}$ flows are lower than or equal to $[f_{ij}^{lk}]_{LP\rightarrow MIP}$ flows, energy constraint is not violated.
4) The bandwidth constraint (Equation 22) is satisfied with $\{[f_{ij}^{lk}]_{LP\rightarrow MIP}, N_{rnd-LP}\}$, therefore, it is also satisfied with $\{\widehat{[f_{ij}^{lk}]_{LP\rightarrow MIP}}, N_{rnd-LP}\}$, hence, the bandwidth constraint is satisfied with $\{\widehat{[f_{ij}^{lk}]_{LP\rightarrow MIP}}, \widehat{N_{rnd}^1}\}$ if $\frac{\widehat{N_{rnd}^1}}{N_{rnd-LP}} \geq \frac{\varsigma(i)}{\widehat{N_{rnd}^1} T_{rnd}}$, $\forall i \in V$. ■

Corollary 1: The feasible solution of A1 problem defined by the variables $\{\widehat{[f_{ij}^{lk}]_{LP\rightarrow MIP}}, \widehat{N_{rnd}^1}\}$ and $\widehat{s_i^2} = 0$, is also a feasible solution of the original IP problem.

Theorem 1: $(N_{rnd-LP} - N_{rnd-IP}) \leq l_{max}^2(N_N - 1)$.

Proof: Since $\{[\widehat{f_{ij}^{lk}}]_{LP \to MIP}, \widehat{N_{rnd}^1}\}$ is a feasible solution to the original IP problem, the difference between the optimal integer solution and optimal LP solution is not larger than $l_{max}^2(N_N - 1)$. ■

Corollary 2: For all strategies other than the GPLD strategy, $(N_{rnd-LP} - N_{rnd-IP}) \leq (N_N - 1)$ because the number of outgoing and incoming links at each node is limited by $(N_N - 1)$.

The constraint $\frac{\widehat{N_{rnd}^1}}{N_{rnd-LP}} \geq \frac{\varsigma(i)}{\widehat{N_{rnd}^1} T_{rnd}}$, $\forall i \in V$, is not tight in our application. Since, our N_{rnd-LP} values are larger than 10^5 and $N_N \leq 25$, $\frac{\widehat{N_{rnd}^1}}{N_{rnd-LP}} \geq 0.8$ and $\frac{\varsigma(i)}{\widehat{N_{rnd}^1} T_{rnd}} \leq 0.05$. Therefore, there is a very large margin for this constraint to hold. Furthermore, for LPLD, $\frac{\widehat{N_{rnd}^1}}{N_{rnd-LP}} \geq 0.999$.

J. Putting The Strategies in Perspective

All strategies we present in this study except the GPLD and LPLD strategies are representative of certain transmission power level optimization approaches for WSN lifetime maximization proposed in the literature. Indeed, we motivate each strategy by referring to certain transmission power control approaches proposed in WSN literature. Therefore, one of our contributions is to provide a comparative evaluation of prominent examples of transmission power control approaches proposed in the literature under optimal conditions within a unified framework that provides compatibility in comparisons. Furthermore, each strategy we propose is, in fact, for testing a hypothesis on link level handshake transmission power maximization. Research questions posed in Section I are also addressed by employing the aforementioned strategies.

GPLD strategy is the most generic strategy we propose which maximizes the network lifetime by considering all possible combinations of data and ACK packet transmission power levels for each link. We use GPLD strategy as our gold standard. All other strategies (except GPLD-SPLA) are link scope transmission power assignment strategies (*i.e.*, data and ACK packet transmission power levels for each link are assigned by considering the energy dissipations of the transmitter and receiver of that particular link only). By construction, the lifetime obtained for a particular WSN setting with GPLD is not lower than the lifetime obtained with any other strategy except LPLD-PF and LPLD-PFZA.

In LPLD strategy, transmission power level decisions are made by minimizing the energy dissipation for each link. Both data and ACK packet transmission power levels are allowed to take any combination of the available power levels. The difference of LPLD-EPL strategy from LPLD strategy is that in LPLD-EPL transmission power levels for data and ACK packets should be equal to each other. LPLD-EPL strategy is an idealized abstraction for link level transmission power control strategies (*e.g.*, [14], [19]–[22]).

In LPLD-MAPL strategy, ACK packets are transmitted by using the highest transmission power level available and the data packet transmission power levels are optimized per link which is inspired by the transmission power control approach in [19]. Using the maximum transmission power is a strategy employed by several studies on transmission power control to benchmark against [22], [47]. Indeed, the highest transmission power level is utilized for both data and ACK packets at all links in LPLD-MPL strategy.

TABLE II: Strategies descriptions, and representations.

Strategy	Description	Represents
Global Power Level Decisions (GPLD)	Power level at each link and the amount of flow for each power level is determined jointly as global decisions	–
Local Power Level Decisions (LPLD)	Power levels are determined locally	–
Local Power Level Decisions with Equal Power Level Assignment (LPLD-EPL)	Power levels are determined locally by using the same power level for both data and ACK packets on each link	[14], [20], [21]
Local Power Level Decisions with Maximum ACK Power Level Assignment (LPLD-MAPL)	Only data packet transmission levels are optimized locally while transmitting the ACK packets by using the highest power level	[19]
Local Power Level Decisions with Maximum Power Level Assignment (LPLD-MPL)	Both data and ACK packets are transmitted by using the highest power level	[22], [47]
Local Power Level Decisions with Perfect Feedback (LPLD-PF)	ACK packets are assumed to be error-free	[48]
Local Power Level Decisions with Perfect Feedback and Zero ACK Length (LPLD-PFZA)	ACK packet are assumed to be both error-free and zero-sized	[5], [7], [24], [31]–[35], [49]–[54]
Global Power Level Decisions with Single Power Level Assignment (GPLD-SPLA)	The same power level is used for both data and ACK packets on all links and the power level giving the highest lifetime is employed	[17], [18]

As stated in Section II, network level strategies [17], [18] are important classes of transmission power control strategies. Therefore, we develop GPLD-SPLA strategy as an idealized abstraction of network level strategies.

In literature a common assumption on ACK packets is that the failure of ACK packets can be ignored without leading to significant energy dissipation characterization errors [49], [50]. In fact, in many studies the existence of a perfect feedback channel is (either explicitly or implicitly) assumed [48], [51]–[54]. While it is tempting to state that the energy cost of link level handshake failures due to ACK packet failures in WSNs is insignificant, we are not aware of any clear scientific evidence or convincing systematic analysis to support such a conjecture. Hence, LPLD-PF and LPLD-PFZA strategies are proposed to evaluate the lifetime values under perfect feedback channel assumption. In these strategies we assume that the ACK packets have a success probability of unity. ACK packet sizes are taken as 20 Bytes and zero in LPLD-PF and LPLD-PFZA strategies, respectively. Therefore, lifetime values obtained with LPLD-PF and LPLD-PFZA strategies, by construction, are not lower than other link scope strategies.

Although, most of our strategies are inspired by already existing transmission power control approaches, ACK packet transmission power assignment has never been addressed in these studies (the only exception is the maximum power level assignment for the ACK packets [19]), hence, we extended the basic ideas by incorporating ACK packet transmission power control in addition to data packet transmission power control (*i.e.*, the whole handshake cycle is modeled instead of only data packet transmissions). For convenience, we present the condensed summaries of the proposed eight strategies in Table II.

V. Analysis

In this section, we present the results of numerical analysis to investigate the performances of proposed optimization models. We used a disk shaped deployment area for the sensor nodes and placed the base station at the center of the disk. Nodes are deployed using a uniform random distribution.

We use MATLAB to construct the instances of the system model presented in Section III. General Algebraic Modeling System (GAMS) with CPLEX solver is employed for the solutions of the optimization problems presented in Section IV. All data points presented in this section are the averages of 100 random runs (*i.e.*, at each run path loss values of all links and node positions are regenerated). We utilized two data packet lengths (64 Bytes and 256 Bytes) to investigate the effects of data packet size on the performance of the strategies ($M_A = 20$ Bytes and $s_i = 1$ packet). Note that for CC1000 radios used in Mica2 platforms the maximum allowed packet size is 256 Bytes [55].

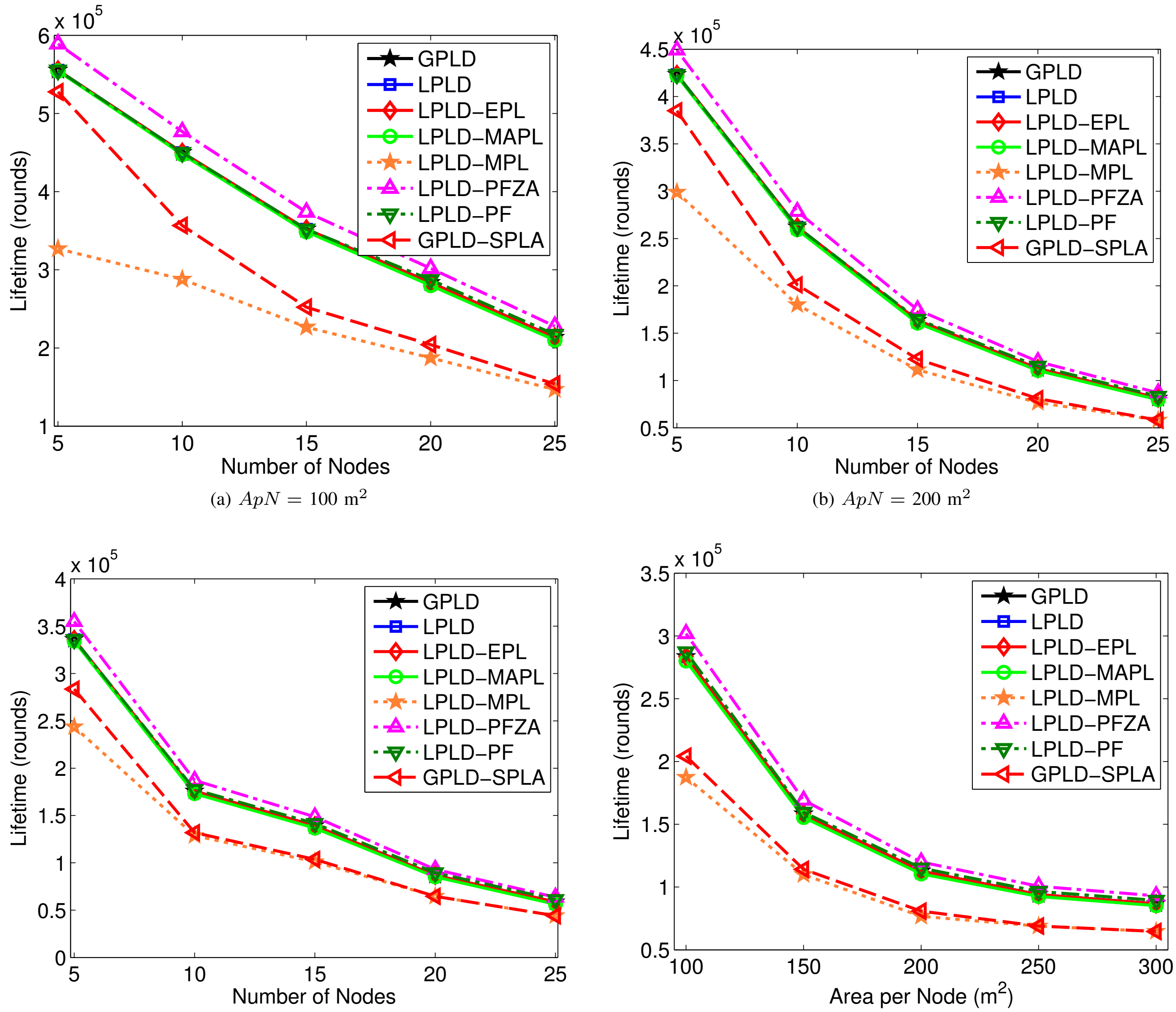
Since the variables in our mathematical programming models are integer valued (*i.e.*, flow variables are representing the number of data packets), all our models are Mixed Integer Programs (MIP). We present the exact integer solutions of our problems, first. Later in this section, we are going to present efficient solution heuristics.

In Figure 1, we present network lifetime for the eight strategies as functions of Number of Nodes (N_N) in the network and Area per Node (ApN) when $M_P = 256$ Bytes. We calculate ApN values by using the following formula $ApN = \frac{\pi R_{net}^2}{N_N}$ where R_{net} is the network radius. Increasing ApN results in longer distances and larger path loss values (*i.e.*, the higher the ApN is, the sparser the network is). For example, when $N_N = 20$, average distance between node pairs are calculated as 21.07 m, 29.79 m, and 36.49 m for $ApN = 100$ m^2, $ApN = 200$ m^2, and $ApN = 300$ m^2, respectively. By varying N_N, we explore the effects of higher number of links and more complex interactions on the network lifetime. For example, considering LPLD-MPL strategy the average number of links of nodes with $N_N = 5$ are 3.75, 3.13, and 2.71, for $ApN = 100$ m^2, $ApN = 200$ m^2, and $ApN = 300$ m^2, respectively, whereas, with $N_N = 25$ the average number of links increase to 9.12, 5.33, and 4.46 for $ApN = 100$ m^2, $ApN = 200$ m^2, and $ApN = 300$ m^2, respectively.

In Figure 1a, Figure 1b, and Figure 1c, ApN values are 100 m^2, 200 m^2, and 300 m^2, respectively (*i.e.*, the effects of varying N_N for a constant ApN in each figure is investigated). In Figure 1d, N_N is kept constant (*i.e.*, 20 nodes) and ApN is varied. To investigate the effects of data packet length we also obtained results by using $M_P = 64$ Bytes which is presented in Figure 2. The difference in Figure 1 and Figure 2 is only the data packet size and the comments on Figure 1 pertaining to the variation of N_N and ApN are also valid for Figure 2. Network lifetime decreases for all strategies as ApN increases. For example, network lifetimes obtained when LPLD strategy is used with $N_N = 20$ are 2.83×10^5 rounds, 1.13×10^5 rounds, and 0.87×10^5 rounds for $ApN = 100$ m^2, $ApN = 200$ m^2, and $ApN = 300$ m^2, respectively (Figure 1d). Average distance to be traversed to reach the base station increases which results in higher energy cost for data flows. For example, the average distances traversed by data packets to reach the base station are 20.58 m, 34.89 m, and 44.93 m for $ApN = 100$ m^2, $ApN = 200$ m^2, and $ApN = 300$ m^2, respectively, when LPLD strategy is used with $N_N = 20$. Increasing N_N also decreases the network lifetime for all strategies. For example, considering LPLD strategy with $ApN = 200$ m^2 in Figure 1b, network lifetimes and average distances traversed by data packets are (2.62×10^5 rounds, 20.92 m), (1.63×10^5 rounds, 28.01 m), and (1.13×10^5 rounds, 34.89 m) for $N_N = 10$, N_N =15, and $N_N = 20$, respectively.

Except for the perfect feedback strategies (LPLD-PF and LPLD-PFZA), network lifetime values obtained for GPLD are higher than or equal to the other strategies because GPLD power assignment decisions are based on global optimizations whereas in the other strategies power level decisions are based on link scope optimizations. However, network lifetime values obtained by using LPLD and LPLD-EPL are always within 1.0% neighborhood of GPLD. The reason for such behavior is that the power levels assigned by GPLD strategy and LPLD strategy under the same settings coincide for the overwhelming majority of the links. It is also worth mentioning that LPLD lifetime values are slightly larger than LPLD-EPL lifetime values as a general trend because the local optimization for LPLD-EPL is performed with one less degree of freedom than for LPLD. Nevertheless, our results show that global optimization of power levels in link level handshaking in WSNs can be closely approximated by using well designed link scope power level assignment heuristics.

Network lifetime values for LPLD-MAPL lie within 6.0% neighborhood of lifetime values obtained with GPLD. For example, in Figure 2b LPLD-MAPL and GPLD lifetimes are 2.25×10^5 rounds and 2.39×10^5 rounds, respectively, for $N_N = 25$ and $ApN = 200$ m^2 (LPLD-MAPL lifetime is 5.86% lower than GPLD lifetime). The maximum power level is not used for ACK packets in a significant portion of the links by GPLD strategy, however, LPLD-MAPL strategy is designed to assign the maximum power level for ACK packets. Therefore, LPLD-MAPL wastes energy for unnecessarily high ACK packet power levels. As an illustrative example, consider a pair of nodes (*i.e.*, node-i and node-j) where node-i transmits a data packet to node-j successfully. Node-j transmits node-i an ACK packet for the successfully received data packet. The path loss on this link is given as 93 dB (*i.e.*, $\Upsilon_{ij} = 93$ dB). The probability of successfully transmitting an ACK packet on (j, i) link with power level $l = 3$ is $p_{ij}^s(l = 3, M_A) > 0.99$ (by using Equation 4) with the transmission energy cost of



(a) $ApN = 100$ m^2

(b) $ApN = 200$ m^2

(c) $ApN = 300$ m^2

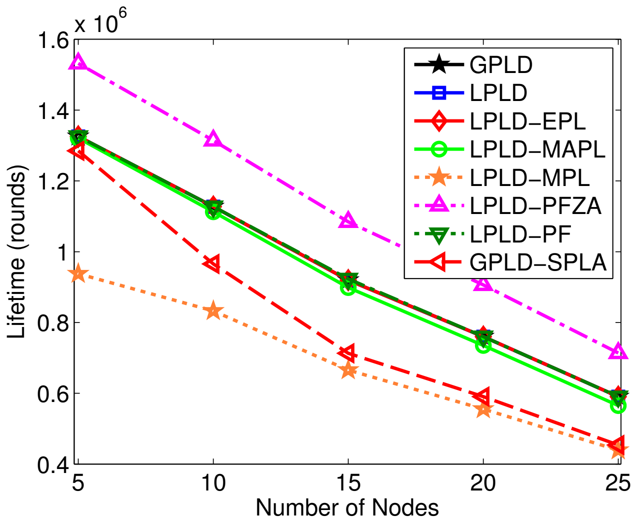
(d) $N_N = 20$

Fig. 1: Network lifetimes for all strategies with $M_P = 256$ Bytes.

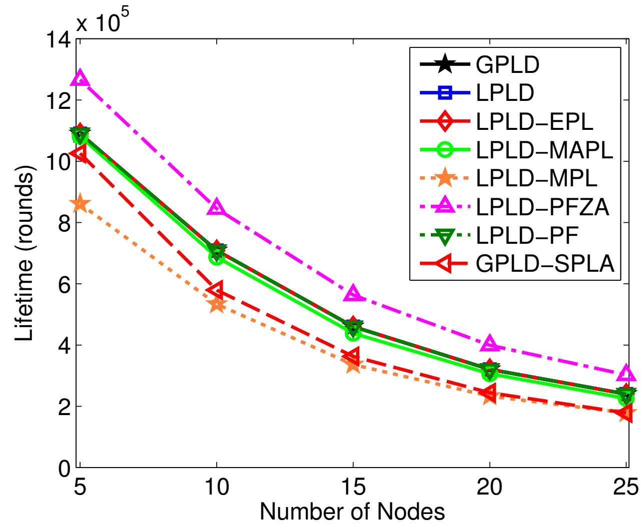
2.25×10^{-4} J (*i.e.*, $E^P_{tx}(l = 3, M_A) = 2.25 \times 10^{-4}$ J calculated by using Equation 9). However, if node-j transmits the ACK packet with the maximum power level (*i.e.*, $l_{max} = 26$) it would dissipate $E^P_{tx}(l_{max} = 26, M_A) = 6.35 \times 10^{-4}$ J of transmission energy (*i.e.*, almost three times the optimal energy is dissipated for only an increment in the fourth significant digit after the decimal point of the ACK success probability).

LPLD-MPL is the simplest strategy we consider. Indeed, in LPLD-MPL, transmission power levels for both data and ACK packets are set to the maximum level. As a general trend, the ratio of LPLD-MPL lifetime and GPLD lifetime increases for increasing ApN which results in larger link distances and on the average larger path loss values. As ApN increases GPLD utilizes higher power levels, therefore, power levels assigned by GPLD and LPLD-MPL get closer to each other which in turn decreases the difference between GPLD and LPLD-MPL lifetime. LPLD-MPL lifetime values can be as low as 59% of GPLD lifetime (Figure 1a for $N_N = 5$) and can be as high as 80% of GPLD lifetime (Figure 2c for $N_N = 5$).

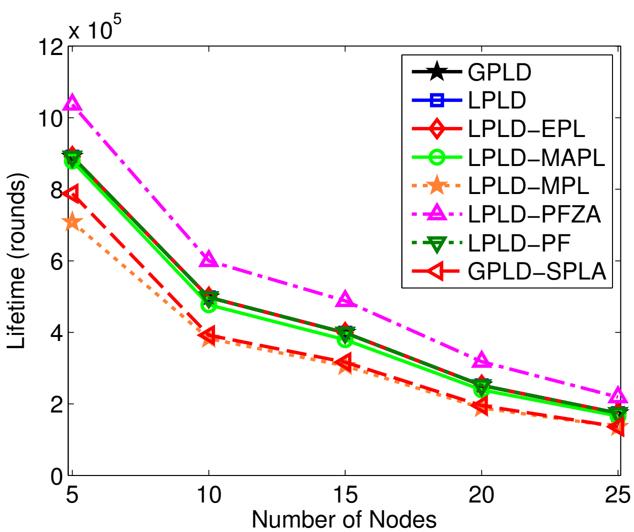
GPLD-SPLA is also a fixed transmission power strategy like LPLD-MPL, however, in GPLD-SPLA, the optimal transmission power is used instead of the maximum power in LPLD-MPL. Network lifetimes obtained with GPLD-SPLA are larger than LPLD-MPL. For example, the average optimal power levels chosen by GPLD-SPLA with $ApN = 100\ m^2$ are 23.14, 24.93, and 25.48 for $N_N = 10$, $N_N = 15$, and $N_N = 20$, respectively. GPLD-SPLA lifetimes with $ApN = 100$ m^2 are 15.99%, 7.06%, and 6.49% higher than LPLD-MPL lifetimes for $N_N = 10$, $N_N = 15$, and $N_N = 20$, respectively. Lifetime difference between GPLD-SPLA and LPLD-MPL is at most 61% (Figure 1a, $N_N = 5$). Yet, GPLD-SPLA lifetimes are lower than LPLD-EPL and LPLD-MAPL because GPLD-SPLA has less degrees of freedom in power level



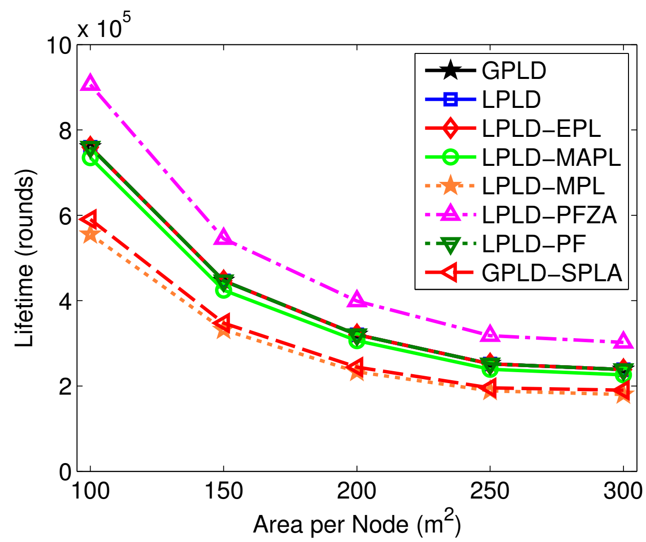
(a) $ApN = 100$ m^2



(b) $ApN = 200$ m^2



(c) $ApN = 300$ m^2



(d) $N_N = 20$

Fig. 2: Network lifetimes for all strategies with $M_P = 64$ Bytes.

assignment when compared to these strategies (*i.e.*, in LPLD-EPL and LPLD-MAPL power level for each link is determined independently, however, in GPLD-SPLA all links use a single power level for a given network topology).

LPLD-PF and LPLD-PFZA strategies are used to investigate the validity of the perfect feedback assumption in WSNs. Packet failure probability for ACK packets is set to zero, therefore, failure of a handshake is due to data packet failures only in both LPLD-PF and LPLD-PFZA strategies. In LPLD-PF strategy ACK packet length is kept the same as the other strategies (*i.e.*, $M_A = 20$ Bytes), hence, ACK packet transmission and receptions are still accounted for in the energy budget, whereas, in LPLD-PFZA strategy, ACK packet length is set to zero and no power is dissipated on transmitting or receiving ACK packets. Both LPLD-PF and LPLD-PFZA strategies are based on the LPLD-EPL strategy because in LPLD-EPL strategy both data and ACK packet power levels are set to the same level (*i.e.*, ACK transmission level is not a constant for all links) and its performance is the best after GPLD and LPLD strategies. If GPLD or LPLD strategies were used then the ACK power levels would be set to the lowest level which would result in an unfair model.

Network lifetimes obtained with both LPLD-PF and LPLD-PFZA strategies are higher than the lifetime obtained with LPLD-EPL strategy, by design. In fact, we want to quantify the network lifetime over estimation due to perfect feedback channel assumption. The difference between the lifetimes of LPLD-EPL and LPLD-PF strategies is due to ACK packet failures which are not accounted for in LPLD-PF strategy. The difference between the lifetimes of LPLD-PF and LPLD-PFZA strategies arises due to the zero ACK packet length in LPLD-PFZA strategy.

LPLD-PF lifetime values are at most 5% (Figure 1c, $N_N = 25$) and 1% (Figure 2c, $N_N = 25$) higher than GPLD lifetime

TABLE III: Solution times (in seconds) for all strategies when $ApN = 200$ m^2.

M_P (Bytes)	N_N	Solution Times (s)							
		GPLD	LPLD	LPLD-EPL	LPLD-MPL	LPLD-MAPL	LPLD-PF	LPLD-PFZA	GPLD-SPLA
256	5	1.34	0.26	0.22	0.21	0.23	0.22	0.21	10.58
	10	8.52	0.27	0.23	0.22	0.24	0.23	0.22	11.93
	15	18.17	0.29	0.25	0.24	0.26	0.25	0.24	13.82
	20	50.65	0.31	0.30	0.29	0.30	0.30	0.28	15.47
	25	147.25	0.63	0.61	0.55	0.61	0.53	0.53	28.27
64	5	0.69	0.23	0.18	0.19	0.23	0.21	0.20	11.45
	10	4.14	0.24	0.19	0.20	0.24	0.22	0.21	12.43
	15	18.48	0.26	0.20	0.21	0.26	0.23	0.23	13.21
	20	56.60	0.29	0.26	0.28	0.29	0.28	0.26	14.70
	25	158.49	0.53	0.50	0.53	0.53	0.50	0.48	29.36

values for $M_P = 256$ Bytes and $M_P = 64$ Bytes, respectively. Lifetime values for LPLD-PFZA are 5-9% and 16-26% higher than GPLD lifetime values for $M_P = 256$ Bytes and $M_P = 64$ Bytes, respectively. The lifetime difference between both strategies (*i.e.*, LPLD-PF and LPLD-PFZA) and GPLD increases as the average link distance increases, as a general trend. For example, for $ApN = 300$ m^2, $M_P = 256$ Bytes, and $N_N = 5$ (Figure 1c) average link distance is 14.26 m and lifetimes of LPLD-PFZA and LPLD-PF are 5.65% and 0.01% higher than GPLD lifetime, respectively, whereas, with $N_N = 25$ average link distance increases to 41.69 m and lifetimes of LPLD-PFZA and LPLD-PF are 8.53% and 4.27% higher than GPLD lifetime, respectively. The reason for such behavior is that transmission power levels for both data and ACK packets are higher for larger path loss values and packet failure probability also increases as the link distance increases. For example, for $ApN = 100$ m^2, $M_P = 256$ Bytes, and $N_N = 10$ (Figure 1a), average link distance is 13.80 m and GPLD data and ACK average transmission power levels are 14.34 and 17.01, respectively, whereas, for $ApN = 300$ m^2, $M_P = 256$ Bytes, and $N_N = 10$ (Figure 1c), average link distance is 23.91 m and GPLD data and ACK average transmission power levels are 17.87 and 19.61, respectively.

Lifetime difference between LPLD-PFZA and GPLD for $M_P = 64$ Bytes is higher than $M_P = 256$ Bytes at a given point in the parameter space. For example, for $ApN = 300$ m^2, $M_P = 256$ Bytes, and $N_N = 25$ (Figure 1c), LPLD-PFZA lifetime is 8% higher than GPLD lifetime. However, for $ApN = 300$ m^2, $M_P = 64$ Bytes, and $N_N = 25$ (Figure 2c) LPLD-PFZA lifetime is 26% higher than GPLD lifetime. The reason for such behavior is that the ratio of the ACK packet length to the data packet length is higher for $M_P = 64$ Bytes (*i.e.*, $M_P/M_A = 3.20$) than $M_P = 256$ Bytes (*i.e.*, $M_P/M_A = 12.80$). In other words, contribution of ACK packets to energy dissipation is more for lower data packet sizes. Hence the impact of ACK packet is higher when data packet size is lower.

General MIP models are computationally difficult problems [56], which can be mitigated using heuristics. We investigated the option of solving the optimization problems under Linear Programming (LP) relaxation assumption (*i.e.*, flows are allowed to take fractional values) because LP problems are solvable in polynomial time. We proved in Subsection IV-I that the maximum difference of LP-relaxation solutions of the GPLD and LPLD problems are bounded by $l_{max}^2(N_N - 1)$ and $(N_N - 1)$, respectively. Furthermore, we solved each problem instance presented in Figure 1 and Figure 2 by using LP-relaxation, also. The maximum difference is found to be less than 0.00025%, which is within the bounds we proved. For example, for $ApN = 300$ m^2, $M_P = 256$ Bytes, and $N_N = 25$, LPLD lifetime obtained by the exact MIP solution and the LP-relaxation solution are 469068 rounds and 469069.04 rounds (*i.e.*, the difference is 1.04 round). The bound we provided in Corollary 2 (Subsection IV-I), estimates that the maximum difference is upper limited by $(N_N - 1) = 24$ rounds.

One distinct advantage of strategies based on link scope power assignment over global power level assignment strategy is lower computational complexity. The size of the optimization space for GPLD, LPLD, LPLD-EPL, LPLD-MPL, LPLD-MAPL, LPLD-PF, LPLD-PFZA, and GPLD-SPLA are $N_N^2 \times l_{max}^2$, $N_N^2 + l_{max}^2$, $N_N^2 + l_{max}$, N_N^2, $N_N^2 + l_{max}$, $N_N^2 + l_{max}$, $N_N^2 + l_{max}$, and $N_N^2 \times l_{max}$, respectively. Solution times for all LPLD strategies are lower than GPLD and GPLD-SPLA. Furthermore, as N_N increases the difference between the solution times also increase. Note that for small problem sizes (*e.g.*, $N_N = 5$), GPLD-SPLA solution times are larger than GPLD solution times, however, as the problem size increases this trend is reversed. We present Table III which contains average solution times for all strategies with $ApN = 200$ m^2 as functions of M_P and N_N.

To explore the impact of finite retransmission count, we solved each problem instance presented in Figure 1 and Figure 2 for $N_{rtr} = 3$ by using LP-relaxation. The difference in lifetimes are found to be upper bounded by 0.0003%. Lifetime differences between $N_{rtr} \to \infty$ and $N_{rtr} = 3$ cases for $ApN = 200$ m^2 are presented in Table IV.

VI. Discussion

In this study, we do not propose a new network protocol for link level handshake transmission power level optimization to maximize WSN lifetime. Instead, we analyze the performances of handshake transmission power assignment strategies from network lifetime maximization perspective within a general

TABLE IV: Lifetime difference (%) between $N_{rtr} \to \infty$ and $N_{rtr} = 3$ cases when $ApN = 200$ m^2.

M_P (Bytes)	N_N	Difference (%)							
		GPLD	LPLD	LPLD-EPL	LPLD-MPL	LPLD-MAPL	LPLD-PF	LPLD-PFZA	GPLD-SPLA
256	5	0.000030	0.000030	0.000030	0.000030	0.000042	0.000028	0.000030	0.000032
	10	0.000048	0.000048	0.000048	0.000048	0.000069	0.000045	0.000048	0.000062
	15	0.000076	0.000076	0.000076	0.000078	0.000112	0.000072	0.000076	0.000102
	20	0.000111	0.000111	0.000111	0.000113	0.000163	0.000104	0.000109	0.000155
	25	0.000154	0.000154	0.000154	0.000157	0.000215	0.000144	0.000150	0.000215
64	5	0.000011	0.000011	0.000011	0.000012	0.000015	0.000010	0.000011	0.000012
	10	0.000018	0.000018	0.000018	0.000018	0.000023	0.000015	0.000018	0.000022
	15	0.000027	0.000027	0.000027	0.000029	0.000037	0.000022	0.000027	0.000034
	20	0.000039	0.000039	0.000039	0.000041	0.000054	0.000031	0.000039	0.000051
	25	0.000052	0.000052	0.000052	0.000055	0.000070	0.000041	0.000052	0.000070

framework and without going into the details of specific routing protocols or algorithms. In fact, MIP based optimization of data flows in the network to maximize the lifetime is an abstraction for an idealized WSN routing protocol. By doing so we eliminate the possible suboptimal behaviors of routing protocols' implementation details not specifically related to the concept under investigation, *per se*.

In GPLD, routing layer decisions (*e.g.*, the amount of data on each link and chain of links forming routes from each sensor node to the base station) and link layer decisions (*e.g.*, power level assignments) are made jointly. Therefore, GPLD is an idealized abstraction for a monolithic link and network layer protocol (*i.e.*, cross layer design). On the other hand, in link scope strategies, power level assignment decisions are made independent of the network layer decisions. Furthermore, in link scope strategies, power level assignment decisions are made by considering only the energy dissipations of the transmitter and the receiver on a link, thus, proposed link scope power level assignment strategies can be used as guidelines in designing distributed algorithms.

It is worth remarking that the link layer model we employed is specific to a certain hardware platform. This is due to the fact that it is not possible to produce realistic results at this level of analysis without utilizing the features of a specific platform. As discussed in Section I, one of our motivating factors in this study is that most of the mathematical programming based studies make over simplified assumptions in modeling the link layer which may lead to erroneous characterizations. Nevertheless, our link layer model can easily be tailored to model other platforms. In fact, only the parameter values are required to be changed in most cases.

In this study, we considered a stable communication channel for each link where the path loss does not change. Nevertheless, the results we present are averages of 100 independent scenarios where in each scenario the path loss values varies greatly, hence, the variations in channel conditions do not affect our conclusions provided that the channel state can be estimated accurately. Indeed, it is shown through direct experimentation in [14] that channel conditions can be estimated accurately in WSNs with very low overhead.

In our framework, each node can transmit or receive one data packet at each slot. However, the number of slots utilized by each node is not limited to one. The bandwidth constraint (Equation 23) is used to ensure that the bandwidth used by each node is upper limited by the channel bandwidth. In the parameter space we investigated, the left side of the inequality is more than an order of magnitude lower than the right side. Therefore, nodes have ample time to transmit multiple packets at each round. Hence, it is possible to construct a time schedule such that each node delivers all data packets it receives, as well as it generates in one round to the intended next-hop destinations, within the same round.

VII. Conclusion

In this study, we investigate the impact of transmission power control for link level handshaking on WSN lifetime. We develop a novel link level abstraction to be able to model various transmission power assignment strategies. Different from the existing studies in literature which were focused on data packet transmission power control only, we construct a family of mathematical programming models to explore the impact of transmission power control strategies for link level handshaking and to test the validity of certain conjectures on link level handshaking. This approach gives us the opportunity to perform numerical analysis spanning a wide range of parameter space. Since the motivation for this paper is provided in the form of a series of questions in Section I, we present conclusions in reply to these questions itemized as follows:

1) We build a link level abstraction based on Mica2 mote's energy dissipation characteristics and a path-loss model with log-normal shadowing to be able to construct an MIP framework that enables us to explore the impact of transmission power control for link-level handshaking in the presence of data and ACK packet failures.
2) We proved that the difference between the lifetime values obtained by exact solutions and LP-relaxation solutions of GPLD and LPLD are upper bounded by $l_{max}^2(N_N - 1)$ and $(N_N - 1)$, respectively. Furthermore, we show that the solutions of the MIP models can be approximated by LP-relaxation with insignificant approximation errors (less than 0.00025%).
3) Transmission power level assignment for data and ACK packets as well as the amount of data flow on each link should be optimized jointly by considering the decisions made for other links. In fact, these decisions are all

interrelated (*e.g.*, the path loss between two nodes effects the transmission power level chosen which in turn effects the amount of data flow on the link). Thus, the maximum possible network lifetime cannot be achieved without treating data and ACK packet transmission levels as global decision variables, which is confirmed by the results of numerical analysis (GPLD lifetime is higher than LPLD lifetime for the whole parameter space).

4) Although link scope optimization of transmission power level assignment for handshaking results in suboptimal solutions, the extent of the decrease in network lifetime is not significantly high (LPLD lifetime values are always within 1.0% neighborhood of GPLD lifetime values). Furthermore, due to the reduction in computational complexity, link scope optimization problems can be solved remarkably faster than global optimization problems (GLPD solutions takes up to two orders of magnitude more time than LPLD solutions).
5) A further reduction of computational complexity for links scope optimization is achieved by reducing the power assignment to a single dimension where data and ACK packets are transmitted at the same level, yet, this strategy leads to only marginal reductions in computation times. However, the extent of network lifetime decrease is also marginal (LPLD-EPL lifetimes are within 1.0% neighborhood of GPLD lifetime values).
6) Transmitting ACK packets by using the highest available power level for all links is a good strategy provided that ACK packet length is very small when compared to the data packet length (LPLD-MAPL lifetime values are within 1.0% neighborhood of LPLD lifetime values for $M_P = 256$ Bytes). However, as the ratio of ACK packet length to data packet length gets higher, the performance of the strategy of transmitting the ACK packets by using the highest power level decreases considerably (LPLD-MAPL lifetime can be 6% lower than GPLD lifetime for $M_P = 64$ Bytes). Transmitting both data and ACK packets by utilizing a fixed transmission level is not preferable (LPLD-MPL and GPLD-SPLA network lifetimes can be as low as 59.0% and 71.0% of GPLD lifetime, respectively).
7) The assumption of perfect feedback channel can be justified in the analysis of WSNs if the handshake failure probability is very low provided that the finite (*i.e.*, non-zero) length of ACK packets, which result in a certain amount of energy dissipation, are accounted for. However, for higher handshake failure probabilities, even if the finite length of ACK packets are accounted for, perfect feedback channel assumption can lead to non-negligible over estimation of WSN lifetime.

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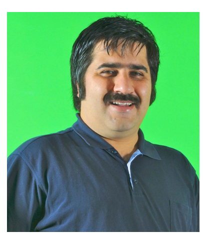
Huseyin Ugur Yildiz received the BSc degree from the Department of Electrical and Electronics Engineering, Bilkent University, Ankara, Turkey, in 2009, and the MSc degree from the Department of Electrical and Electronics Engineering, TOBB University of Economics and Technology, Ankara, Turkey, in 2013, where he is currently pursuing the PhD degree. He is currently with Turk Telekom, Ankara, as a senior network engineer. His research interests lie in the areas of wireless communications, wireless sensor networks, and network optimization.



Bulent Tavli is an associate professor at the Electrical and Electronics Engineering Department, TOBB-ETU, Ankara, Turkey. He received the BSc degree in Electrical & Electronics Engineering in 1996 from the Middle East Technical University, Ankara, Turkey. He received the MSc and PhD degrees in Electrical and Computer Engineering in 2001 and 2005 from the University of Rochester, Rochester, NY, USA. Telecommunications and embedded systems are his current research areas.

Halim Yanikomeroglu is a Professor in the Department of Systems and Computer Engineering at Carleton University, Ottawa. His research interests cover many aspects of the physical, medium access, and networking layers of wireless communications. He is a senior member of the IEEE.