The Impact of Random Power Assignment in Handshaking on Wireless Sensor Network Lifetime

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***Abstract*—Optimization of data and acknowledgement (ACK) packets' transmission power levels is necessary to prolong the lifetime of wireless sensor networks (WSNs). Utilizing the maximum power level available results in the minimum level of handshake failures, however, such a strategy will also result in energy waste because it may not be necessary to utilize the maximum power level at each link. Alternatively, the optimal data and ACK packet transmission levels can be determined for each link that minimizes the energy cost of handshaking. Accomplishing this task requires that the packet failure rates for each combination of power levels for data and ACK packets are measured through a close loop scheme which brings extra overhead when compared to the strategy of employing the highest power level. In this paper, we propose a novel strategy based on random power level assignments that do not require the overhead necessary to measure the handshake failure rate, yet, at the same time performs better than the maximum power level assignment strategy. To evaluate the performance of the proposed strategy we built a novel mixed integer programming (MIP) framework. Our results show that random power assignment performs better than maximum power assignment in terms of network lifetime.**

***Index Terms*—wireless sensor networks, network lifetime, energy efficiency, power control, mixed integer programming.**

I. Introduction

Wireless sensor networks (WSNs) are a certain type of ad hoc networks composed of a plurality of battery powered sensor nodes and a central base station deployed over a geographical area for monitoring the environment by collecting sensor data like temperature, humidity, and acoustic vibrations [1]. Measurements by the sensor nodes are conveyed to the central base station for further processing. Energy dissipation in a WSN can be categorized into two broad categories: communication and computation energy dissipations. The energy required for communication, usually, dominates the total energy budget [2], [3]. Recharging or replacing the battery of a sensor node is not preferred, thus, network designers should consider a feasible solution in which sensor nodes dissipate their energies in a balanced fashion so that over-utilization of energy by any node is avoided (*i.e.*, the lifetime of WSN is maximized) [2].

Transmission power control (TPC) is a research topic that have been investigated extensively in the literature due to the potential energy savings that can prolong the WSN lifetime. However, the amount of published studies on the performance of assigning power levels randomly is limited. In [4], a comparative study of fixed power assignment and random power assignment in WSNs is presented. It is shown through simulations that random power assignment can provide insignificant lifetime gains (*e.g.*, less than 2 %). In [5], an analysis of fixed and random transmission power assignment strategies are performed for wireless ad hoc networks. It is reported that randomizing transmit power has positive effect of reducing high interferences to the other nodes, and improves network connectivity, in high-density networks. In [6], the outage probabilities of fixed and random power allocation schemes in WSNs are investigated. the main conclusion of this study is that random power assignment cannot improve the outage performance considerably.

The existing body of research on investigating random power assignment in WSNs compared only the performances of random and fixed power assignment schemes, however, the relative performance of optimal power assignment should also be considered to assess the potential gains brought by the random power assignment approach. A complete characterization requires the whole handshake cycle to be considered in the analysis which lacks in all aforementioned studies. Note that handshaking is the default mechanism for data exchange in practical WSN deployments. Energy dissipation of a WSN platform includes not only energy dissipation for data transmission but also many other terms which are ignored in above mentioned studies. Furthermore, WSN lifetime is the most important metric in evaluating transmission power assignment strategies which is not covered by prior studies.

To fill the gap in the literature on random power assignment in WSNs we address all these points in this paper. We present a novel mixed integer programming (MIP) framework to accurately model the energy dissipation in WSNs by adopting an experimentally verified channel model and Mica2 mote platforms characteristics. We incorporate a detailed link layer model of data exchange (two-way handshaking) in our model. We explored a wide range of parameter space through the numerical analysis using the MIP model. The performances of fixed, optimal, and various random power assignment strategies' are characterized in terms of network lifetime achieved. Nevertheless, the main research question we seek answer to can be posed as follows: What is the performance gains/losses brought by random power assignment in WSNs in comparison to optimal and fixed power assignments?

II. System Model

This section presents a brief overview of the system model and the link layer model which lays the foundations for the

MIP model presented in Section III.

A. Overview

The network consists of a base station and multiple sensor nodes. All data generated at sensor nodes terminate at the base station (*i.e.*, convergecast traffic). Data reaches from sensor nodes to the base station either directly (single-hop) or through other sensor nodes acting as relays (multi-hop). Time is organized into equal timed rounds of duration 500 ms ($T_{rnd} = 500$ ms). At each round each sensor node generates s_i number of data packets. A two-way handshake mechanism (data packets are replied with ACK packets) is employed for data exchange between node pairs. 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. Data Link Layer Model

We utilize Mica2 motes' energy consumption characteristics equipped with CC1000 radios which are the most heavily utilized sensor nodes in experimental WSN research due to their well-characterized energy dissipation properties [8]. 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. Size of a data packet is denoted as M_P and two distinct packet sizes of 256 and 64 Bytes are considered throughout this work. The size of an ACK packet is $M_A = 20$ Bytes. The slot time (T_{slot}) is taken as 115 ms and 36 ms for $M_P = 256$ Bytes and $M_P = 64$ Bytes, respectively.

We adopt log-normal shadowing path loss model and utilize the parameters presented in [9]. In this model the path loss (Υ_{ij}) at a distance d_{ij} is

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

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.

The received signal power ($P_{rx,ij}^{ant}(l)$) due to a transmission at power level-l over the link-(i, j) is

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

Signal-to-noise ratio (SNR) is

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

where the noise power (P_n) is -115 dBm at the temperature of 300 Kelvin for Mica2 motes [9].

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) [8].

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 packet reception [9] of a φ-Byte packet transmitted at power level-l over the link-(i, j) is

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

and failure probability is

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

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

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

provided that $P_{rx,ij}^{ant}(l) \geq P_{sns}$ and $P_{rx,ji}^{ant}(k) \geq P_{sns}$. Otherwise (*i.e.*, $P_{rx,ij}^{ant}(l) < P_{sns}$ and $P_{rx,ji}^{ant}(k) < P_{sns}$), $p_{ij}^{HS,s}(l, k) = 0$ where P_{sns} denotes the reception sensitivity of the Mica2 motes (P_{sns} = -102 dBm) [8]. The probability of a failed handshake is given as

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

On the average, each data packet has to be transmitted

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

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

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

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 ($\xi = 19.2$ Kbps) [10]. Likewise, $T_{tx}(M_A)$ denotes the duration of an ACK packet. A node stays in receiving mode when it is not transmitting. Hence, the total energy dissipation of a transmitter in a slot (during a single handshake) is

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

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

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

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

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

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

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

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

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

III. MIP Framework

In this section, we present the MIP framework used to model six power control strategies for WSN lifetime maximization problem. 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 is represented as f_{ij}.

A. The Basic Model

The basic optimization problem for maximizing the network lifetime is presented in Figure 1. We will utilize the basic model to model the transmission power control strategies described in subsequent subsections. 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 $N_{rnd} \times T_{rnd}$. Equation (15) is used for flow balancing at each sensor node (*i.e.*, $\forall i \in W$) stating that data flowing into node-i plus data generated by node-i is equal to the data flowing out of node-i. Equation (16) ensures that all data generated at each source node eventually flows into the base station (node-1). Total busy time in a sensor node is obtained as in Equation (17). Equation (18) states that for all nodes except the base station total energy dissipation is bounded by the energy stored in batteries (ϱ). Energy dissipation terms on the left side of inequality in this equation accounts for transmission, sleep, reception, and data acquisition energies, respectively. Note that 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. Each sensor node is assigned equal initial energy ($\varrho = 25$ KJ) at the beginning of the network operation (energy provided by two AA batteries). The constraint for bandwidth is presented in Equation (19). In this equation it is guaranteed that the channel bandwidth required to perform communication operations at each node is strictly bounded by the available bandwidth (19.2 Kbps for Mica2 motes). 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 [11]. 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. Interference function ($I^i_{jn}(l,k)$) is formulated in Equation (20). 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. Equation (21) states that all flows are non-negative.

Maximize N_{rnd}
Subject to:

$$\sum_{(i,j)\in A} f_{ij} - \sum_{(j,i)\in A} f_{ji} = N_{rnd}s_i \ \forall i \in W \quad (15)$$

$$\sum_{(j,1)\in A} f_{j1} = N_{rnd}\sum_{j\in W} s_j \quad (16)$$

$$T_{bsy,i} = T_{slot}\left[\sum_{(i,j)\in A}\lambda_{ij}(l,k)f_{ij} + \sum_{(j,i)\in A}\lambda_{ji}(l,k)f_{ji}\right] + N_{rnd}T_{DA} \ \forall i \in W \quad (17)$$

$$\underbrace{\sum_{(i,j)\in A} E^D_{tx,ij}(l,k)f_{ij}}_{\textbf{transmission}} + \underbrace{P_{slp}(N_{rnd}T_{rnd} - T_{bsy,i})}_{\textbf{sleep}} + \underbrace{\sum_{(j,i)\in A} E^D_{rx,ji}(l,k)f_{ji}}_{\textbf{reception}} + \underbrace{N_{rnd}E_{DA}}_{\textbf{acquisiton}} \leq \varrho \ \forall i \in W \quad (18)$$

$$T_{slot}\left[\sum_{(i,j)\in A}\lambda_{ij}(l,k)f_{ij} + \sum_{(j,i)\in A}\lambda_{ij}(l,k)f_{ji} + \sum_{(j,n)\in A}\lambda_{jn}(l,k)f_{jn}I^i_{jn}(l,k)\right] \leq N_{rnd}T_{rnd}, \ \forall i \in V \quad (19)$$

$$I^i_{jn}(l,k) = \begin{cases} 1 \text{ if } P^{ant}_{rx,ji}(l) \geq P_{sns} \text{ or } P^{ant}_{rx,ni}(k) \geq P_{sns} \\ 0 \text{ o.w.} \end{cases} \quad (20)$$

$$f_{ij} \geq 0 \ \forall (i,j) \in A \quad (21)$$

Fig. 1: MIP framework for lifetime maximization.

The MIP model presented in Figure 1 assumes the transmission power levels for data and ACK packets are already determined externally by the transmission power assignment strategies. Hence, the basic model is an idealized abstraction for a routing layer that optimizes the flows to maximize the network lifetime given the data and ACK transmission power levels on each link. By employing such an abstraction we eliminate the effects of a specific routing layer that can interfere our investigation of the impact power level assignment strategies on WSN lifetime.

B. Local Power Level Decisions (LPLD) Strategy

In LPLD strategy, data and ACK transmission power levels are determined for each link considering the total 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 optimization scheme

$$\{l_{ij}^{opt}, k_{ji}^{opt}\} = \underset{l \in S_L k \in S_L}{\text{argmin}} \left(E_{tx,ij}^{D}(l,k) + E_{rx,ji}^{D}(l,k) \right). \quad (22)$$

Note that to perform the above optimization scheme, handshake success rates should be measured for all the transmit and receive power levels. However, for the remaining strategies that will be introduced in the rest of this section no such measurements are required, hence, their implementation complexity is lower.

C. Random Local Power Level Decisions (RLPLD) Strategy

In RLPLD strategy, data and ACK transmission power levels are randomly selected for each link as long as the receiving antenna can sense the transmitted packets (*i.e.*, $P_{rx,ji}^{ant}(l_{sns}) \geq P_{sns}$ and $P_{rx,ij}^{ant}(k_{sns}) \geq P_{sns}$). The lowest transmission power levels that satisfy the sensitivity criterion for a particular link are denoted as $l_{ij,sns}$ and $k_{ji,sns}$. We determine a single random power level for data packet transmission (l_{ij}^{rand}) and another single random power level for ACK packet transmission (k_{ji}^{rand}) for each link-(i,j) which can be expressed as

$$\{l_{ij}^{rand}, k_{ji}^{rand}\} = \{U(l_{ij,sns}, l_{max}), U(k_{ji,sns}, k_{max})\}, \quad (23)$$

where $U(a,b)$ denotes a discrete uniform random variable in the interval $[a,b]$ and l_{max} (or k_{max}) refers to the maximum power level.

D. Random Local Power Level Decisions with Equal Power Level Assignment (RLPLD-EPL) Strategy

Although in RLPLD strategy, power level assignment for data and ACK packets are uniformly distributed, it is possible to assign equal random power levels for both data and ACK packets on each link. For this purpose, we define a single random power level (m_{ij}^{rand}) for both data packet and ACK transmission over the link-(i,j) which is obtained as

$$\{m_{ij}^{rand}\} = \{U(m_{ij,sns}, l_{max})\}, \quad (24)$$

where $m_{ij,sns} = max(l_{ij,sns}, k_{ji,sns})$.

E. Random Local Power Level Decisions with Maximum Data Power Level Assignment (RLPLD-MDPL) Strategy

In RLPLD-MDPL strategy a single random power level is used for ACK transmission (n_{ji}^{opt}) at each link and all data packets are sent at the maximum power level. ACK transmission power level is obtained as follows

$$\{n_{ji}^{rand}\} = \{U(k_{ji,sns}, l_{max})\}. \quad (25)$$

F. Random Local Power Level Decisions with Maximum ACK Power Level Assignment (RLPLD-MAPL) Strategy

In RLPLD-MAPL strategy a single random power level is used for data transmission (r_{ji}^{opt}) at each link and ACK data packets are sent by using the maximum power level. Data packet transmission power level is given by

$$\{r_{ij}^{rand}\} = \{U(l_{ij,sns}, l_{max})\}. \quad (26)$$

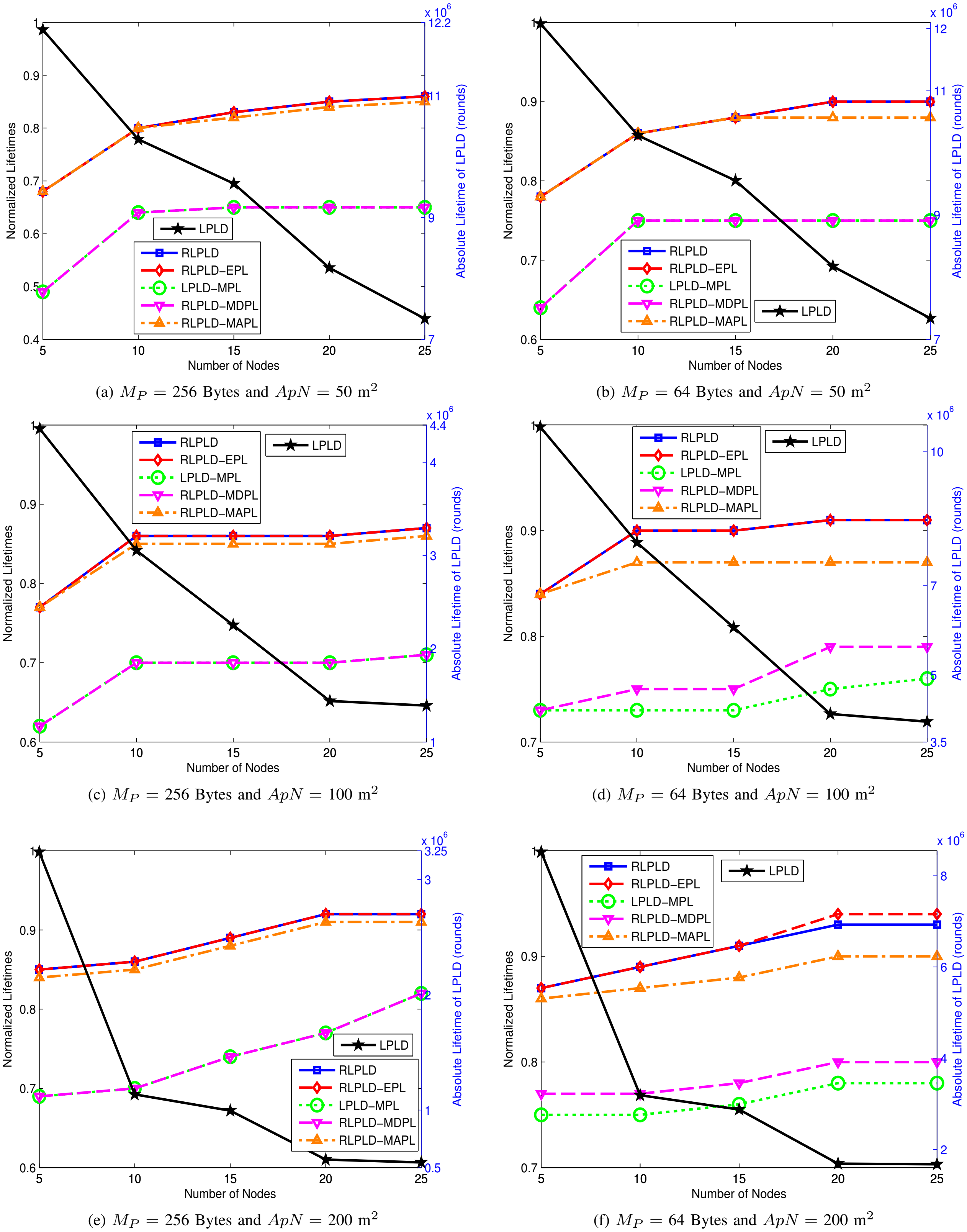
G. Local Power Level Decisions with Maximum Power Level Assignment (LPLD-MPL) Strategy

In LPLD-MPL strategy, both data and ACK packets for all links are sent by using the highest transmission power available. This strategy provides the minimum handshake failure probability among all strategies. However, such a strategy will also increase the transmission energy dissipation for both data and ACK packets. Furthermore, all the existing studies on random power assignment in WSNs used fixed power assignment as a benchmark, hence, we use LPLD-MPL strategy as one of our benchmarks in this study.

IV. Analysis

In this section, we present the results of numerical analysis to investigate the performances of proposed schemes. We use a disk shaped network where nodes are uniformly deployed within the disk and the base station is at the center of the disk. MATLAB is used to construct the data link layer (Section II-B) and General Algebraic Modeling System (GAMS) with XPRESS solver for the optimization problems (Section III). The results presented in Figure 2 are the averages of 100 random runs (*i.e.*, at each run path loss values of all links are regenerated). Two data packet lengths (*i.e.*, $M_P = 64$ Bytes and $M_P = 256$ Bytes) with three Area per Node (ApN) levels which is obtained by dividing the network area to the number of nodes in the network.

We present network lifetime for the six strategies as functions of Number of Nodes (N_N) in the network when $M_P = 256$ Bytes for $ApN = 50$ m^2, $ApN = 100$ m^2, and $ApN = 200$ m^2 in Figure 2a, Figure 2c, and Figure 2e, respectively. To investigate the effects of data packet length we also perform numerical analysis by using $M_P = 64$ Bytes which is presented in Figures 2b, 2d, 2f. The absolute lifetime for LPLD strategy in terms of rounds is presented on the right y-axis. For other strategies only the normalized lifetime values are shown on the left y-axis since we are interested in the relative performances. Normalization is achieved by dividing the absolute lifetime value of a strategy for a given point in



(a) $M_P = 256$ Bytes and $ApN = 50$ m^2

(b) $M_P = 64$ Bytes and $ApN = 50$ m^2

(c) $M_P = 256$ Bytes and $ApN = 100$ m^2

(d) $M_P = 64$ Bytes and $ApN = 100$ m^2

(e) $M_P = 256$ Bytes and $ApN = 200$ m^2

(f) $M_P = 64$ Bytes and $ApN = 200$ m^2

Fig. 2: Network lifetimes for all strategies as a function of N_N in the network for various M_P and ApN values.

the parameter space to the absolute lifetime value of the LPLD strategy at that point.

Increasing N_N decreases the absolute network lifetime for all strategies because the average distance of the nodes to the base station increases as N_N increases. In a similar manner, increasing ApN results in longer distances and larger path loss values hence average distance to be traversed to reach the base station increases which results in higher energy cost for packet flows consequently decreasing the absolute network lifetime.

As a general trend, normalized lifetime values for all strategies for all strategies (except for LPLD strategy) increases with increasing number of nodes in the network because the routing options for energy balancing proliferates with increasing number of the potential relay nodes which counter balances the minimized energy dissipation advantage of LPLD strategy against the other strategies. For example, normalized network lifetime values for RLPLD with $ApN = 200$ m^2 and $M_P = 256$ Bytes are 0.87, 0.91, and 0.93 for $N_N = 5$, $N_N = 15$, and $N_N = 25$, respectively (Figure 2e).

The highest normalized lifetimes are obtained with RLPLD and RLPLD-EPL within the whole parameter space. Normalized lifetime values for RLPLD lies in 0.78-0.93 band. Furthermore, both RLPLD and RLPLD-EPL lifetimes are within 10 % neighborhood of LPLD lifetime provided that $N_N \geq 20$. The difference between RLPLD and RLPLD-EPL lifetimes are insignificant (*i.e.*, normalized lifetime differences of RLPLD and RLPLD-EPL are at most 0.01). For example, RLPLD and RLPLD-EPL lifetimes are 0.93 and 0.94, respectively, for $ApN = 200$ m^2, $M_P = 64$ Bytes, and $N_N = 20$ (Figure 2f).

RLPLD-MAPL strategy is the best strategy after RLPLD and RLPLD-EPL in terms of lifetime it achieves throughout the parameter space explored. Normalized lifetime difference between RLPLD-MAPL and RLPLD is at most 0.04. On the other hand, RLPLD-MDPL strategy results in significant lifetime losses. Normalized lifetime difference between RLPLD and RLPLD-MDPL strategies lies within 0.10–0.16 band. LPLD-MPL strategy is the worst performing strategy within the explored parameter space. However, normalized lifetime difference between LPLD-MPL and RLPLD-MDPL strategies is at most 0.04 (for majority of the data points the difference is less than 0.02).

V. Conclusion

We investigate the impact of random power assignment strategies for link level handshaking in WSNs. Mica2 motes' energy dissipation characteristics and log-normal shadowing path loss is adopted to built the link layer abstraction which in turn forms the infrastructure for the developed MIP model. Network lifetime values for six transmission power assignment strategies (four of these strategies are variations of the random power assignment) are obtained through numerical evaluations of the MIP models spanning a large parameter space.

The results of this study show that random power assignment cannot achieve the lifetime values obtained by the optimized power assignment strategy (LPLD), however, the difference between two random power level assignment strategies (RLPLD and RLPLD-EPL) and the optimal strategy can be as low as 7 %. Yet, the overhead required for the measurements enabling the optimal strategy is not needed for the random assignment strategies.

Fixed power assignment strategy (LPLD-MPL) gives the worst performance results (*e.g.*, in most cases LPLD-MPL lifetime is 15 % less than RLPLD lifetime). In fact, minimizing the handshake failure by utilizing the highest power level available does not result in maximized lifetime. On the contrary, the redundant energy dissipation brought by the LPLD-MPL strategy outweighs the benefit of minimizing the handshake failure probability.

Nevertheless, the main conclusions of this study are (i) well designed random power assignment strategies reduces the complexity of power assignment when compared to the optimal strategy, however, the price paid for this gain is a modest decrease in network lifetime and (ii) maximum power level strategy results in, roughly, doubling the loss of lifetime when compared to the best performing random strategies without bringing any advantages.

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References

[1] S. Gandham, M. Dawande, R. Prakash, and S. Venkatesan, "Energy efficient schemes for wireless sensor networks with multiple mobile base stations," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM)*, vol. 1, 2003, pp. 377–381 Vol.1.

[2] Z. Cheng, M. Perillo, and W. Heinzelman, "General network lifetime and cost models for evaluating sensor network deployment strategies," *IEEE Transaction on Mobile Computing*, vol. 7, pp. 484–497, 2008.

[3] M. Rahimi, R. Baer, O. Iroezi, J. Garcia, J. Warrior, D. Estrin, and M. Srivastava, "Cyclops: in situ image sensing and interpretation in wireless sensor networks," in *Proceedings of the ACM Conference on Embedded Networked Sensor Systems (SenSys)*, 2005, pp. 192–204.

[4] Y. Zhu, Y. Xu, S. Guan, and J. He, "Connectivity analysis of random power control in wireless sensor networks," in *Proceedings of the IEEE International Conference on Communication Technology (ICCT)*, 2010, pp. 1248–1251.

[5] T.-S. Kim and S.-L. Kim, "Random power control in wireless ad hoc networks," *IEEE Communications Letters*, vol. 9, no. 12, pp. 1046–1048, 2005.

[6] M. Elmusrati, N. Tarhuni, and R. Jantti, "Framework for random power allocation of wireless sensor networks in fading channels," *Wireless Sensor Network*, vol. 4, no. 3, 2012.

[7] A. Gogu, D. Nace, A. Dilo, and N. Meratnia, "Review of optimization problems in wireless sensor networks," in *Telecommunications Networks - Current Status and Future Trends*, J. Hamilton Ortiz, Ed. InTech, 2012, pp. 153–180.

[8] J. Vales-Alonso, E. Egea-Lopez, A. Martinez-Sala, P. Pavon-Marino, M. V. Bueno-Delgado, and J. Garcia-Haro, "Performance evaluation of MAC transmission power control in wireless sensor networks," *Computer Networks*, vol. 51, pp. 1483–1498, 2007.

[9] M. Zuniga and B. Krishnamachari, "Analyzing the transitional region in low power wireless links," in *Proceedings of the IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, 2004, pp. 517–526.

[10] K. Bilinska, M. Filo, and R. Krystowski. (2007) Mica, Mica2, MicaZ. [Online]. Available: http://wwwpub.zih.tu-dresden.de/ dargie/wsn/slides/students/MICA.ppt

[11] H. Cotuk, B. Tavli, K. Bicakci, and M. B. Akgun, "The impact of bandwidth constraints on the energy consumption of wireless sensor networks," in *Proceedings of the IEEE Wireless Communication and Networking Conference (WCNC)*, 2014.