On the Optimality of Route Selection in Grid Wireless Sensor Networks: Theory and Applications

Yaser Khamayseh [1*], Wail Mardini[1], Monther Aldwairi[1,2], and Hussein Mouftah[3]
[1]*Jordan university of Science and Technology, 22110 Irbid, Jordan*
{yaser, wmardini}@just.edu.jo
[2]*College of Technological Innovation, Zayed University, Abu Dhabi, UAE*
monther.aldwairi@zu.ac.ae
[3]*School of Electrical Engineering and Computer Science, University of Ottawa*
Ottawa, Ontario, Canada
mouftah@uottawa.ca

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Abstract

Wireless Sensor Networks (WSNs) provides the necessary infrastructure for the successful realization of emerging technological advancements such as smart places. Information, in WSN, is collected from the target locations using sensors, sensors can act as relay nodes for the successful delivery of the collected data to the base station. Energy is scarce in sensors, and usually, it cannot be renewed. To prolong the network overall lifetime, it is essential to prolong each sensors' lifetime. Therefore, nodes placements and route selection are vital elements for WSNs, as it can significantly affect both the network performance and lifetime. Nodes in WSNs can be deployed in several ways: randomly or in an fixed manner. In this paper, we are concerned about the fixed deployment of sensors in a grid topology. In such topology, many possible routes exist between a source and a destination nodes. To reduce power consumption, it is important to find the optimal route. This paper sheds the light on the optimality of the route selection in 2x2 grid topology and presents some findings regarding this issue. The obtained optimal routes consider the power consumption factor. Some theoretical bounds were derived on the optimal number of relay nodes in a 2x2 grid. Finally, a preliminary heuristic approach is proposed, namely; Energy-Aware Routing (EAR), based on the findings obtained in this paper. The performance of the proposed heuristic is evaluated using simulation. Preliminary results show that the proposed scheme was able to prolong the network lifetime.

Keywords: Optimal Route, Power Consumption, Wireless Sensor Networks, Relay Nodes, Routing, Grid Topology

1 Introduction

The enormous growth in emerging and affordable wireless technologies paved the way for Sensor Networks (SN) toward the wireless domain. Moreover, the new and innovative applications of smart places and the Internet of Things (IoT) require self-organized, self-controlled and self-managed Wireless Sensor Networks (WSNs). WSN must function with optimal designs and protocols to achieve shortest path, lowest power consumption, and extended lifetime [1]. WSNs presents a more economical connectivity solution to the physical world in comparison with the wired domain. The reachability and accuracy of

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*Corresponding author: Department of Computer Sciences, Jordan university of Science and Technology, 22110 Irbid, Jordan, Tel: +962-720-2222

the data gathered by such networks (i.e., WSNs) make them preferred by both researchers and industry sectors.

Wireless Sensor Networks (WSNs) are projected to play an essential role in providing the communication infrastructure required for the deployment of many promising technological advancements such as the Internet of Things (IoT) and Smart places. The two key operations provided by WSNs are: gathering data and transmitting these data to a central unit for further processing. Hence, two concepts are essential to the successful deployment of WSNs: coverage and lifetime [1]. WSNs are required to cover the entire target area and are expected to last for an extended period of time. WSN consists of many (in some cases, tens of thousands) of sensors deployed in the target area to gather specific data from the physical environment and forward these data to the central unit for further processing [2].

In general, sensors are equipped with hard-to-replace batteries (i.e., a fixed source of power) to operate. Thus, each sensor can live for a specific amount of time, depending on the amount of work performed by the sensors. As explained earlier, sensors perform two primary operations: gathering and transmissions. The gathering operation involves sensing and basic processing operations depending on the sensor and the target physical environment. This operation usually does not require extensive usage of battery energy. On the other hand, the transmission operation, require the sensor to use its antenna to communicate with other nodes/units in the network. The amount of consumed energy depends on both the amount of transmitted data and the distance between the sensor and the receiving end. Most of the energy (about 80%) consumed by sensors is spent on transmission operations [3] [4].

Deploying sensors in the target area is a fundamental issue for WSNs, it must ensure the coverage and the survivability of the network [5]. Either can achieve sensors deployment by randomly dropping the sensors in the target area (random placement), or by fixing the exact location of each sensor in the target area (fixed placement). The random placement strategy is suitable for harsh and inaccessible environments such as forests and volcanoes. While the fixed placement strategy is ideal for urban and accessible environments such as campus, buildings, and roads. This work focuses on a particular case of the fixed placement strategy, which is the grid placement. In grid placement, sensors are placed in a grid topology with fixed distances between the neighboring sensors on the same row and fixed distances between the neighboring sensors on the same column.

The grid topology placement ensures the full coverage of the target area, taking into consideration the conditions mentioned above for fixed deployment. However, the reachability and the survivability of the network is still under question. Theoretically, any node (sensor) can reach (communicate with) any other sensor in the network by tuning its transmission power to an acceptable level (i.e., increase its transmission power to reach further nodes, and reduce it to reach nearby nodes). In one hand, increasing the power level will result in the following:

1. Increased energy consumption, we note that the amount of available power for sensors is scarce and usually not renewable.
2. Increased interference for other transmissions in the network. One's transmission is perceived as noise by the other sensors.
3. Reaching the target node directly. Transmitting the data to the destination in a single hop.

On the other hand, decreasing the power level will result in the following:

1. Decreased power consumption
2. Decreased interference
3. Reaching the target destination using multi-hop transmission instead of a single hope transmission.

As multi-hop transmissions may play a significant role in prolonging the network lifetime, it also poses many challenges to the network. In multi-hop scenarios, network nodes are required to work and cooperate to facilitate network routing operations. This coordination may deem as resource consumer as many control messages are needed to be exchanged to establish and maintain this cooperation. Hence, the tradeoff between a single hop and multi-hop mechanism is a crucial issue for WSN. Even more, in multi-hop scenarios, the optimal number of hops is with matching importance as well. The main goal of this paper is to investigate the issue of single-hop versus multi-hop routing in grid topology for WSN. Identify the optimal option and the optimal number of hops.

The rest of the paper is organized as follows: Section 2 presents some of the related works done in this area. Section 3 introduces the used network model. The derived theoretical bounds and their proof of the optimal relay placement are presented in Section 4. The proposed heuristic routing algorithm is devised in Section 5. Section 6 presents the simulation and the obtained results. Finally, the paper is concluded in Section 7.

2 literature Review

A wireless sensor network is a collection of sensors with limited resources that work together to monitor a certain physical phenomenon. In [6], the authors studied the challenge of non-line-of-sight wireless communication within the WSN system in urban areas. A proof of concept system was implemented and test that contains gas sensors and a monitoring system in further point.

Another application for monitoring the railway infrastructure was studied and surveyed in [7]. As the human inspection requirements could be significantly reduced when automated systems monitoring are used, and therefore, this will reduce maintenance requirements by detecting faults before they escalate, and thus improves safety and reliability. The authors provided a detailed study of different types and configurations for sensors used in such systems.

Power consumption can be considered at different communication levels. The work in [3] outlines power consumption as the main factor when dealing with WSNs by examining the network level activities. In the network level, you can find many factors that affect the power consumed by the sensors; such as re-transmission attempts and channel listening. The authors proposed a stochastic model that aims to capture the expected energy consumption of sensors based on utilizing renewal theory, random stopping criteria, and Wald's inequality. It works by computing the expected cycle lifetime of sensors and thus the network lifetime. The model moreover gives the minimum and the maximum bounds in such energy consumed per node operation cycle.

The work in [4] is concerned with power conservation in WSN at the data processing layer, through the design and implementation of intelligent algorithms/application towards power consumption. Single relay communication in cooperative communication systems is studied, and a novel selective single-relay cooperative communication is proposed. Different potential relays are computed based on the MAC-layer RTS-CTS signaling and the required transmission power. The selection process for the best choice between these different options is performed in a distributed fashion. Moreover, minimize the energy consumption per data packet and maximize the network lifetime are the main objectives used in the proposed model, and the results presented confirm these objectives.

A relay selection scheme in a one-dimensional network was considered in [8]. The main concern is reducing energy consumption in the routing process. The authors looked at ways to reduce the number of nodes involved in the routing process, hence, prolong the network lifetime. They stressed the importance of selecting the minimal number of relay nodes to achieve the above-mentioned objectives. The work in [8] proposed two algorithms: Energy Saving via Opportunistic Routing (ENS-OR) and Geographic Random Forwarding (GeRaF) algorithms. These two algorithms were enhanced by the implementation of a sleep mode function. Results indicate numerous benefits can be achieved through the usage of the sleep mode.

Moreover, the authors in [9], also proposed a relay selection algorithm for one-dimensional networks. The authors employ an opportunistic routing principle for selecting the best relay nodes to the destination node. They proposed An Energy Saving via the Opportunistic Routing (ENS-OR) algorithm. The main objectives for ENS-OR are minimizing power consumption and protecting nodes with minimum residual energy. For each sensor node, ENS-OR uses both its distance to the sink as well as its residual energy to find the optimal route in terms of energy efficiency. Obtained simulations and empirical results show that ENS-OR significantly outperformed other well-known WSN routing schemes in terms of energy saving and wireless connectivity.

Opportunistic routing and relay selection for Energy Harvesting WSNs (EH-WSN) networks are addressed in [10]. Traditional schemes use distance-based calculation for relay nodes calculations. However, the work in [10] considers an opportunistic scheme in which each node considers its location in a 2x2 grid and selects (based on index differential calculations) the best relay node. The main goal is to minimize the number of calculations performed by each node; this approach requires subtraction operation rather than the multiplication operations. Collisions in the same relaying slot are handled using a probabilistic scheme. Simulation results show the superiority of the proposed scheme in reducing the computational complexity in comparison with other traditional schemes. Moreover, the results show that the proposed scheme achieved comparable throughput results.

A novel optimal deployment approach that is energy efficient was proposed in [11]. The authors employed the Artificial Bee Colony algorithm to optimize the network parameters. They try to fill the holes (uncovered areas) caused by the random deployment of sensors because the resulting inter-node free areas could be one of the main factors that affect the performance of the network. The main concern of the approach is to keep the cost and connectivity satisfied while improving network lifetime. The authors compared their approach with another technique named Shortest Path 3-D grid Deployment (SP3D). An Particle Swarm Optimization based scheme is proposed in [12] to solve the relay nodes placement problem for randomly deployed nodes.

The placement issue in WSNs was investigated in terms of many directions. For example, the work in [13] investigated the relationship between nodes placement and nodes' failures. The authors first conducted extensive analysis of placement strategies in the real world. Then, they proposed an effective deployment strategy taking into account nodes' failures using the Set-Covering Algorithm (SCA) and its variant k-SCA. While the work in [14] considered the operational cost of nodes deployment for all types of nodes: sensors, relay nodes, and base stations. The cost issue is also considered in [15].

In [16], the authors study the energy sustainability in WSNs, in particular, the optimal placement of sensors in the objective of assuring the delivery of sensors data to the sink with minimal energy consumption keeping in mind the overall network lifetime. They try to minimize the number of relays to be placed in the network while maintaining the other factors such as connectivity and sustainability. They used a Mixed Integer Linear Program (MILP) approach to solve what they called sustainable minimum-relay maximum-connectivity deployment (SMRMC) problem. The idea of the solution is to form convex-polytopes from the existing relay nodes. They showed through simulation that their approach could prolong the network lifetime by 100%.

The authors in [10] proposed a lightweight grid-based approach for relay selection called EH-WSNs. They tried to reduce the computational and memory complexity using the grid index calculation by grid-based coordination and Manhattan distance. The main idea is to simplify the calculations from multiplications into small-values subtraction. They also proposed a scheme that is based on probability to reduce collisions in the intermediate relay nodes. They evaluated their approach using Contiki OS with Cooja simulator. They measured the computational complexity and the standard performance measures such as delay and throughput. Their approach received better results except for throughput in small networks at which the compared approach; Adaptive Opportunistic Routing (AOR), gets better results.

A modified routing protocol (namely, Multi-Hop Dynamic Path-Selection Algorithm—MHDP) along with multi-hop node selection component is proposed in [17]. The main goal of this scheme is to improve both the communication delay as well as the overhead by considering the residual energy available at each node.

The nodes deployment issue in fixed placement network is investigated in [18]. In which the nodes are deployed in linear formation to monitor oil pipeline. The work only considers the placement issue for equally spaced nodes.

3 Network Model

In this work, we consider the fixed placement strategy for sensors in an *NxN* grid topology. The nodes span over the distance of d_{row} meters, both horizontally and vertically. Each sensor is spaced equally from all of its neighbors. The investigated topology is depicted in Figure 1. The total number of nodes is N^2.

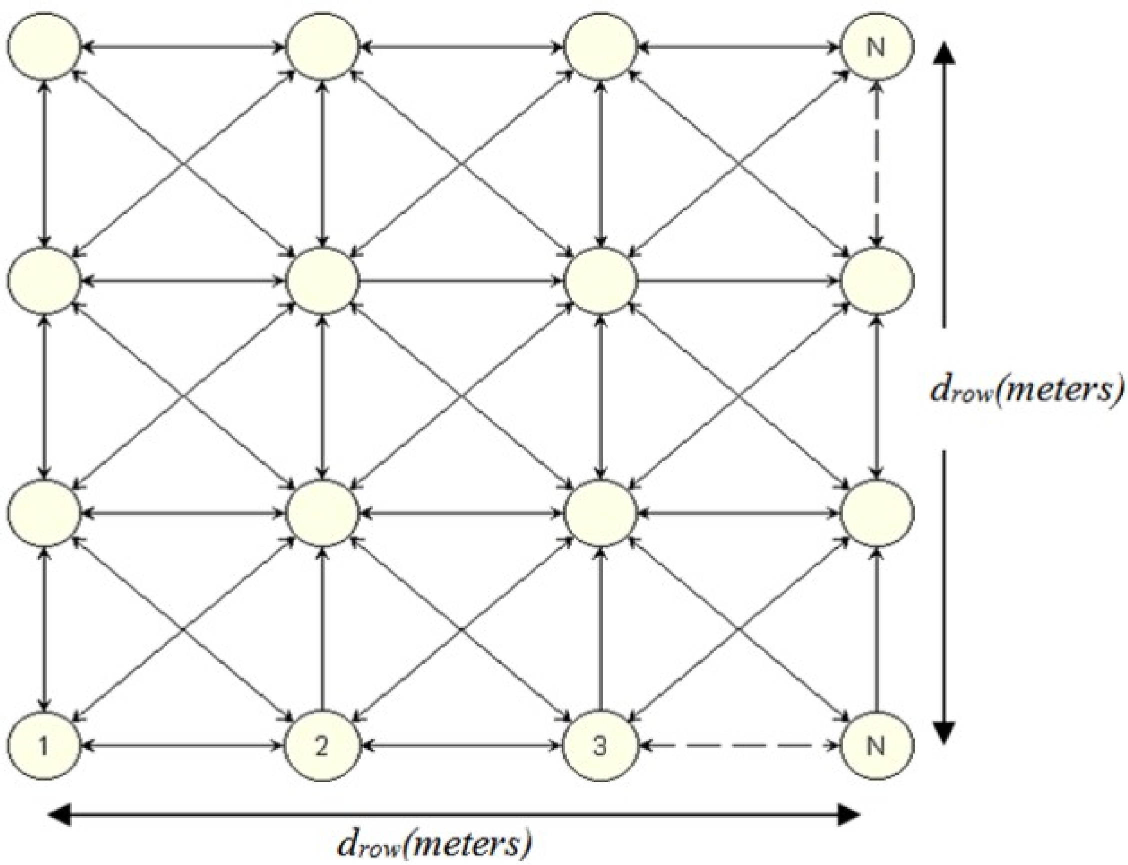

Figure 1: An NxN Grid topology

The horizontal distance between the farthest two nodes is denoted as d_{row}, and the diagonal distance between the farthest two nodes is denoted as D. Hence, $D = (\sqrt{2}d_{row})$. The horizontal distance between two adjacent nodes is $(\frac{d_{row}}{(N-1)})$ and between two diagonal nodes is $\frac{D}{N-1}$. In order to reduce the power consumption, assuming there is a known path between the sender and the receiver (the path selection issue will be discussed in Section 4), the nodes can communicate using intermediate nodes (relays) rather than directly. Each intermediate node will receive the data and re-transmit it to the next node along the transmission path. Each intermediate node (relay) consumes energy during this process to perform three basic operations: receiving the data signals, amplifying the data signals and (re)-transmitting the data signals. Power consumption is expressed mathematically using Equations 1 and 2 as follows [19] [20]:

$$E_{TX}(K,d) = (E_{TX-elec} \times K) + (\varepsilon_{amp} \times K \times d^2) \tag{1}$$

$$E_{RX}(K) = E_{(RX-elec)} \tag{2}$$

Where:
$E_{TX}(k,d)$ is the power consumed to send K bits for distance d
$E_{RX}(k)$ is the power consumed to receive K bits
$E_{RX-elec}$ is the power consumed by the receiver circuit to process 1 bit
$E_{TX-elec}$ is the power consumed by the transmitter circuit to process 1 bit
ε_{amp} is the power consumed by the amplifier
K is the data size in bits
d is the distance between the source and destination nodes

For 1 bit and assuming $E_{RX-elec} = E_{TX-elec} = E_{elec}$, the power consumption in the transmission and reception for distance d is E_d. Such that:

$$E_d = 2E_{elec} + \varepsilon_{amp} d^2 \tag{3}$$

Intuitively, using more relays to reduce power consumption is anticipated to have a significant impact in reducing the overall power consumption as the sum of the square distance of all segments is less than the square total distance (i.e., when, $d = d_1 + d_2 + ... + d_h$, then $d_2 >> d_{12} + d_{22} + \ldots + dh_2$). However, we note that for each extra relay, there is an additional energy needed to receive, process and re-transmit the data by this relay [19]. Hence, we need to strike a balance between these two factors to achieve the optimal power consumption. We acknowledge the importance of this trade-off to design an energy efficient wireless sensor networks.

4 Analysis of Optimal Relays Placement

Choosing the best path with the least energy consumption is a critical design function in WSNs. This section develops a list of theorems about relay nodes and their best placement locations. Basically, it tries to answers the following questions: which node(s) is best to use as a relay node(s) to reach the destination node? The developed theorems examine all possible scenarios for relay nodes placements and define the optimal placements. It shows that no single choice is always the best choice. The best placement depends heavily on the distance between the nodes. The following theorems derive the optimal relay(s) placements based on the distance. All presented theorems in this paper assume that the source node and the destination nodes are the farthest two nodes in the grid (on the opposite diagonal), as illustrated in Figure 2.

Theorem 4.1. *In NxN Grid with N^2 Nodes, transmitting data along the main (or the secondary diagonal) between the farthest two nodes using one relay placed precisely in the middle of the diagonal path between the 2 nodes (called relay-diagonal-middle), consumes less energy than using a relay node that is shifted from the middle node along of the diagonal (called relay-diagonal-shifted).*

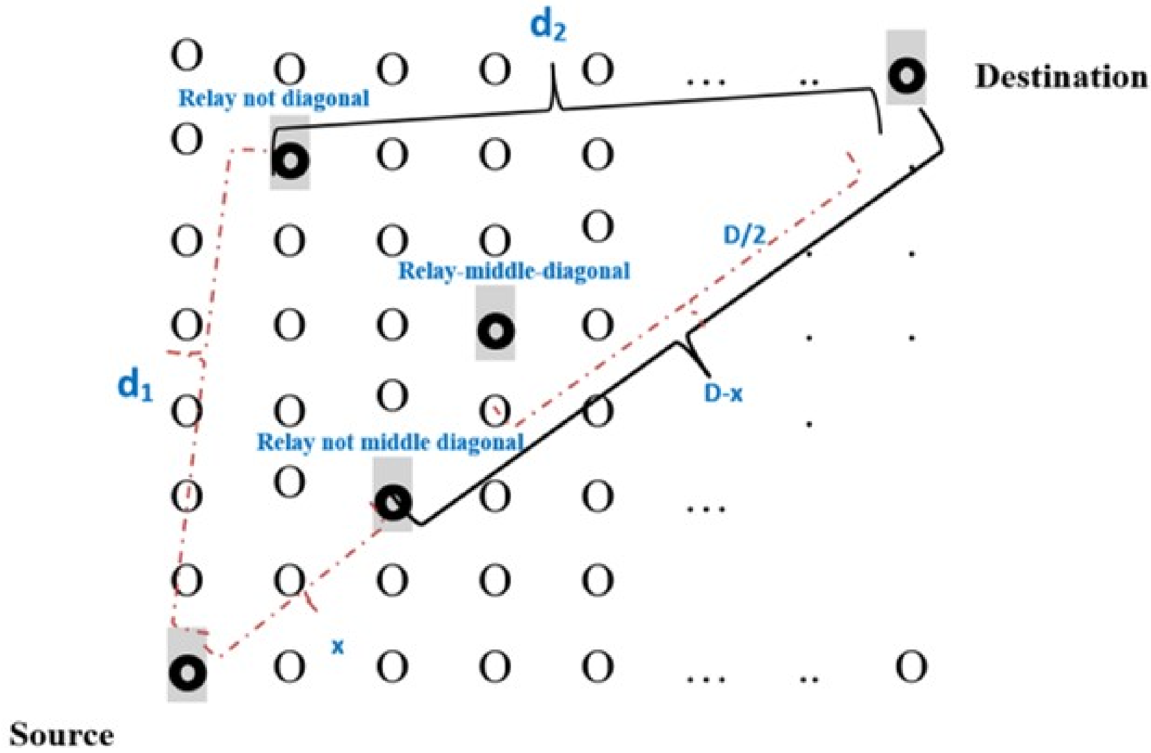

Figure 2: Illustration of One Relay Placement

Proof. For the relay-diagonal middle case, the distance from the relay node to the source node and destination node is the same and equal $\frac{D}{2}$. Therefore,

$$E_{N\times N-one\ relay\ diagonal-middle} = 2\left(\varepsilon_{amp}\times\left(\frac{D}{2}\right)^2 + 2E_{elec}\right)$$

$$E_{N\times N-one\ relay\ diagonal-middle} = \varepsilon_{amp}\times\frac{D^2}{2} + 4E_{elec} \tag{4}$$

For the shifted node and without loss of generality, assume that the relay in the diagonal is x hops away from the source node; thus the distance to the destination node is D-x (see Figure 2).
Hence,

$$E_{N\times N-one\ relay\ diagonal-shifted} = \varepsilon_{amp}\times x^2 + 2E_{elec} + \varepsilon_{amp}\times(D-x)^2 + 2E_{elec}$$

$$E_{N\times N-one\ relay\ diagonal-shifted} = \varepsilon_{amp}\times x^2 + 4E_{elec} + \varepsilon_{amp}\times\left(D^2 - 2Dx + x^2\right) \tag{5}$$

Thus,

$$E_{N\times N-one\ relay\ diagonal-shifted} = E_{N\times N-one\ relay\ diagonal-middle} + \varepsilon_{amp}\times\left(\frac{D}{2}^2 - 2Dx + 2x^2\right) \tag{6}$$

Since $\frac{D}{2}^2 - 2Dx + 2x^2 = 0$ when $x = \frac{D}{2}$ and positive otherwise, then $E_{N\times N-one\ relay\ diagonal-middle}$ is always better than $E_{N\times N-one\ relay\ diagonal-biased}$.

□

Theorem 4.2. *In NxN Grid with N^2 Nodes, transmitting data along the main (or the secondary diagonal) between the farthest two nodes using one relay in the middle is always better than using one relay, not on the diagonal.*

Proof. For the relay-diagonal middle case and from (4):

$$E_{N\times N-one\ relay\ diagonal-middle} = \varepsilon_{amp} \times \frac{D^2}{2} + 4E_{elec} \tag{7}$$

In the second case, and without loss of generality, assume that the relay is y hops away horizontally from the diagonal and z hops away vertically from the diagonal. Assume that the direct distance from the relay to the transmitting node and receiving node is d_1 and d_2 (see Figure 2). Therefore,

$$E_{N\times N-one\ relay\ not\ diagonal} = \varepsilon_{amp} \times {d_1}^2 + 2E_{elec} + \ \varepsilon_{amp} \times {d_2}^2 + 2E_{elec} \tag{8}$$

$$E_{N\times N-one\ relay\ not\ diagonal} = \ \varepsilon_{amp} \times \left({d_1}^2 + \ {d_2}^2\right) + 4E_{elec} \qquad (10)$$

Since $\frac{D}{2}^2 < {d_1}^2 + {d_2}^2$, then $E_{N\times N-one\ relay\ diagonal-middle}$ is always better than $E_{N\times N-one\ relay\ not\ diagonal}$.
□

Theorem 4.3. *In NxN Grid with N^2 Nodes, transmitting data along the main (or the secondary diagonal) between the farthest two nodes using one relay in the middle is better than direct transmission for distances greater than $\sqrt{4\frac{E_{elec}}{\varepsilon_{amp}}}$ meter.*

Proof. When the relay is in the middle, the distance from it to the transmission and receiving node is $\frac{D}{2}$. Therefore from (4):

$$E_{N\times N-one\ relay\ diagonal-middle} = \varepsilon_{amp} \times \frac{D^2}{2} + 4E_{elec} \tag{9}$$

For the direct transmission case:

$$E_{N\times N-direct} = \varepsilon_{amp} \times D^2 + 2E_{elec}$$

The intersection point is

$$\varepsilon_{amp} \times D^2 + 2E_{elec} = \varepsilon_{amp} \times \frac{D^2}{2} + 4E_{elec}$$

$$\varepsilon_{amp} \times \frac{D^2}{2} = 2E_{elec}$$

$$D = \sqrt{4\frac{E_{elec}}{\varepsilon_{amp}}}$$

For example, when $\varepsilon_{amp} = 100pJ/bit/m^2$, $E_{RX-elec} = 50nJ/bit$, and $ETX - elec = 50nJ/bit$, then

$$D = \sqrt{2000} \approx 44.72$$

□

Theorem 4.4. *In NxN Grid with N^2 Nodes, transmitting data along the main (or the secondary diagonal) between the farthest two nodes using two relays equally spaced is better than any other allocation using two relays that are not evenly spaced along the diagonal.*

Proof. For the two relays equally spaced case:

$$E_{N\times N-two\ relays\ diagonal-equally} = 3\left(\cdot 1 \times \left(\frac{D}{3}\right)^2 + 100\right) \tag{10}$$

Using two relays shifted by a and b distanced from the evenly spaced points. The first relay point is $\frac{D}{3+a}$ from the transmitting node. The second relay node is $\frac{D}{3+(b-a)}$ from the first relay. Ultimately, the distance from the second relay to the destination is $\frac{D-2D}{3-b}$.

$$E_{N\times N-two\ relays\ diagonal-shifted} = \left(\cdot 1 \times \left(\frac{D}{3}+a\right)^2 + 100\right) + \left(\cdot 1 \times \left(\frac{D}{3}+b-a\right)^2 + 100\right) + \left(\cdot 1 \times \left(D-\frac{2D}{3}-b\right)^2 + 100\right) \tag{11}$$

It is clear that these results are larger than the two relays equal size (note that this result includes more positive terms than the equal case).

□

Theorem 4.5. *In NxN Grid with N^2 Nodes, transmitting data along the main (or the secondary diagonal) between the farthest two nodes using k-relays equally spaced is better than using (k+1)-relays equally spaced for D $< 10\sqrt{k(k+1)}$*

Proof. Using k-relays equally spaced

$$E_{N\times N-k-relays\ diagonal-equally} = k\left(\cdot 1 \times \left(\frac{D}{k}\right)^2 + 100\right) = \quad \cdot 1 \times \frac{D^2}{k} + 100k \tag{12}$$

Using k+1-relays equally spaced

$$E_{N\times N-k+1-relays\ diagonal-equally} = (k+1)\left(\cdot 1 \times \left(\frac{D}{k+1}\right)^2 + 100\right) = \quad \cdot 1 \times \frac{D^2}{k+1} + 100\,(k+1) \tag{13}$$

To find the equality distance point between k and k+ 1 cases:

$$\cdot 1 \times \frac{D^2}{k+1} + 100\,(k+1) \ = \cdot 1 \times \frac{D^2}{k} + 100k$$

$$100 \ = \frac{D^2}{k} - \frac{D^2}{k+1}$$

$$100 \ = \frac{(k+1)\,D^2 - kD^2}{k\,(k+1)}$$

$$100k(k+1) \ = D^2$$

$$D = \sqrt{100k(k+1)}$$

Thus, when D $< 10\sqrt{k(k+1)}$ the k relays are better than k+1 relays. □

Theorem 4.6. *In NxN Grid with N^2 Nodes, transmitting data along the main (or the secondary diagonal) between the farthest two nodes using k-relays equally spaced is better than using k-relays not evenly spaced.*

Proof. For the case using k-relays equally spaced

$$E_{N\times N-k-relays\ diagonal-equally} = k\left(\cdot 1\times\left(\frac{D}{k}\right)^2+100\right) = \quad \cdot 1\times\frac{D^2}{k}+100k \tag{14}$$

For the case of using k-relays shifted:

$$E_{N\times N-k-relays\ diagonal-equally} = \sum_{i=1}^{k}\left(\cdot 1\times\left(\frac{D}{k}+\in_i\right)^2+100\right) \tag{15}$$

Where $\in_i$ a small negative or positive value in which relay is shifted from the position of the equally spaced case.

This formula will have the same terms in addition to some extra positive terms than the previous case, and therefore it will have worse energy consumption value.

□

Theorem 4.7. *In NxN Grid with N^2 Nodes, to transmit data along the main (or the secondary diagonal) between the farthest two nodes using m-relays ....*

Proof.

$$P_{mid} = 2\left[0.1\left(\frac{(n-1)\,d}{2}\right)^2+100\right]$$

$$P_{mid} = 0.1\left(\frac{(n-1)^2d^2}{2}\right)+200$$

$$P_{biased} = 0.1\left(\frac{(n-1)\,d}{2}+\varepsilon\right)^2+0.1\left(\frac{(n-1)\,d}{2}-\varepsilon\right)^2$$

$$P_{biased} = \frac{0.1\,(n-1)^2d^2}{2}+0.2\varepsilon^2$$

Which implies that

$$P_{biased} > P_{mid}$$

□

Now, we derive the main theoretical findings from the theorems 1 to 7 discussed above in Table 1.

5 Proposed energy aware Routing Algorithm (EAR)

To establish communication between any two nodes (source and destination), we need to form a subgrid between these 2 nodes. The constructed subgrid then can use the results listed in Table 1 to find the optimal path between the source and the destination. Hence we propose the following subgrid formation algorithm. We note that it is not always possible to form one grid to facilitate this communication; in many cases, we need to form 2 intersecting subgrids. These intersecting grids have a common corner node, namely, intersecting node. For the first subgrid, the source node represents one corner, and the intersecting node is the opposite corner. For the second subgrid, the intersecting node represents one corner, and the destination node is the opposite corner. Applying the finding in Table 1 to these subgrid results in a sub-optimal path between the source and destination nodes.

Table 1: Summary of main theoretical findings when the Source and Destination nodes are placed at the corners of the NxN grid

Number of relays	**Best strategy**	**Conditions**	**Theorem**
1	*relay-diagonal-middle* better than *relay-diagonal-shifted and relay not diagonal*	None	1, 2
0 or 1	*Use one relay-diagonal-middle better than direct*	Distance greater than $\sqrt{4\frac{E_{elec}}{\varepsilon_{amp}}}$ meter	3
2	two relays equally spaced along the diagonal is better than any other allocation using two relays that are not equally spaced along the diagonal	None	4
k or $k+1$	Use $k+1$ equally spaced better than k	$D > 10\sqrt{k(k+1)}$	5
K	k-relays equally spaced is better than using k-relays not equally spaced	none	6

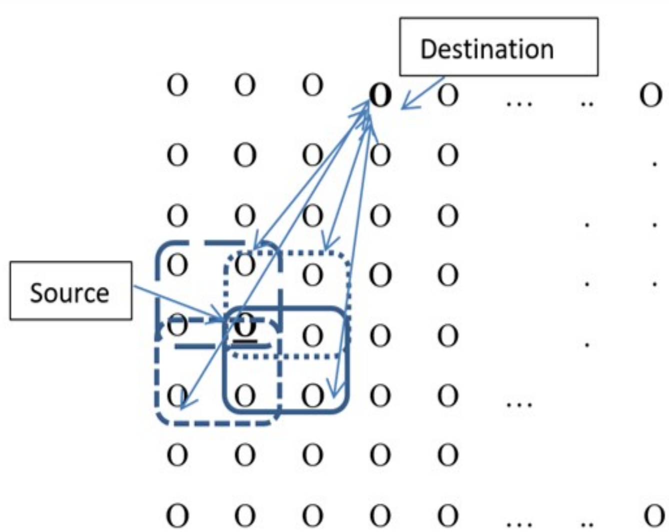

Figure 3: Illustration of the four possible subgrids around the source

Forming the subgrids is done in a repetitive fashion; we start with a (2x2) nodes around the source node and toward the destination node. Any node in the network (except for boundary nodes) can form 4 (2x2)-subgrids as outlined in Figure 3. The distance from the opposite corner for each of these four subgrids to the destination node is measured d_1, d_2, d_3, and d_4. We select the subgrid with the minimum distance. If the destination node is not included in the subgrid, the grid grows to include more nodes and to ultimately reach the destination node if possible. The subgrid formation function is shown in Figure 4.

Now, we devise the proposed Energy Aware Routing protocol, called EAR. The EAR consists of two phases, initialization phase and operation phase. In the first phase, each node should know the distance

Sub-grid Formation Function

Input: Source (S) and Destination (T) Nodes

Output: Optimal path to the destination node from the source node

Step 1 Set N_d=2, $d_{min}=\infty$

Step 2 Form the four possible grids of size N_d X N_d

Step 3 Measure the distance from the opposite corner of the four grids and the destination node (d_1, d_2, d_3, d_4)

Step 4 d_{curr_min}= min (d_1, d_2, d_3, d_4)

Step 5 If $d_{curr\_min} < d_{min}$ Then

- Increment N_d by 1
- d_{min} =min(d_{curr_min},d_{min})
- Goto step 2

Step 6 ElseIf ($d_{curr\_min} > d_{min}$)

- Set the corner of the current grid (intersecting node) as a new source, Invoke the **subgrid-formation** (newly selected sources)
- If the destination node is reachable then
  - Exit ()

Figure 4: Subgrid Formation Function

between it and all other nodes in the grid. This can be accomplished by a simple flooding technique by exchanging packets and record the direction (top, down, left, right) from which the packet is received. Many works in the literature assume that this information can be stored at the initialization phase at each node [10].

In the second phase, the source and destination nodes apply the subgrid formation function, as discussed in Figure 4.

6 Simulation and Results

The performance of the proposed scheme (EAR) is evaluated using simulation. An event-driven simulator is used to examine the performance under different working scenarios. The performance of the proposed algorithm is compared against a direct transmission algorithm as well as a middle-relay based algorithm. In this setting, we assume a 2-D grid topology with NxN nodes. Nodes are assumed to be fixed and equally spaced (with distance [D_{row}/(N-1)] meters) from each other. All nodes will start with the same energy level (E_{total}). Table 2 lists the parameters used in the simulations. Since energy computation is the primary concern in WSNs, the performance metrics used in this study to measure the performance are: Time for the first node to die, time for 50% of nodes to die, and time for 90% of nodes die. To simplify the comparison, packets are assumed to arrive at the destination without errors (i.e., no need for re-transmissions).

Now, we present the main findings and results of this work. It presents some preliminary results regarding the behavior of the proposed algorithm in terms of energy consumption. Sensor devices are equipped with an energy-limited source. Once the source is run out of power, the device will die. Intuitively, prolonging device lifetime will prolong the entire network lifetime. Therefore, this section reports basic energy consumption results only. Other performance metrics will be considered in the future.

Figure 6 reports the results for the time of the occurrence of the first death (first sensor node die)

Table 2: Simulation Parameters

Parameter	**Value**
ε_{amp}	100 pJ/bit/m^2
E_{RX_elec}	50 nJ/bit
ETX_elec	50 nJ/bit
N	2, 4, 6, 8, 10
Packet Size	512 bits
Simulation Time	10000 time units
E_{total}	10000 J

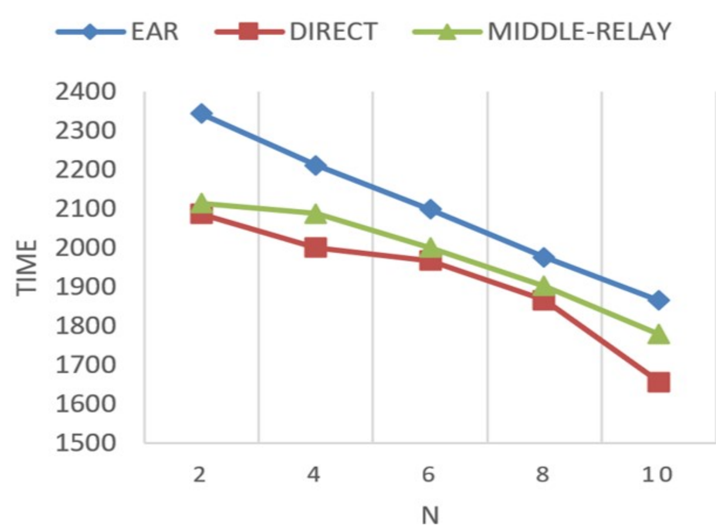

Figure 5: Time for First Node to Die in the Network

event for a various number of nodes. For all algorithms, as the number of nodes increases, the number of data exchanges increases; hence, the time of the first death decrease. It is apparent that the EAR algorithm outperformed both direct and middle-relay algorithms. For the direct and the middle relay, the middle relay has a slight improvement over the direct algorithm.

Figure 7 depicts the results for the time when half of the nodes are dead. While Figure 8 illustrates the results for the time when 90% of the nodes are dead. In both cases, EAR achieves the best performance followed by the middle relay, and finally, the direct algorithm. For all cases, as the number of nodes increase, the number of data exchanges increases; hence, the time decrease.

The proposed EAR algorithm outperformed both direct and middle-way algorithms in terms of energy consumption. To further understand the network behavior, more experiments were conducted to examine the death patterns in the network (if one exists). The new set of experiments investigated the behavior of the proposed EAR protocol only. For this purpose, we classify nodes into three classes: boundary, semi boundary, and central nodes. Boundary nodes are the utmost nodes in the network, while central nodes are located in the middle of the network. Semi boundary nodes are in between boundary and central nodes.

Figure 9 depicts the distribution of the first death in the three defined classes. It shows that for all possible cases of N, the first death always occurs in the central nodes.

The results shown in Figures 9-11 indicate that the first deaths are more likely to occur in the central

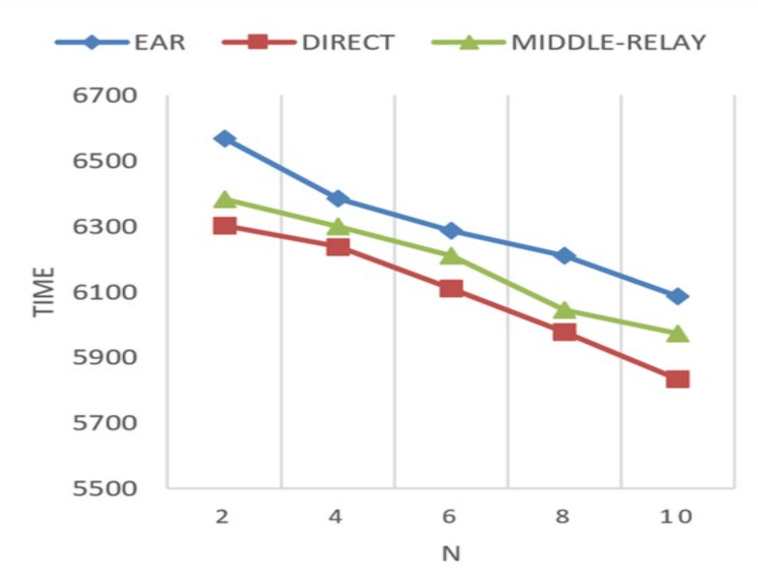

Figure 6: Time for First 50% of Nodes to Die in the Network

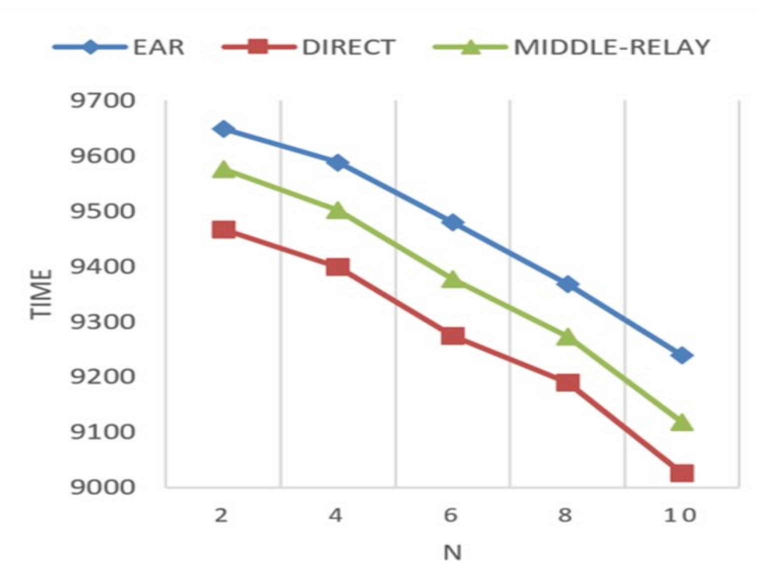

Figure 7: Time for First 90% of Nodes to Die in the Network

region of the network, followed by the semi-boundary region, and little to no deaths occurring in the boundary region of the network. These findings are key in designing an energy-aware as well as load balanced routing protocol. Such a design will be considered in future work.

7 Conclusion and Future Work

Wireless Sensor Networks (WSNs) are a promising technology to build modern smart places. In WSN, sensor nodes collect and transmit certain data to a central unit. Energy is a key factor in designing and building Wireless Sensor Networks (WSNs). The limited energy available to WSNs require a careful

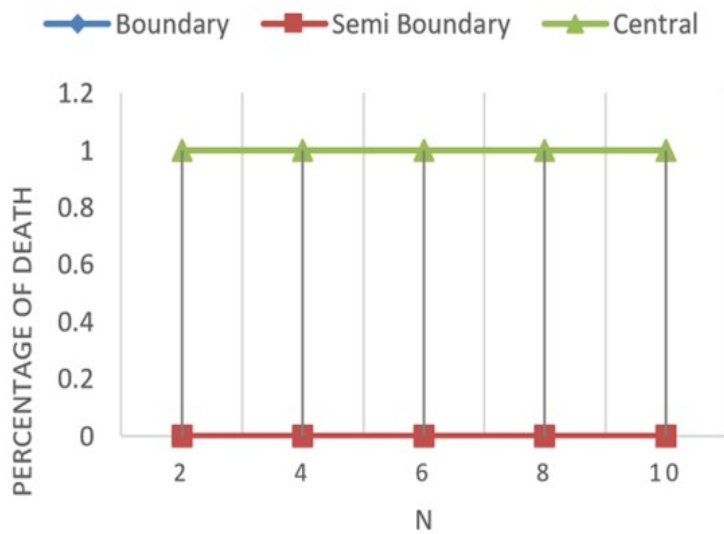

Figure 8: Distribution of First Death in the Network

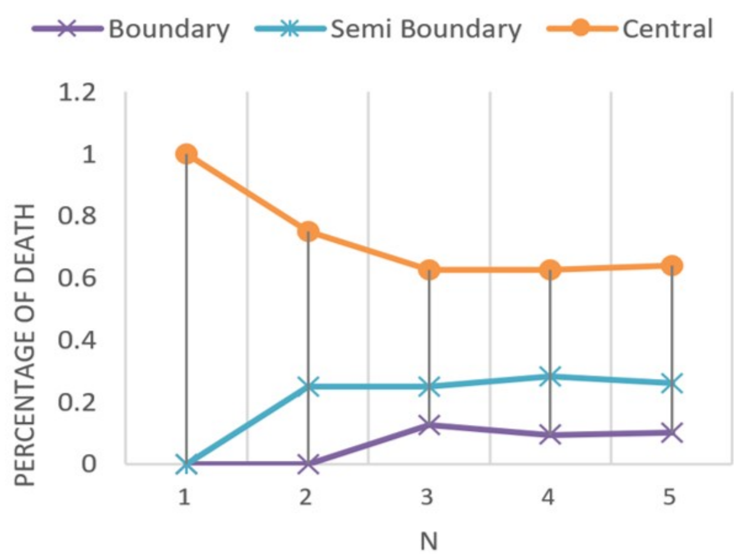

Figure 9: Distribution of first 50% Deaths in the Network

design for the forwarding/communications operations performed by these devices. Hence, it is essential to develop energy-aware protocols and algorithms for WSNs.

In this paper, we investigate the sensors placement issue and its strong ties to the energy consumption challenge. We seek an optimal routing algorithm for fixed placement sensors in an NxN grid topology. Several theoretical bounds were derived to highlight this relation and to devise an optimal routing strategy. For example, it is proved that it more energy efficient to directly transmit from the source node to the destination node if the distance between the two nodes is less than 44.72 meters. The findings obtained from these theorems were used to propose an energy-aware routing algorithm for WSNs, namely Energy Aware Routing (EAR). This algorithm considers the energy consumption as the primary key de-

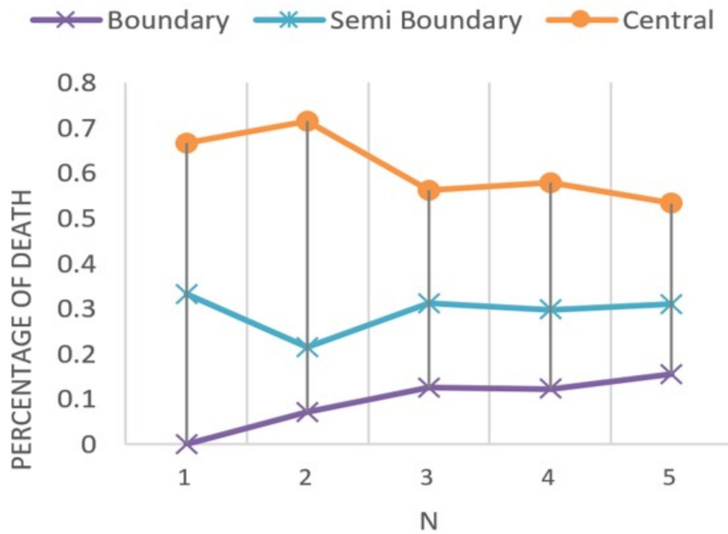

Figure 10: Distribution of first 90% Deaths in the Network

sign factor. The performance of the EAR algorithm is evaluated using simulation. The proposed EAR algorithm outperformed other classical techniques such as direct transmission and one-relay techniques in terms of several performance metrics. For future work, we propose to enhance the proposed EAR algorithm to account for more factors such as load balancing. More detailed scenarios are also needed to be investigated to evaluate the performance of the proposed algorithm.

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Authors Biography

Yaser Khamayseh is an associate professor at Jordan University of Science and Technology. He received the B.Sc. degree in computer science from Yarmouk University, Jordan in 1998, and M.Sc. from University of New Brunswick, Canada in 2001. He received the Ph.D. degree in computer science in 2007 from University of Alberta, Edmonton, Canada. In 2007 he joined the faculty of computer and information technology at Jordan University of Science and Technology, Jordan, as an assistant professor of computer science. He has served as a technical program committee member of various conferences. His research interests include wireless network optimization, resource management, and protocol design and analysis for future generation wireless communication networks and systems.

Wail Mardini is an Associate professor of Computer Science at Jordan University of Science and Technology (JUST) in Jordan. Dr. Mardini received his Ph.D. degree in Computer Science from University of Ottawa/Canada at 2006 and his Masters degree from University of New Brunswick/Canada at 2001. Dr. Mardini worked at JUST since 2006 and was the CS department chair during the academic years 2010/2011 and 2011/2012, and the faculty vice dean during the academic year 2012/2013. Dr. Mardini has many publications in the area of network survivability, wireless and wireless sensor networks, and optical-wireless networks. He is currently working on Wireless Mesh Networks, Wireless Sensor Networks, Optical Network Survivability, WiMax Technology, Scheduling in Parallel Computing and Intrusion Detection in database Techniques.

Monther Aldwairi is an associate professor at the College of Technological Innovation at Zayed University since fall of 2014 and an associate professor in Network Engineering and Security at Jordan University of Science and Technology (JUST) since 2012. He received his B.S. in electrical engineering from JUST in 1998, and his M.S. and PhD in computer engineering from North Carolina State University (NCSU), Raleigh, NC, in 2001 and 2006, respectively. Prior to joining ZU, he was an assistant professor of Computer Engineering at JUST since 2007. He served as the Vice Dean of the Faculty of Computer and Information Technology from 2010 to 2012 and was the Assistant Dean for Student Affairs in 2008. In addition, he was an Adjunct Professor at New York Institute of Technology (NYiT) from 2009 to 2012. He worked at NCSU as Post-Doctoral Research Associate in 2007 and as a research assistant from 2001 to 2007. He worked as a system integration engineer for ARAMEX from 1998 to 2000. Dr. Aldwairi's research interests are in information, network, Cloud, IoT and web security, intrusion detection, digital forensics, reconfigurable architectures, parallel architectures and algorithms, IoT, artificial intelligence and pattern matching.

Hussein Mouftah After four years of industrial experience mainly at Bell-Northern Research (BNR), Dr. Hussein T. Mouftah started his academic career as an Assistant Professor in the Department of Electrical and Computer Engineering at Queen's University in 1979. In 1988 he became full professor there and from 1998 until 2002 he was Associate Head for the Department. Since 2002 he has been a Tier 1 Canada Research Chair at the University of Ottawa, SITE and in 2006 he was appointed Distinguished University Professor. During his sabbatical leaves, he did consulting work for BNR and Nortel Networks (1986-87; 1993-94; and 2000-01). Dr. Mouftah has published over 1000 technical papers, 7 books and 48 book chapters. To his credit he has 12 patents and 140 industrial reports. He has received research grants and contracts totalling close to 40 million and he has supervised more than 300 highly qualified personnel of which 95 are Master's and 63 are PhD graduates and 30 are post-doctoral fellows.