# Communication/Computation Trade-offs in Wireless Sensor Networks: Comparing Network-Level and Node-Level Strategies

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***Abstract*—In wireless sensor networks, nodes having limited battery resources convey data to an energy-unconstrained base station. The amount of data transmitted by a node usually depends on how much local processing is performed. In other words, more computation on a node means less communication with the base station and vice versa. Hence improving energy efficiency and prolonging the network lifetime requires a careful trade-off analysis. This analysis may be performed at a network-level or at a node-level. The latter is more fine-grained allowing different nodes to implement different solutions. In our work, we propose a novel mixed integer programming framework to model and optimize node-level strategies. Using this framework, we show that hybrid use of digital signature algorithms in a network could extend the lifetime up to 21.25% as compared to a network-level optimal strategy where all nodes use a single algorithm.**

## I. INTRODUCTION

We consider the following scenario to motivate our work. A wireless sensor network (WSN) is deployed for surveillance purposes. Each node has a built-in camera periodically capturing still images. Transmission to the base station may use other nodes as relays (multi-hop communication). The base station processes the collected data and interacts with a user.

In such an application, if the design goal is to prolong the network lifetime, then the following question becomes highly relevant. How much processing should be performed locally on the nodes? On one extreme, there may be no local processing at all and nodes simply transmit raw images. On the other extreme, nodes may run the most sophisticated image processing and machine vision algorithms so that only minimal amount of data is transmitted to the base station (*e.g.*, only semantic data pertaining to a suspicious situation). Other options may lie in the middle with a moderate amount of local processing (*e.g.*, images may be compressed before transmission).

Unlike computational costs, energy consumption of communication cannot be expressed with a simple formula because it depends not only on the distance between the node and the base station but also on the exact route taken which may change throughout the lifetime. A linear programming model with the optimization objective of maximizing lifetime has been proposed in earlier work [1] which can be used to analyze the trade-off exemplified above. However, there is one issue which has not been investigated yet. Instead of adopting a single option applied to all nodes in the network, we may implement a hybrid solution. Turning back to our motivating scenario, we may choose to perform local processing only in a subset of nodes in the network but not in the remaining ones. Then, the research problem we study in our work could be briefly described as follows. How much improvement with respect to network lifetime could we attain with a strategy in which different nodes may implement different options (*i.e.*, use of node-level strategy where we acknowledge that this strategy brings additional complexity and may not be always applicable.) instead of network-level strategy? To answer this question, we build and discuss a novel mixed integer programming (MIP) framework in our work (Section II). As an application example of this framework, we analyze the hybrid use of digital signature (DS) algorithms and its impact on network lifetime (Section III). An example regarding security is chosen due to availability of energy overhead information from previous work [1] but our framework could be easily tailored to analyze other computation/communication trade-offs once the required numerical data is available.

## II. THE SYSTEM MODEL

Throughout this work, we use the energy model introduced in [2], where the amount of energy to transmit a bit is represented as $E_{tx,ij} = E_{Elec} + \varepsilon_{amp}\ d_{ij}^{\alpha}$, and the amount of energy to receive a bit is represented as $E_{rx} = E_{Elec}$ where $E_{Elec}$ refers to the energy dissipation on electronic circuitry, $\varepsilon_{amp}$ denotes the transmitter efficiency, $\alpha$ represents the path loss, and $d_{ij}$ is the distance between node-$i$ and node-$j$. We adopt the network lifetime definition given in [2] which is the time when the first sensor node exhausts all its battery power. In our framework, each sensor node-$i$ creates a minimum of $s_i$ unit of raw data per unit time to be conveyed to the base station.

The network topology is represented as a directed graph $G = (V, A)$ where we define V as the set of all nodes including the base station (node-1). We also define set W which includes all nodes except the base station $W = V \setminus \{1\}$. $A = \{(i, j) : i \in W,\ j \in V - i\}$ is the set of arcs. The amount of traffic that flows from node-$i$ to node-$j$ is represented as $f_{ij}$. Traffic generated at each node terminates at the base station either by direct transfer or through other sensors acting as relay nodes.

The optimization problem in its general form is formulated with the objective of maximizing $t$ (the minimum lifetime of sensor nodes) subject to the following constraints:

$$\sum_{j \in V} f_{ij} - \sum_{j \in W} f_{ji} = s_i t + S_{c,i} \ \forall i \in W \tag{1}$$

$$E_{rx} \sum_{j \in W} f_{ji} + \sum_{j \in V} f_{ij} \ E_{tx,ij} + E_{c,i} \leq e_i \ \forall i \in W \tag{2}$$

$$S_{c,i} = s_i \times r \times t \times \{\sum_{k=1}^{n} o_1^k \times a_k^i\} \ \forall i \in W \tag{3}$$

$$E_{c,i} = s_i \times r \times t \times \{\sum_{k=1}^{n} o_2^k \times a_k^i\} \ \forall i \in W \tag{4}$$

$$\sum_{k=1}^{n} a_k^i = 1 \ \forall i \in W \tag{5}$$

$$f_{ij} \geq 0 \ \forall (i,j) \in A \tag{6}$$

$$a_k^i \in \{0,1\} \ \forall i \in W, \forall k \in [1,n] \tag{7}$$

Equation (1) is the flow balancing constraint which states that for all nodes except the base station, the difference between the amount of data flowing out of node-$i$ and the amount of data flowing into node-$i$ is equal to the amount of total data generated by node-$i$ which is the sum of information bits generated by node-$i$ throughout the lifetime ($s_i t$) and the signature overhead bits ($S_{c,i}$). Equation (2) is the energy constraint. Total energy dissipation in a sensor node is comprised of reception energy, transmission energy, and also the energy overhead ($E_{c,i}$) due to processing performed on the node. This equation states that no sensor node can spend more than its initial battery energy ($e_i$).

Equation (3) and Equation (4) give the total amount of signature overhead bits and computation energy overhead arising due to DS operations at node-$i$, respectively. Only these equations need to be modified to model other aspects of communication/computation trade-offs. The total number of signing operations during the entire network lifetime ($t$) is given by the term $s_i \times t \times r$, where $r$ is the signing rate [1]. Signature sizes and signing energy costs of different DS algorithms are denoted by $o_1^k$ and $o_2^k$, respectively. The results of the summations in both Equation (3) and Equation (4) are a single value of $o_1^k$ and $o_2^k$ for each node, respectively, due to the constraint over the binary variable $a_k^i$ given in Equation (5). For example, if $a_1^3 = 1$, then $a_2^3 = a_3^3 = 0$ and the only nonzero terms of the summations in Equation (3) and Equation (4) are $o_1^1$ and $o_2^1$, respectively (*i.e.*, node-3 utilizes OTS). Hence, for each node the optimal selection of the signature algorithm that maximizes the network lifetime is selected (*i.e.*, different nodes can implement different types of DS algorithms – node-level strategy). Equation (6) states that all flows within the network are non-negative. Equation (7) enforces $a_k^i$ to take binary values.

Multiplication of the continuous variable $t$ and the binary variable $a_k^i$ in Equations (3) and (4) makes the optimization problem nonlinear. However, the optimization problem can be transformed into an equivalent linear MIP model. We opt to present the nonlinear optimization problem first because it is easier comprehend the nonlinear formulation.

For linearization we replace the nonlinear term $t \times a_k^i$ with a single continuous variable, $w_k^i$ (see Equations (8) and (9)).

$$S_{c,i} = s_i \times r \times \{\sum_{k=1}^{n} o_1^k \times \underbrace{w_k^i}_{t \times a_k^i}\} \ \forall i \in W \tag{8}$$

$$E_{c,i} = s_i \times r \times \{\sum_{k=1}^{n} o_2^k \times \underbrace{w_k^i}_{t \times a_k^i}\} \ \forall i \in W \tag{9}$$

Then, we include the following constraints to ensure that the continuous variable possess the characteristics of its constituent variables (*i.e.*, $w_k^i = t$ for only one value of $k$ and it is zero for all other values at each node). Regardless of the $a_k^i$ values, $w_k^i$ cannot exceed $t$ as enforced by Equation (10).

$$w_k^i \leq t \ \forall i \in W, \forall k \in [1,n] \tag{10}$$

Equation (11) states that $t$ cannot exceed $M$ which is the lifetime obtained without using any DS algorithm ($t < M$).

$$w_k^i \leq M \times a_k^i \ \forall i \in W, \forall k \in [1,n] \tag{11}$$

In order to guarantee that $w_k^i$ is equal to zero when $a_k^i$ equals to zero, we add a nonnegativity constraint as in Equation (12).

$$w_k^i \geq 0 \ \forall i \in W, \forall k \in [1,n] \tag{12}$$

If $a_k^i = 1$, we need to enforce $w_k^i = t$ thus we include Equation (13) which works besides Equation (10) for this purpose.

$$w_k^i \geq t - M \times (1 - a_k^i) \ \forall i \in W, \forall k \in [1,n] \tag{13}$$

Note that if $a_k^i = 0$, then the right hand side of the Equation (13) cannot be positive, therefore $w_k^i$ takes the correct value of zero because it cannot have a negative value due to Equation (12). As a result, the linearized MIP model is formulated with the objective of maximizing $t$ subject to the constraints stated in Equations (1), (2), and Equations (5) to (13).

## III. Analysis

In this section, we analyze the trade-off discussed in Section I in more concrete terms by investigating the hybrid use of DS algorithms in a *WSN*. We choose three DS algorithms ($n = 3$) as in [1] and use them at two different security levels; 80-bits and 112-bits. OTS-80, RSA-1024 and ECDSA-160 provides 80-bits security. For 112-bits security, OTS-112, RSA-2048 and ECDSA-224 are used. The parameters of signatures required for our analysis are listed in Table I.

Energy parameters provided in [2] are used in our analysis ($E_{Elec} = 50 \ nJ$ and $\varepsilon_{amp} = 100 \ pJ$). Initial battery energy of nodes is equal ($e_i = 243 \ J$). We assume sensor nodes create data at a constant rate ($s_i = 128$ bytes/minute). We choose $r = 1/25344$ and $\alpha = 4$. GAMS IDE ver. 23.9.1 system and CPLEX ver. 12.4 solver are used to obtain solutions.

TABLE I
SIGNATURE PARAMETERS

| k | DS Algorithm | Signature Size *(bits)* $o_1^k$ | Signature Cost *(mJ)* $o_2^k$ |
|---|---|---|---|
| 1 | OTS-80 | 3120 | 0 |
| 2 | RSA-1024 | 1024 | 304 |
| 3 | ECDSA-160 | 320 | 22.82 |
| 1 | OTS-112 | 6160 | 0 |
| 2 | RSA-2048 | 2048 | 2302.7 |
| 3 | ECDSA-224 | 448 | 61.54 |

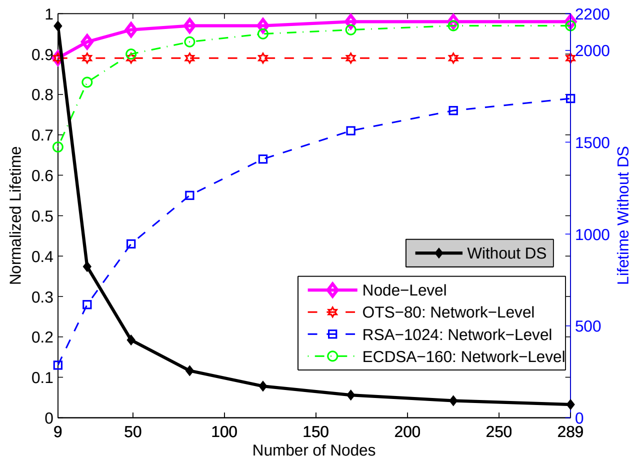


Fig. 1. Normalized lifetimes in the square topology for 80-bit security level.

We solve the linear MIP problem for the two-dimensional (2D) topology in which the base station is placed at the center of a square area. The distances between adjacent nodes in the vertical axis and horizontal axis are equal and fixed to 10 m. We also solve the linear programming model given in [1] to obtain results of network level strategy in which all nodes in the network use the same DS algorithm.

In Figure 1 and Figure 2, network lifetimes with node-level and network-level strategies are normalized with the lifetime obtained without use of DS and plotted for different network sizes. The absolute network lifetimes are also presented in terms of hours for the base case (when DS algorithms are not employed) on the right y-axis.

Node-level strategy can extend the lifetime up to 10.11% as compared to the optimal network-level strategy where OTS-80 (in small-size networks) or ECDSA-160 (in larger-size networks) is used throughout the whole network. If we have a closer look at the node-level strategy we see that if nodes close to the base station use OTS-80 and nodes farther away prefer ECDSA-160, then the lifetime is always prolonged in networks which comprise more than 9 nodes. The improvement in network lifetime with node-level strategy is even higher (*i.e.*, up to 21.25%) for 112-bit security.

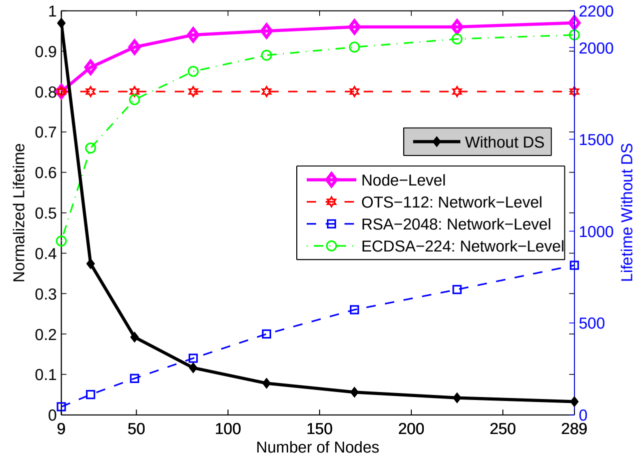


Fig. 2. Normalized lifetimes in the square topology for 112-bit security level.

## IV. Conclusions & Future Work

To extend network lifetime, empowering the design of WSNs with the ability to make computation/communication trade-offs is important. Quantitative investigation of these trade-offs may be performed using mathematical programming. In this work, we revisit the LP model of network-level trade-off analysis discussed in [1]. Our key insight is identification of more fine-grained node-level strategies so that tradeoffs can be exploited even further. We propose a novel linear MIP framework to model and optimize node-level strategies. Using this framework, we show that hybrid use of DS algorithms could extend the lifetime up to 21.25% as compared to an optimal strategy where all nodes use a single algorithm.

For small-size networks where computational costs dominate the transmission energy, OTS algorithm with practically zero computational cost performs significantly better than other algorithms. But, as network size grows and transmission energy begins to dominate, ECDSA with its much shorter signature size becomes more preferable. However, even in very large networks sole use of ECDSA does not yield the optimal network lifetime. The best strategy is the hybrid approach; use OTS in nodes close to the base station and ECDSA in the rest. As a future work, we aim to investigate other possible applications of our framework. We also plan to develop a heuristic method in order to reduce the computational complexity of the proposed MIP model.

## References


[1] K. Bicakci, I. E. Bagci, and B. Tavli, "Communication/computation tradeoffs for prolonging network lifetime in wireless sensor networks: The case of digital signatures," *Inf. Sci.*, vol. 188, pp. 44–63, Apr. 2012.

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