Towards a Performability Analysis for Environmental Sensor Networks

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Abstract. Wireless sensor and actor networks constitute one of the supporting technologies for cooperative applications. Particularly, in the case of environmental monitoring systems, ambient conditions can be conveniently modified by means of the so-called actuators (actors), which are driven by commands issued by a decision-making process on the basis of the information gathered by sensor nodes. In this context, sensor nodes are typically deployed at strategic locations on the basis of application requirements. These locations may be far apart from each other, leading to unfeasible or highly energy-consuming transmission distances. This paper provides an assessment of the impact of relay node insertion on performance and reliability.

Keywords: Sensor network, data-gathering tree, TDMA (Time-Division Multiple Access), network delay, packet loss rate, reliability.

1 Introduction

Figure 1 shows the architecture (semi-automated version) of an environmental monitoring system supported by a sensor network. This kind of systems are based on a continuous and dynamic cooperation between the application running on top of sensor nodes, the decision-making process at a remote data management center, and the application running on top of actuators. Among these three system components, the sensor segment represents the weakest part. This is due to the resource limitation of sensor nodes in terms of processing, communication and energy availability.

The sensor networks supporting the cooperative systems just described belong to the proactive or time-driven class. More specifically, in *proactive* or *time-driven* sensor networks (TD-WSN), nodes take readings of the environment and report the corresponding data following a regular or periodic pattern [1]. This data flow model makes the traffic generated by these networks very predictable, fact that recommends the use of the so-called contention-free scheduled MAC protocols. Some interesting scenarios of sensor networks for environmental monitoring are described in [1].

It is also common that TD-WSN are manually deployed [2], either by placing nodes at strategic locations that are of special interest, or according to some regular sampling pattern. In any case, the resulting locations are not necessarily close to each other, thus generally giving rise to large inter-node distances. However, large

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inter-node distances require long communication ranges, which are impractical or unfeasible for sensor networks. Hence, in order to make such wide-area deployments feasible, it becomes necessary to introduce additional nodes that mitigate the energy waste experienced by regular nodes. These supplementary resources can be introduced either randomly or following a structured approach. In the first case, relay nodes are randomly scattered over the sensor field until certain design requirements are fulfilled. However, the disadvantage of this approach is its poor scalability, since the total number of nodes to be deployed in case of large and sparse networks may be excessive. On the other hand, the structured approach, either over the field or along critical links, exhibits better balance between connectivity and lifetime enhancement and number of relay nodes. Examples of this approach are [3]-[5] and references therein.

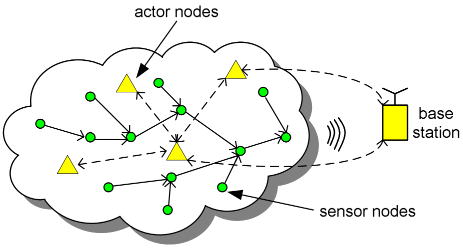

Fig. 1. Basic architecture of environmental monitoring systems based on sensor networks

However, deployment of supplementary nodes also has an impact on the *performability* of the cooperative system. Accordingly, in this paper, in contrast to the previous works, an assessment of both performance and reliability effects of relay node insertion is carried out.

2 Insertion of Relay Nodes

As stated in [2], it is common that packets in structured (and possibly sparse) sensor networks are routed through multi-hop pre-determined paths, forming the so-called *data-gathering tree* [6]. On the other hand, the predictability of the traffic pattern generated by these networks makes contention-free scheduled MAC protocols specially appropriate [1] [6]. To analyze the benefits of introducing additional nodes on lifetime, it is first necessary to characterize the dependence of energy consumption on transmission distance. Assuming a sensor network with N nodes accessing the communication channel via TDMA, and the radio model proposed in [6], it can be shown that the energy consumed by node i per communication round is as follows:

$$E(i) = \left(g(i) + 2\sigma(i)\right) \cdot E_e \cdot m + \left(g(i) + \sigma(i)\right) \cdot E_w \cdot m \cdot d^f(i)\,,\ i = 1 \ldots N \quad (1)$$

Here, E_e is the energy dissipated by the transceiver circuitry to transmit or receive a single bit, E_w is the energy radiated to the wireless medium when transmitting a single bit over a distance of 1 meter, f is the path loss exponent, m is the packet length in bits, $g(i)$ is a measure of the *traffic intensity* per node, which is defined as the number of packets generated by node i per round of communication, and $\sigma(i)$ is the *forwarding degree*, that is, the number of packets forwarded by node i during every round of communication.

The simplest way to introduce relay nodes in the network is by inserting them into critical links, that is, links that exceed the transmission range of nodes or that do not allow to achieve a minimum network lifetime, even if their length is below the maximum range. The reference scheme is shown in Figure 2, where several relay nodes are inserted in the segment (hop) between node i and node j. Correspondingly, the following algorithm provides an iterative method to determine the number of relay nodes in every link of the network:

```
program Relay Node Insertion
for $i$ = 1 to $N$ do
  $n(i)$ = 0 //variable that will contain the number of nodes
           to be inserted in link i
  Evaluate $l(i)$ //expected lifetime of node $i$
  while ($l(i)$ < $L$ || $d(i)/(n(i)$ + 1)) < $R_{max}$ do
    $n(i)$ = $n(i)$ + 1
    Evaluate $l(i)$
  end while
end for
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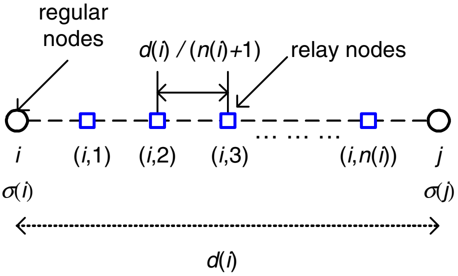

Fig. 2. Insertion of equally-spaced relay nodes in the link between two regular nodes

As it can be noticed, it is assumed that nodes are equipped with an initial battery level B and have maximum transmission range R_{max}, whereas L is the requirement on network lifetime, defined as the time until first node death. When the lifetime requirement is more restrictive that the maximum transmission range (that is, all link distances are below the maximum transmission range), the number of relay nodes to be inserted in the segment headed by node i can be expressed as follows:

$$n(i,L) = \left\lceil \left(\frac{L \cdot E_w \cdot m\big(\sigma(i) + g(i)\big) d(i)^f}{B - L \cdot E_e \cdot m\big(2\sigma(i) + g(i)\big)} \right)^{1/f} - 1 \right\rceil, \; i = 1 \ldots N \qquad (2)$$

A proof of the cost-effectiveness of relay node insertion is provided in Figure 3, which plots the amplification of lifetime of regular nodes in terms of the number of relay nodes, for different values of the link distance. The values for the workload-based parameters are set as follows: $g = 1$ and $\sigma = 5$. The rest of parameters are taken from [7] and typical operating conditions: E_e = 50nJ/bit, E_{fs} = 10pJ/bit/m^2, E_{mp} = 0.0013pJ/bit/m^4, $f = 4$, d_0 = 75m, B = 15kJ and m = 125B. As it can be noticed, node lifetime can be significantly amplified just by inserting a relatively low number of relay nodes. For instance, by inserting 4 nodes in a 300m-link, the new lifetime for the node is about 80 times greater. Also, it can be observed that the effectiveness of relay node insertion increases with the target distance.

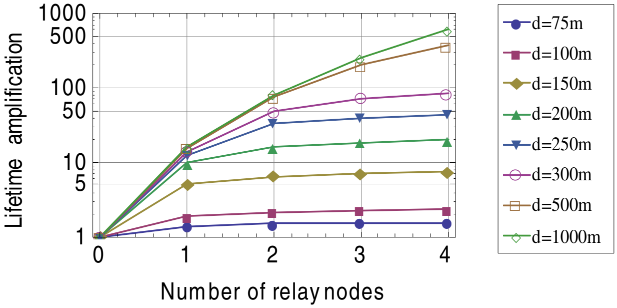

Fig. 3. Amplification of node lifetime versus number of relay nodes, for different values of the target distance

3 Performability Plot

Unfortunately, the insertion of relay nodes for network lifetime enhancement degrades system performability. As a first-step approach to this problem, the performance in terms of packet delay and packet loss rate, and the dependability formulated as reliability, are analyzed separately. To perform this analysis, let us first define τ as the duration of packets, q as the packet error probability at the receiver of any node in the network, and $r(t)$ as the node reliability function, that is, the probability that a node (regular or relay) remains operational at time t, given that it started working at time 0. Considering again the reference segment shown in Figure 2, the increase in delay, the packet delivery rate and the reliability at segment levels can be respectively formulated, for the segment headed by node i, as follows:

$$\Delta D(i) = \tau \cdot n(i) \text{ , } i = 1 \ldots N \tag{3}$$

$$PDR(i) = (1-q)^{n(i)+1} \text{ , } i = 1 \ldots N \tag{4}$$

$$R(i,t) = r(t) \cdot \prod_{j=1}^{n(i)} r(t) = r(t)^{n(i)+1} \text{ , } i = 1 \ldots N \tag{5}$$

In particular, expression (4) is based on three assumptions: (a) Homogeneous electromagnetic environment, (b) power control capability enabled (already adopted in the formulation of energy consumption), which guarantees the same signal-to-noise ratio at all receivers, and (c) packets received in error are discarded and not retransmitted. The latter assumption is common in time-driven sensor networks, because subsequent packets refresh the lost information, though up to some level beyond which the reconstruction process can be severely distorted.

In order to visualize the trade-off between the above segment-level metrics and network lifetime, the performability plot shown in Figure 4 can be constructed. In this plot, the segment index is omitted for simplicity and the dependence on the required lifetime is explicitly indicated. Most parameter values were already used in Figure 3: E_e = 50nJ/bit, E_{fs} = 10pJ/bit/m^2, E_{mp} = 0.0013pJ/bit/m^4, f = 4, d_0 = 75m, B = 15kJ, m = 125B, σ = 7, g = 2, d = 500m and q = 5%. For the node reliability, a constant failure rate is assumed, with an *MTTF* of 15 million rounds [8]. This means that $r(L) = r(t)\big|_{t=L} = \exp(-t/15\cdot 10^6)\big|_{t=L} = \exp(-L/15\cdot 10^6)$.

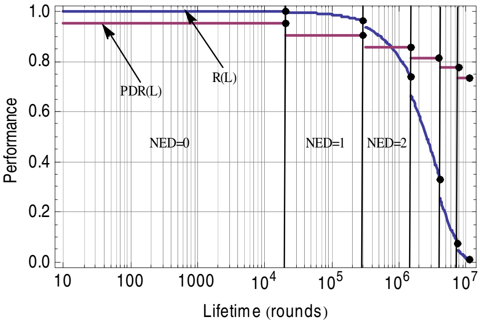

Fig. 4. Performability plot. NED stands for the extra delay normalized to the packet duration.

Specifically, the figure shows the degradation at segment level of both reliability and packet delivery rate as the required network lifetime increases. The metrics at segment level (and the performability plot) can be easily extended to other scales, like a path along the network or the overall network.

4 Numerical Results

In order to illustrate the effects of relay node insertion, the test scenario shown in Figure 5 is considered, which represents a medium-size network constituted by 20 regular nodes and a base station. Link distances (in meters) are shown as link labels. Since the link layer protocol is assumed to be TDMA, the geographical distribution of node locations that would allow the construction of an interference map, is not relevant. Thus, the logical network shown in the figure suffices.

With no loss of generality, all nodes are supposed to generate 1 packet per communication round, that is, $g(i) = 1 \ \forall i$. Accordingly, the forwarding degrees for all nodes are also indicated in the figure. Again the radio model parameters used in the previous sections are adopted, and a time interval of 15000 slots is considered. With 125B-packets transmitted at 250Kbps, this time interval would correspond to a reporting period of 1 minute. Then, considering precisely m = 125B, and B = 15kJ, the energy consumption model given by (1) leads to a network lifetime of 127552 rounds, which is determined by node 17. For the reporting time of 1 minute, this corresponds to roughly 2 months. Now, let us assume that a network lifetime 20 times larger is required. By applying the technique described in Section 2, 8 relay nodes should be inserted as also shown in Figure 5. The new distribution of node lifetimes is shown and compared to the previous one in Figure 6. It can be noticed that the new distribution of node lifetimes is more uniform, since a significant subset of nodes were below the lifetime requirement and thus had to be enhanced. The new network lifetime is 3437932 rounds (around 27 times larger than the lifetime of the original network), and it is now determined by node 5. This enhancement has been achieved with just 40% theoretically inexpensive additional nodes.

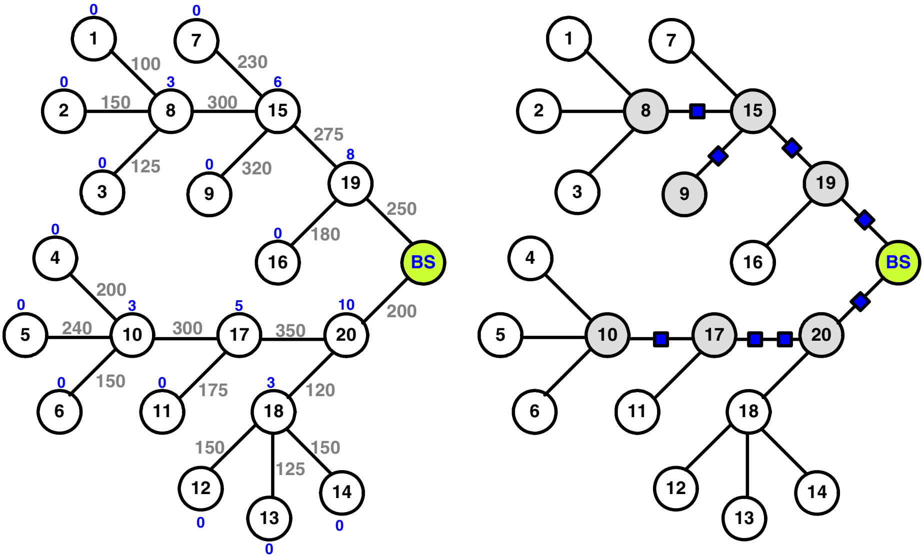

Fig. 5. Test scenario: before relay node insertion (left), and after relay node insertion (right)

In contrast to the benefits in energy consumption and lifetime, performance metrics are degraded. The impact on some path delays and network reliability can be easily derived from the enhanced network shown in Figure 5. In particular, the increase in path delay is rather unimportant for most environmental monitoring applications, which generally do not impose severe time constraints. However, the effects on packet delivery rate need more careful attention, as signal reconstruction in some parts of the sensor field might be damaged. Figure 7 shows the variations in packet loss rate per node as a result of node insertion. This variation reflects the increase in packet loss rate for the full path between every node and the base station, so it accounts for all segments along a path. It can be shown that this variation can be mathematically expressed as follows, where a path is represented by a sequence of p regular nodes $(i_1 \ldots i_p)$:

$$\Delta PLR(i_1, i_2 \ldots i_\mathrm{p}) = (1-q)^p \cdot \left(1 - (1-q)^{\sum_{\lambda=1}^{p} n(i_\lambda)} \right), i_1, i_2 \ldots i_p = 1 \ldots N, i_1 \neq i_2 \ldots \neq i_p \quad (6)$$

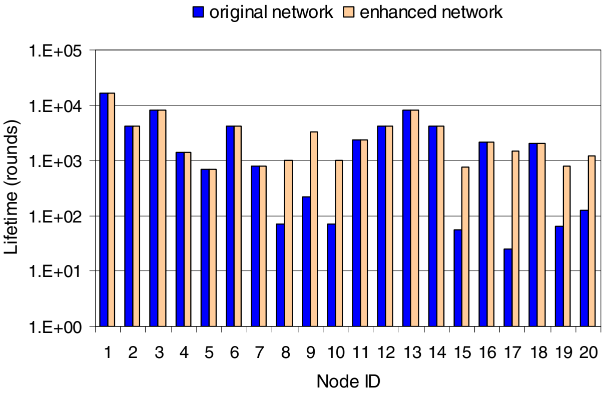

Fig. 6. Distribution of node lifetimes before and after relay node insertion

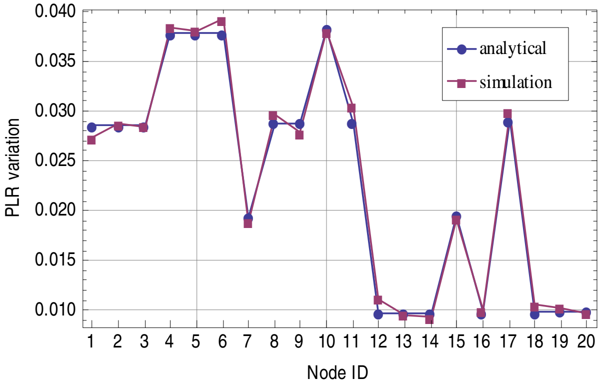

Fig. 7. Packet loss rate variation due to node insertion in the test network

As it can be noticed, Figure 7 also includes simulation results, which almost perfectly match the analytical ones. The former have been obtained after 150 runs, by assuming a Depth First Scheduling (DFS) TDMA slot assignment scheme with no slot reuse (see [6] for more details) and a battery of just 3J. This small battery value is intended to reduce the simulation time (as long as the battery value allows the simulated network to achieve its steady state and persist in this state for sufficient amount of time, so that any transient-based bias can be neglected).

5 Conclusions

In this paper, the effects of relay node insertion on lifetime, performance and reliability of a time-driven sensor network supporting a cooperative system have been analyzed. The obtained results are part of an overall work that can be accomplished in two directions: (a) analysis of performance and reliability when clusters instead of single nodes are deployed at locations of interest, and (b) formulation of a performability metric and its characterization by means of a Markov Reward model.

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