An Energy-Efficient M2M Communication Method for Leakage Detection in Underground Water Pipes

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ABSTRACT

An application of machine-to-machine (M2M) communication for leakage detection in underground water infrastructures is considered. A mobile sensor immersed in the water pipe is assumed to communicate with relay nodes on the ground surface, relaying its measured information to a base station for processing. An energy-efficient communication approach based on the cooperation between relay nodes is proposed. The optimal energy minimizing solution is derived and compared to a practical low complexity method. The proposed approach is shown to lead to significant energy savings and to perform closely to the optimal solution. In addition, it is shown to lead to data transmission with considerably shorter delays.

Categories and Subject Descriptors

J.2 [**Computer Applications**]: Physical Sciences and Engineering; H.4.3 [**Information Systems Applications**]: Communications Applications; F.2.m [**Analysis of Algorithms and Problem Complexity**]: Miscellaneous

General Terms

Theory, Algorithms, Performance

Keywords

Machine-to-machine, water leakage, wireless sensor networks, energy minimization.

1. INTRODUCTION

Water resources are becoming more scarce and thus there is a need to make the most efficient use out of the available resources and avoid any unnecessary waste, due for example to leakages from water infrastructures. Leakages are mainly caused by generally aged and consequently breakable water distribution infrastructure. Depending on the oldness and degradation of the conduits, the percentage of unaccounted water can range up to 70%, while a percentage of less than 20% is not considered a leak and restorations are mandatory only when the percentage exceeds 50% [13], [2].

The restoration of damaged pipelines is a complex task, since water pipes are interred in the ground and their path is not known with sufficient precision. Since pipes are not directly accessible, the identification of leakages is based on an approximate localization, between two consecutive accessible valves, bifurcations, or pressure monitors. Wireless sensor networks (WSNs) are proposed as an advanced monitoring technology to avoid carrying out expensive excavations over the pipe path until the exact position of the leakage is detected [5]. It is argued in [5] that WSN based methods are more suited for this application than other techniques, such as tracer gases [12], thermography, and ground penetration radars (GPRs) [11], which are not suitable to identify small leakages or to survey pipes in order to prevent damages [5].

In fact, WSNs will constitute an integral part of the Internet of Things (IoT) paradigm, spanning different application areas including environment, smart grid, vehicular communication, and agriculture [10]. The IoT is expected to include billions of connected devices communicating in a machine-to-machine (M2M) fashion [3]. In the WSN-based water leakage detection approach of [5], a mobile sensor inside the pipe is assumed to communicate with relay nodes (RNs) located at fixed positions along the pipe path, and these RNs communicate the received data to a central base station (BS) for processing. The electromagnetic properties of the sensor used in the approach of [5] are presented in [4].

The RNs might not be connected to a power source and hence need to operate long enough without draining their batteries. Hence, in this paper, we present a cooperative communication approach between the RNs receiving the sensor signal in order to relay their measured data to the BS in an energy-efficient manner.

The paper is organized as follows. The system description is presented in Section 2. The proposed approach is described in Section 3. Simulation results are presented and discussed in Section 4. Finally, conclusions are summarized in Section 5.

2. SYSTEM DESCRIPTION

In this section, we present a high level description of the system architecture and describe the role of the RNs where the proposed approach of Section 3 will be applied. The system under investigation, shown in Fig. 1, is composed of three main tiers:

- Tier 1 - The sensing module: it accommodates the

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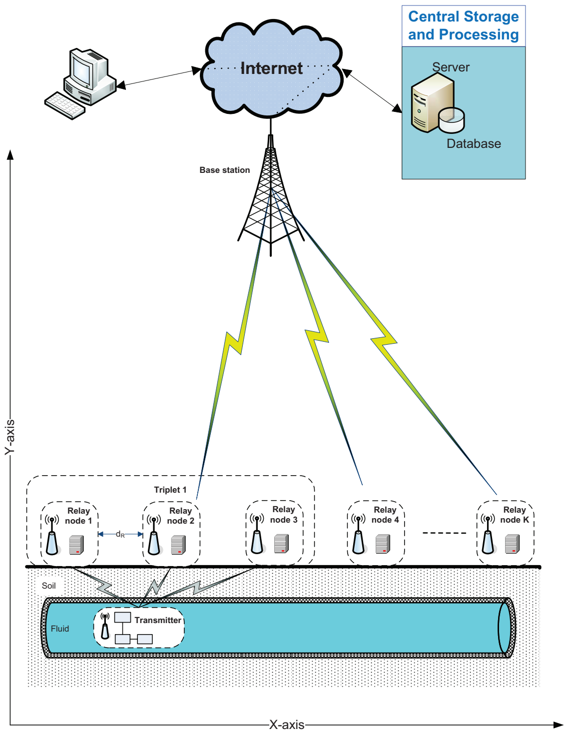

Figure 1: System Description.

sensor, that measures the required parameters inside the water pipe and transmits the measured data. Its main components are: an acoustic sensor, also known as hydrophone, a microcontroller, a radio frequency part, an antenna, a power supply, and the casing.

- Tier 2 - The relay nodes (RNs): these devices capture the data of the transmitter of Tier 1 and transmit the data to the base station of Tier 3.
- Tier 3 - The base station (BS): the BS receives the data transmitted by the RNs. The data is then routed to a server in a processing center where further processing and data analysis can be performed.

Without loss of generality, the pipe is assumed to be aligned with the $x-$axis. The RNs are placed on the ground along the pipe path, with uniform distance separation d_R between them.

It should be noted that data from the sensing module is sent wirelessly to the RNs, which eliminates the need for using wires as in other leakage detection techniques. The electromagnetic properties and transmission techniques from the sensing module to the RNs are presented in [5] and [4]. In this paper, the interest is in the link between the RNs and the BS. Thus, the proposed approach is not confined to water leakage applications. It can be used to ensure energy-efficient communications for applications dealing with monitoring any pipe-based infrastructure, e.g., in the oil and gas industry.

According to the speed of the sensing module, more than one RN can receive its transmissions. Practical measurements have shown that up to three RNs can simultaneously receive the transmissions of the sensing module. These RNs have to send their received data to the BS. In the traditional approach, the collected data is sent independently by each RN to the BS over the cellular network (e.g., GPRS, 3G, LTE, etc). Depending on the channel conditions on each long range (LR) RN-BS link, the data rates achieved might not be too high, which leads to prolonged transmission and thus increased battery consumption.

Consequently, we propose a method based on collaboration between the RNs over the short range (SR) wireless links. The RNs are grouped into mutually exclusive triplets. In each triplet, the proposed approach consists of selecting one RN to relay the data to the BS. The other RNs in the triplet will send their collected information to the selected RN by using an appropriate communication technology on the SR. An example is shown in Fig. 1.

Depending on the amount of data collected, ZigBee might not be suitable to ensure the transmission at rates high enough over the distances separating the RNs [9]. Thus, WiFi can be used for communications between RNs, as it has been already investigated in several IoT related WSN applications [9]. Two orthogonal WiFi frequencies can be selected by the RNs in the triplet to simultaneously transmit on the SR, without interference, to the RN selected for LR transmission.

It should be noted that embedding the Internet Protocol (IP) in resource constrained sensor nodes might be a challenging task [7]. Thus, the sensing module can communicate with the RNs using any proprietary protocol. The RNs, however, would in this case play the role of the gateways between the sensing module and the internet, as described in [7], in order to achieve a true IoT.

3. PROPOSED APPROACH

As the sensor traverses the pipe, we consider that each RN accumulates S_T bits of information. These bits include the data sent from the sensing module in addition to any bits resulting from additional processing done locally at the RN, before transmitting the data for further processing at the server. After all members of a triplet accumulate their S_T bits, transmission starts, either directly to the BS without collaboration, or via SR collaboration before LR transmission.

We use the term "node" to refer to either an RN or to the BS, for the purpose of simplifying the notations: We assume we have K RNs numbered from node 1 to K, with the BS numbered as node 0. The term $\mathcal{T}_k$ is used to denote the triplet of nodes $\{k, k+1, k+2\}$, with $k \geq 1$. Triplets are disjoint sets, i.e., a node cannot be a member of more than one triplet. Consequently, we have: $\mathcal{T}_k \neq \emptyset$ if and only if ($k \mod 3 = 1$), with " mod " representing the modulo operation. When K is not a multiple of three, the last one or two RNs are assumed to form a "triplet" of their own (with a slight abuse of the term). In the example of Fig. 1, RNs 1, 2, and 3 form triplet $\mathcal{T}_1$. Although at certain instants, after the sensing module moves inside the pipe, RN 3 will be receiving along with RNs 4 and 5, the first triplet transmission on the LR occurs after RN 3 receives all its S_T information bits. In other words, RNs 1 and 2 wait for RN 3 even after they stop receiving as the sensor moves. Similarly, in the second triplet $\mathcal{T}_4$, RNs 4 and 5 will start transmission after RN 6 starts and completes the reception of the S_T bits.

With each node having collected data of size S_T bits, the time needed to transmit this content on a link between nodes k and j having an achievable rate R_{kj} bps is given by S_T/R_{kj}. Denoting the power drained from the battery of node j to receive the data from node k by $P_{\mathrm{Rx},kj}$, then the energy consumed by j to receive the data from k is given by $S_T \cdot P_{\mathrm{Rx},kj}/R_{kj}$. Similarly, denoting by $P_{\mathrm{Tx},kj}$ the power drained by the battery of node k to transmit the data to node j, then the energy consumed by k to transmit the content to j is given by $S_T \cdot P_{\mathrm{Tx},kj}/R_{kj}$. It should be noted that $P_{\mathrm{Tx},kj}$ can be expressed as:

$$P_{\mathrm{Tx},kj} = P_{\mathrm{Tx}_{\mathrm{ref}},kj} + P_{t,kj} \tag{1}$$

where $P_{\mathrm{Tx}_{\mathrm{ref}},kj}$ corresponds to the power consumed by the circuitry of node k during transmission on the communication interface with node j, and $P_{t,kj}$ corresponds to the power transmitted over the air interface on the link from node k to node j. Thus, the purpose of this paper is to minimize the energy drained from the batteries of the SNs, which is not to be confused with the transmission power.

The energy consumed in the non-collaborative scenario, with each RN transmitting its data independently to the BS, is given by:

$$E_{\mathrm{no-coop}} = \sum_{k=1}^{K} S_T \cdot \frac{P_{\mathrm{Tx},k0}}{R_{k0}} \tag{2}$$

In the collaborative case, with node j_k^* selected to relay the data of triplet $\mathcal{T}_k$ to the BS, the energy consumption is expressed as follows:

$$\begin{aligned} E_{\mathrm{coop},\mathcal{T}_k} = {} & S_T \cdot \sum_{j\in\mathcal{T}_k, j\neq j_k^*} \frac{P_{\mathrm{Tx},jj_k^*}}{R_{jj_k^*}} + S_T \cdot \sum_{j\in\mathcal{T}_k, j\neq j^*} \frac{P_{\mathrm{Rx},jj_k^*}}{R_{jj_k^*}} \\ & + 3S_T \cdot \frac{P_{\mathrm{Tx},j_k^*0}}{R_{j_k^*0}} \end{aligned} \tag{3}$$

where the first term corresponds to the energy consumption for transmission to j_k^* on the SR, the second term corresponds to the energy consumption for reception by j_k^* on the SR, and the last term corresponds to the energy consumption for transmission of the aggregated data by j_k^* to the BS on the LR (the multiplication by 3 refers to the transmission of the S_T bits of each of the nodes k, $k+1$, and $k+2$).

Hence, the total energy consumption in the collaborative scenario is given by:

$$\begin{aligned} E_{\mathrm{coop}} &= \sum_{k;k \mod 3=1} E_{\mathrm{coop},\mathcal{T}_k} \\ &= \sum_{k;k \mod 3=1} S_T \cdot \\ & \left(\frac{3P_{\mathrm{Tx},j_k^*0}}{R_{j_k^*0}} + \sum_{j\in\mathcal{T}_k, j\neq j_k^*} \frac{P_{\mathrm{Tx},jj_k^*} + P_{\mathrm{Rx},jj_k^*}}{R_{jj_k^*}} \right) \end{aligned} \tag{4}$$

To minimize the energy consumption within each triplet (3), it can be easily shown that j_k^* should be selected to satisfy:

$$j_k^* = \arg\min_{j\in\mathcal{T}_k} \left(\sum_{a\in\mathcal{T}_k, a\neq j} \frac{P_{\mathrm{Tx},aj} + P_{\mathrm{Rx},aj}}{R_{aj}} + \frac{3P_{\mathrm{Tx},j0}}{R_{j0}} \right) \tag{5}$$

The selection of j_k^* according to (5) can be done either in a centralized way by the BS or in a distributed way by the RNs. In the centralized case, the RNs need to exchange channel state information (CSI) about the SR rates and send it to the BS, which makes the decision and informs it to the RNs. In the distributed case, the RNs need to exchange information about their LR rates R_{j0} and implement the calculation in (5) accordingly. To avoid this overhead, a suboptimal selection is suggested as follows:

$$j_k^* = \arg\min_{j\in\mathcal{T}_k} R_{j0} \tag{6}$$

The solution in (6) does not require the exchange of any CSI information between RNs. The BS is aware of the LR data rates R_{j0} via CSI feedback, which is common in state-of-the-art wireless communication systems. Hence, it can simply select the RN having the highest achievable rate in the triplet, which will consequently minimize the last term of (3) if the RNs have similar characteristics (same $P_{\mathrm{Tx},j0}$, which is valid when similar RNs are used, as is the case in practice). This term leads to the highest energy consumption since it corresponds to the transmission of the aggregated triplet data over relatively long distances. In the simulation results, the suboptimal approach of (6) is compared to the optimal solution of (5) in addition to the non-collaborative case.

3.1 Throughput Calculations

Given for each node: the transmit power $P_{t,kj}$ that node k is using in order to transmit to node j, the channel gain H_{kj} of the channel between k and j, and the thermal noise power σ^2, the received signal-to-noise ratio (SNR) γ_{kj} on the link between k and j can be calculated following $\gamma_{kj} = \frac{P_{t,kj}H_{kj}}{\sigma^2}$. Given the target bit error rate P_e and the SNR, the bit rates on the link between any two nodes k and j can be calculated as follows:

$$R_{kj} = W_{kj} \cdot \log_2(1 + \beta\gamma_{kj}) \tag{7}$$

In (7), W_{kj} is the passband bandwidth of the channel between k and j, and β is called the SNR gap. It indicates the difference between the SNR needed to achieve a certain data transmission rate for a practical M-QAM system and the theoretical Shannon limit [6]. It is given by: $\beta = \dfrac{-1.5}{\ln(5P_e)}$. The channel gain is expressed as:

$$H_{kj,\mathrm{dB}} = (-\kappa - \upsilon \log_{10} d_{kj}) - \xi_{kj} + 10\log_{10} F_{kj} \tag{8}$$

In (8), the first factor captures propagation loss, with d_{kj} the distance between nodes k and j, and υ the path loss exponent. The second factor, ξ_{kj}, captures log-normal shadowing with a standard deviation σ_ξ, whereas the last factor, F_{kj}, corresponds to Rayleigh fading (generally considered with a Rayleigh parameter b such that $E[b^2] = 1$).

4. RESULTS AND DISCUSSION

The simulation model consists of a BS receiving the transmissions of RNs, which in turn are relaying the transmissions of the sensing module in the water pipe. Practical guidelines consist of selecting a pipe trench of around 1 km in length to investigate water leakage, with RNs placed at distances $d_R = 50$ meters. Hence, in the simulations, we consider a

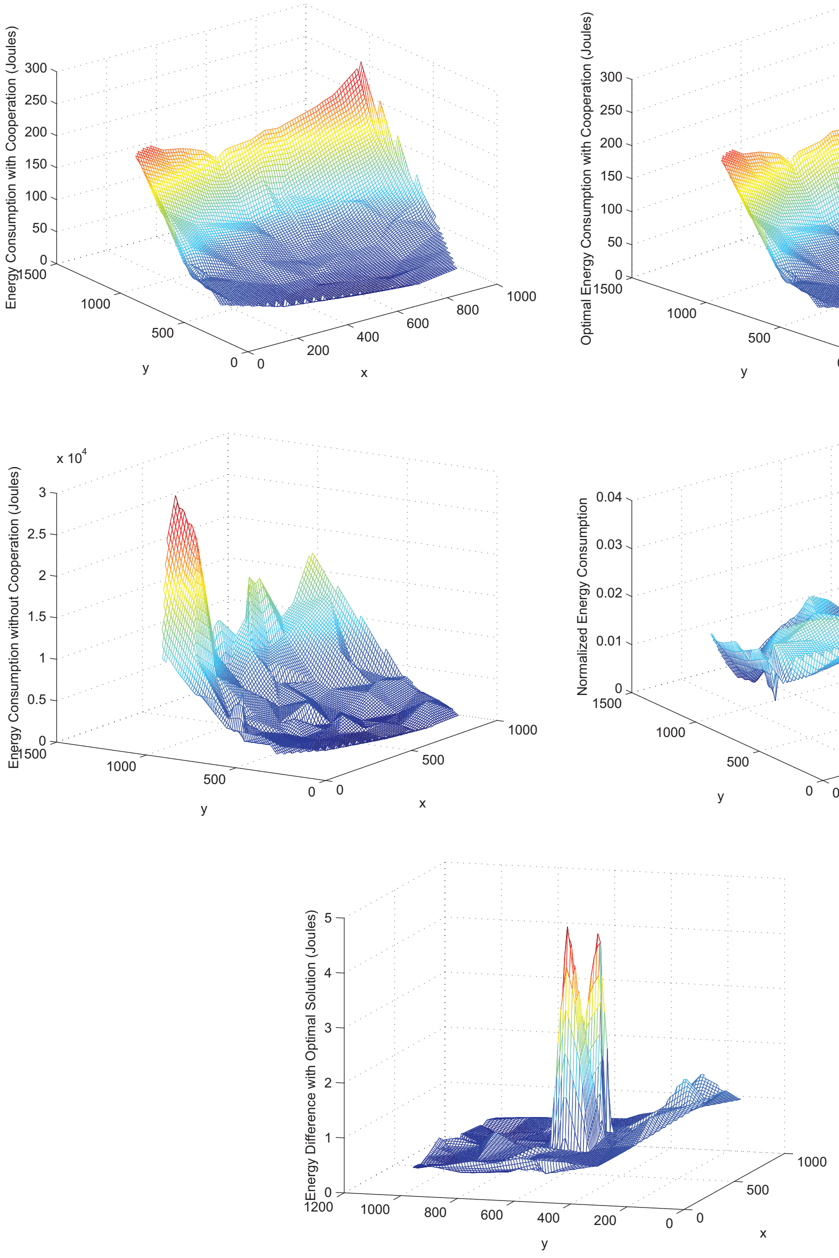

Figure 2: Energy Results versus BS position. Upper Left: Cooperative suboptimal method. Upper Right: Cooperative optimal method. Middle Left: Non-cooperative case. Middle Right: Energy efficiency (ratio of the energy in the upper left to that in the middle left). Lower Figure: Optimality gap between the optimal and suboptimal collaborative methods.

1 km pipe along the x-axis with $K = 21$ RNs (50 m separation over 1 km with one RN at position $(0, 0)$). The leakage might occur at any trench of the pipe and hence the cellular BS serving the location of a trench where leakage occurred might be at a different distance from the pipe than the BS serving another trench. Hence, we investigate the performance for a range of practical positions of the pipe with respect to the position of the serving BS, with coordinates $(X_{\mathrm{BS}}, Y_{\mathrm{BS}})$, by considering the range $0 \leq X_{\mathrm{BS}} \leq 1000$ m, and $100 \leq Y_{\mathrm{BS}} \leq 1100$ m (to make the BS at least 100 m away from the pipe).

The RN transmit power is set to 125 mW. Channel parameters are obtained from [1], whereas energy consumption parameters are taken as in [8]: we set $\kappa = -128.1$ dB, $\upsilon = 3.76$, $\sigma_\xi = 8$ dB, $P_{\mathrm{Tx},k0} = 2.5$ Joules/s, $P_{\mathrm{Tx},kj} = 1.425$ Joules/s and $P_{\mathrm{Rx},kj} = 0.925$ Joules/s, for all $k > 0$ and $j > 0$. The results are averaged over 2500 iterations: 50 shadowing iterations, and 50 fading iterations for each shadowing iteration. We set $S_T = 1$ Mbits.

4.1 Energy Results

Fig. 2 shows the energy results. The upper left part shows

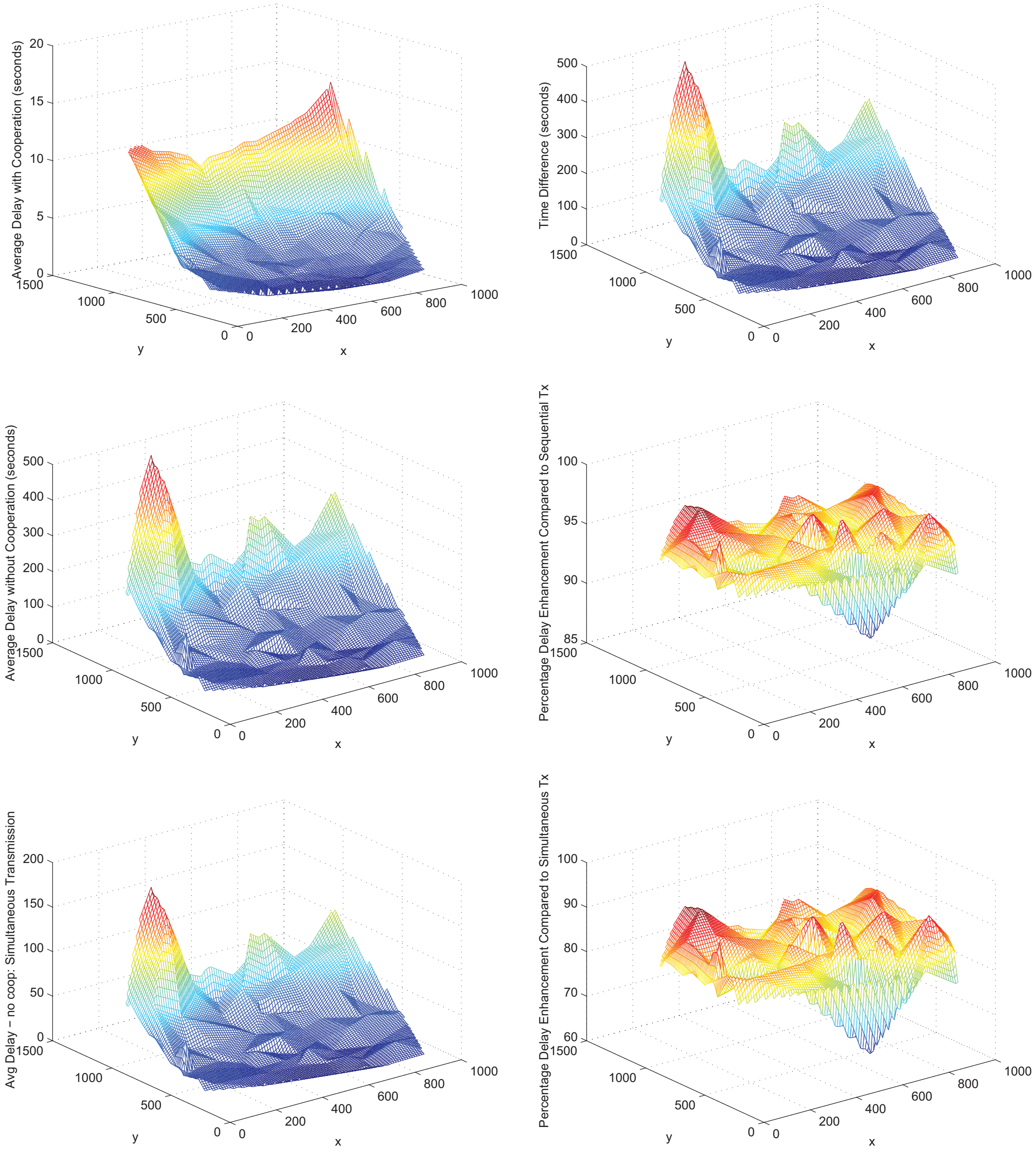

Figure 3: Delay Results versus BS position. Upper Left: Cooperative suboptimal method. Upper Right: Difference in delay between the non-cooperative case and the proposed approach. Middle Left: Non-cooperative case with sequential transmission. Middle Right: Percentage of delay enhancement due to cooperation (upper left compared to middle left). Lower Left: Non-cooperative case with simultaneous transmissions per triplet. Lower Right: Percentage of delay enhancement due to cooperation (upper left compared to lower left).

the energy consumption of the K RNs when the method of (6) is implemented, the upper right part shows the optimal energy consumption of the K RNs when (5) is implemented, whereas the middle left part shows the energy consumption in the non-collaborative case. Savings of orders of magnitude can be seen. In fact, the energy efficiency, defined as the ratio of energy consumption in the collaborative case to that in the non-collaborative case, is plotted in the middle right part. Thus, a successful collaboration leads to a value lower than 1 for the efficiency. Clearly, Fig. 2 shows that huge savings are achieved for all the BS positions in the investigated area.

Fig. 2 shows that the optimal solution leads to a plot having an appearance very similar to the suboptimal case shown in the upper left part of Fig. 2. Hence, we plot the energy difference between the suboptimal approach of (6) and the optimal solution of (5) in the lower part. It can be seen that the differences are very small (a few extra Joules consumed by the suboptimal approach). In fact, they are negligible (less than one) for most of the BS positions, except when the

BS is located around the position ($X_{\mathrm{BS}} = 500, Y_{\mathrm{BS}} = 500$). In this region, the distances from the BS to all RNs are comparable. Hence, the differences in LR rates are expected to be lower than when the BS is at other positions. This makes the differences in the SR energy consumption, taken into account in the optimal solution (5), more important in determining the energy minimizing solution, although huge savings are achieved by the suboptimal approach, as shown in the middle right figure.

4.2 Delay Results

Fig. 3 shows the delay results. We assume that all RNs in a triplet finish receiving their data from the sensing module before the transmission starts. The following scenarios are considered:

- The upper left part shows the average delay when the method of (6) is implemented. In this scenario, one channel is used by each triplet to transmit the data on the LR. The optimal solution of (5) leads to similar performance.
- The middle left part shows the delay in the non-collaborative case, assuming sequential transmission: RNs take turns in transmitting their measured data, starting from node 1 to node K. Hence, one LR channel is occupied at a time, similarly to the suboptimal case of the upper left.
- The lower left part of Fig. 3 shows the non-collaborative delay results, assuming simultaneous LR transmission of the RNs of the same triplet, over three orthogonal LR channels. Although the previous case (middle left) is fair in terms of LR channel occupation compared to the collaborative case, it might be argued that this not the case for the SR. In fact, the non-collaborative case does not use any SR channels, conversely to the proposed method that uses two orthogonal SR channels in addition to the LR channel.

Fig. 3 shows that huge reductions in delay can be achieved by the proposed approach, compared to both non-collaborative scenarios (middle left and lower left). In fact, the middle and lower right parts of Fig. 3 show the percentage reduction in delay due to the proposed suboptimal approach, compared to the non-cooperative case with sequential and simultaneous RN transmissions in each triplet, respectively. Enhancements from 65 to 90% can be reached compared to simultaneous transmission, and these enhancements reach 85 to 95% compared to the scenario of sequential transmission.

5. CONCLUSIONS

Wireless sensor networks for leakage detection were considered. The sensing module is assumed to communicate with relay nodes, relaying its measured data to a base station. An energy-efficient communication approach based on the cooperation between relay nodes was proposed. The optimal energy minimizing solution was derived in addition to a practical low complexity method with reduced overhead. Both the optimal and suboptimal methods showed significant energy savings compared to the non-collaborative case. Furthermore, the suboptimal approach performed closely to the optimal solution. In addition to energy savings, considerably shorter delays were achieved during data transmission with the proposed approach.

6. ACKNOWLEDGMENTS

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