NODE PLACEMENT IN LINEAR WIRELESS SENSOR NETWORKS

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ABSTRACT

A Wireless Sensor Network (WSN) for structural health monitoring (SHM) of bridges is considered. SHM applications tend to produce high volume of sensing data and WSNs require considerable amount of energy to transmit them along the length of a bridge, which highly affect the lifetime of battery-run sensor nodes. Moreover, in such multi-hop linear network topologies some sensors have to handle more traffic than others. As a result, their energy may drain out faster, these sensors die and the network become disconnected. In this paper we propose a methodology for optimum placement of sensor nodes in linear network topologies (e.g., along the length of a bridge) that aims to minimize the link connectivity problems and maximize the lifetime of the network. Both simple packet relay and network coding are considered for the routing of the collected data packets towards two sink nodes positioned at both ends of the bridge. Our mathematical analysis, verified by simulation results, shows that the proposed methodology can lead to significant energy saving and prolonged network lifetime.

***Index Terms*—** network coding, structural health monitoring, wireless sensor networks, energy efficiency

1. INTRODUCTION

Structural Health Monitoring (SHM) systems are dealing with the monitoring and inspection of structures (such as, buildings, bridges, tunnels, water pipes etc.) in order to detect any damages or changes that may affect their performance. These systems measure and collect a variety of information such as temperature, humidity, strain, vibrations, etc. Based on these data, civil-engineers can localize and evaluate the severity of any potential damage, estimate the remaining lifetime and make decisions on further safety plans for the structure. The sampling rate of the monitoring process depends on the structure and the properties of the monitored values. For instance, vibrations on a bridge can change in fractions of second, which requires a very high sampling rate and data traffic volume.

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In the past wired sensing systems (such as piezoelectric accelerometers wired to PCs) were used for monitoring. Such wired systems, although they can support high data capacity and reliable data transfer, they are expensive, hard and time consuming to mount and maintain, and not scalable for structures that require very dense monitoring. This is why nowadays most of these systems are replaced with Wireless Sensor Networks (WSN). Wireless networks are cheaper, easier to deploy, maintain and replace. They are not intrusive, they integrate well with the infrastructure and due to their scalability they can assure complete and dense coverage of most infrastructures.

On the other hand the main drawbacks of the WSN as compared to the wired monitoring systems are their limited energy supply and data transmission reliability. Usually the wireless sensors depend on batteries and therefore have limited energy supply which results to sensing or communication failure when batteries drain out. The limited energy is split between sensing and communicating. Since the sensing energy requirements are bounded by the underling SHM application, the focus of our work is to minimize the energy consumption required for the communications in the sensor network. Moreover the limited communication bandwidth, interference and wireless channel variations may result to low data transmission rates and loss of data packets. A conventional way to deal with high data volumes and low transmission rates in WSN is data aggregation and compression. However, such techniques may result in data distortion and therefore they are not suitable for SHM application where data reliability is of paramount importance. To overcome this problem, in our previous works [1][2] we proposed a network coding based protocol for wireless sensor networks for structural health monitoring of bridges. Network coding increases the transmission rate without distorting the data and decreases the number of data transmission, and therefore the energy consumption throughout the network. However, due to the linear type of the network topology some sensors have to handle more traffic than others. As a result, their energy drains out faster, these sensors die and the network become disconnected. Although this can be resolved by asking sensors to increase their transmission power to preserve the connectivity, this will increase the overall energy consumption and decreases the network lifetime.

Linear wireless network topologies have been of increased research interest due to their simplicity that allows them to be used as a first step to understand, compose and analyse more generic network architectures. A heuristic "level-based" scheduling algorithm that assigns the minimum number of conflict-free slots for packets transmission from each sensor node to their destination (a known NP-complete optimization problem) is proposed in [5]. The original network is first transformed to a linear network where each node corresponds to a "level" in the original network. The schedule of the original network is then obtained based on the coloring of the linear network. In [6] , the lower bound on the number of timeslots required to complete convergecast in a TDMA based linear network of N nodes is shown to be $3N - 3$. The authors also propose an TDMA scheduling algorithm that can achieve convergacast in $3N - 2$ slots. Authors in [7] investigate the power consumption and bandwidth usage for information exchange between two terminal nodes in a linear wireless ad hoc network, and propose a joint network coding and adaptive power control scheme which regulates the transmission power to reduce the overall energy usage and to increase the bandwidth efficiency.

While the focus of the aforementioned works was on the optimization of various objectives, such us fault tolerance, network coverage and connectivity, network lifetime, load balancing, energy and delay efficiency, all of them consider a prearranged network topology. In this work we propose a solution to the uneven data traffic distribution problem which creates discontinuities in the network by optimizing the positions of sensor nodes (i.e., the distribution of the sensors on the bridge). In this way we maximize the total volume of data traffic that can be processed and maximize the overall lifetime of the network. More specifically we develop a numerical solution that calculates the required number of sensors and their optimum positioning over a bridge given the length of the bridge and the required data throughput. Our numerical and simulation results indicate that he proposed method can prolong the network lifetime by up to 25% while at the same time eliminates any discontinuities due to nodes failure.

The remaining of this paper is organized as follows. In Section 2 the system model is described followed by the numerical analysis in Section 3. In Section 4 numerical and simulation results are presented following by conclusions and in Section 5.

2. SYSTEM

2.1. Network Topology

Let us consider a linear wireless sensor network topology comprises a set of identical sensor nodes (in terms of current, voltage, computational and communication capabilities), deployed over a bridge. Two sink nodes (i.e., the nodes which aggregate the information generated by the whole network and serve as a gateway to the Internet) are placed at the two ends of the line. All sensor nodes are collecting information related to the structural health of the bridge periodically and transmit this information to both sink nodes. Since SHM applications require high reliability in terms of packet error, the transmission to both sinks will provide redundancy against packet loss due to wireless channel, interference or other network failures. The cost of using two sink nodes is low given the significance of reliable data collection which is vital in case of infrastructure failure.

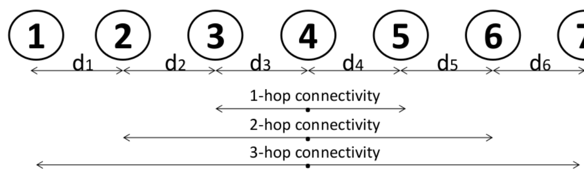

Fig. 1. 1-hop, 2-hops and 3-hops connectivity cases in a linear network topology.

In order to maximize the operational life time of the sensor nodes which have limited energy, sensors need to transmit their data at a limited power and hence form a multi-hop network [4]. Based on the transmission power, let us consider three different network connectivity cases: 1-hop, 2-hop and 3-hop connectivity and let us further assume omnidirectional transmissions. More specifically, in the 1-hop case, each node sets its transmission power level so that only the first neighbour can decode its packets. For instance in Figure 1, if the node with ID 4 transmits, nodes 3 and 5 can decode the message. In the 2-hop case, node 4 further increases its transmission power so that nodes 2 and 6 can also decode its message. Finally, in the case of 3-hop receiving, nodes 1 and 7 can also decode the message sent by node 4.

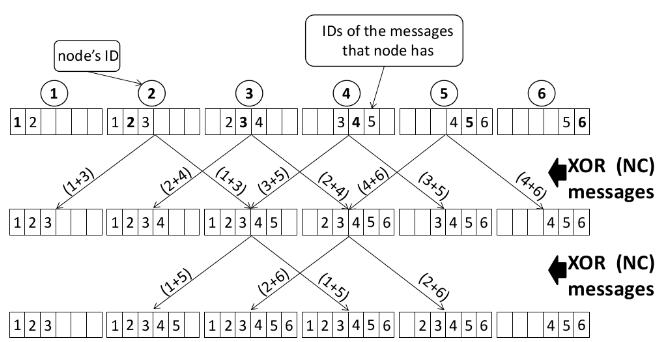

Fig. 2. Network coding based algorithm, for the 1-hop connectivity case - nodes can decode messages from its first neighbours only.

2.2. Network Coding Algorithms

For our analysis we consider the network coding algorithm introduced in our previous work [1] that enables wireless sensors to take XOR network coding [5] decisions by encoding and decoding packet transmitted from their neighbors. We briefly describe the algorithm in the following. For simplicity let us consider the 1-hop connectivity case, where time division multiple access (TDMA) with frequency reuse among distant transmissions is used for sensor nodes to transmit packets to their one-hop neighbors. In the first step, each sensor node performs sensing, generates a data packet with the SHM information and broadcasts the packet. Sensor nodes will receive the transmitted packets from their 1-hop neighbors and will store them in their buffers together with their own generated packet. This is depicted in first row of Figure 2, where each node has buffered the packets from its immediate neighbors. For instance, the buffer of node 3 contains its own message and two messages from its immediate neighbors, i.e., nodes 2 and 4. In the second step, each node performs encoding by applying the XOR operation between packets received from its immediate neighbors in the previous round, and broadcasts the XOR-coded packet. For example, in the second row of Figure 2, node 4 combines packets-3 and 5, and broadcasts the XOR-coded packet to nodes 3 and 5. Node 3 performs an XOR operation again over the received packet and the already obtained packet-3 and decodes packet-5. In a similar manner, node 5 performs XOR decoding over the received packet and its own packet-5 and obtains the packet-3. In the next step, nodes receive, encode and decode the obtained packets from their second-hop neighbors, as shown in the last row of Figure 2, and so on. This process continues until all the packets reach both sink nodes at the edges of the line/bridge. The algorithm operates in a similar way in the 2-hop and 3-hop case as it explained in [1]. It worth mentioning that higher degree of connectivity may require additional power consumption per transmission but on the other hand it provides more opportunities for network coding.

2.3. Channel Model

In our analysis we consider interference limited wireless channels (i.e., the interference power is much higher than the noise level, therefore the noise can be neglected) and we use the Shannon capacity formula [3] to define the wireless link data rate

$$C = B\log_2(1 + SINR), \tag{1}$$

where C is the links capacity in bits/sec/Hz, B is the channel bandwidths in Hz, and $SINR$ is the Signal to Interference plus Noise Ratio. We moreover consider frequency reuse factor of 3, i.e., we allow sensors that are located three times the transmission range away to transmit at the same time. For instance, in the 1-hop connectivity case, nodes that are located three hops away may share the same timeslot. Similarly, in the 2-hop and 3-hop connectivity cases, nodes that are six and nine hops away, respectively, will transmit at the same timeslot. Finally, we consider interference only from the closest interfering node. For instance, in the 1-hop connectivity case, we only consider interference from the sensor which is located two hops away from the receiver and we ignore the interference from the sensor which is located four hops away or any other more distant transmissions. The receiving power of node j is given by $P_{r,j} = P_{t,i}d^{-\gamma}$ where $P_{t,i}$ is the transmitting power from node i, d is the distance between transmitter and receiver and γ is the path-loss exponent, with a value between 2 and 5. The considered SINR is given by

$$SINR = \frac{P_{r,i}}{\Sigma P_{r,j}} = \frac{P_{r,i}}{P_{r,I}}. \tag{2}$$

3. NUMERICAL ANALYSIS

Let us denote by E_{tot} the total energy allocated for data transmission and all nodes initially have the same amount of energy available for the communication. The total energy spend for transmission by node i is given by

$$E_{tot} = P_{t,i}N_{t,i} \tag{3}$$

where $N_{t,i}$ is the total number of transmissions from node i, given by

$$N_{t,i} = \begin{cases} \lceil \frac{i}{h} \rceil, & \lfloor \frac{N}{2} \rfloor < i < N \\ \lfloor \frac{N-i}{h} \rfloor + 1, & 1 < i < \lfloor \frac{N}{2} \rfloor \\ 1, & otherwise \end{cases} \tag{4}$$

The hop factor h can take values 1,2,3 for the 1-hop, 2-hop and 3-hop cases respectively. N denotes the total number of sensors deployed on the bridge, and i is index of the observation node ($i = 1, .., N$). Since nodes located at the center of the bridge will have to relay more packets than those located towards the edges, if all nodes transmit at the same power, nodes at the center will drain out of energy and die quicker and the network will become disconnected. Therefore, nodes at the center must transmit at lower power as compared to the nodes towards the edges. At the same time, as equation (1) indicates, the transmission power affects the data rate of the wireless links. Since we require all nodes to transmit at the same data rate, the distance between nodes at the center must be smaller as compared to the distance of the nodes closer to the edges. In order to account for the aforementioned issues we impose the following two conditions in the network:

- **C1**: All nodes must drain out of energy at the same time. In this way the network will remain connected until the end. In other words, $E_{tot,i} = E_{tot,j}, \forall i, j$.
- **C2**: All sensor nodes must transmit at the same data rate. In this way we avoid any bottleneck in the data

flow and we ensure the availability of packets for network coding. In other words, $C_i = C_j \Rightarrow SINR_i = SINR_j, \forall i, j$.

In the following we calculate the optimum position of the sensor nodes such that the conditions **C1** and **C2** hold. **C2** requires the $SINR$ to be the same for all transmissions, which can be presented as

$$SINR = 2^{C/B} - 1 = \frac{P_{t,s} d_s^{-\gamma}}{P_{t,I} d_I^{-\gamma}} = \frac{N_{t,I}}{N_{t,s}} \left(\frac{d_I}{d_s} \right)^{\gamma} \Rightarrow$$

$$d_I - d_s \sqrt[\gamma]{(2^{(C/B)} - 1) \frac{N_{t,s}}{N_{t,I}}} = 0 \qquad (5)$$

Equation (5) can be generalized as:

$$d_j - d_{j-1} \sqrt[\gamma]{(2^{(C/B)} - 1) \frac{N_{j-1}}{N_{j+1}}} = 0, \qquad (6)$$

where j can be any node with ID $j = 2, 3 \ldots N - 1$. Similarly, if the interference comes from the left side, and useful signal comes from the right side, we have:

$$d_{j-1} - d_j \sqrt[\gamma]{(2^{(C/B)} - 1) \frac{N_{j+1}}{N_{j-1}}} = 0 \qquad (7)$$

The final constraint is related to total number of sensor nodes required to cover the whole length of the bridge (denoted by L)

$$\sum_{j=1}^{N-1} d_j = L \qquad (8)$$

If we solve this set of equations, we can obtain the recommended layout of nodes on the bridge. Following the same principle, in a general case we have

$$\sum_{k=1}^{h} d_{j-k} - d_j \sqrt[\gamma]{(2^{(C/B)} - 1) \frac{N_{j+1}}{N_{j-h}}} = 0, \qquad (9)$$

where $j = h + 1, \ldots N - 1$. For $j = 2, \ldots N - h$,

$$\sum_{k=0}^{h-1} d_{j+k} - d_{j-1} \sqrt[\gamma]{(2^{(C/B)} - 1) \frac{N_{j-1}}{N_{j+h}}} = 0. \qquad (10)$$

Solution of the set of equations that is defined by (8), (9) and (10) provides the optimum distribution of sensor nodes on a bridge such that the bottlenecks are eliminated and the network lifetime is maximized. This set of rules can serve as indicators during the sensor network deployment.

4. NUMERICAL RESULTS

Extensive simulation has been performed to verify the correctness of our numerical analysis and assess the performance improvement of the proposed network deployment rules. Each node is equipped with the AA alkaline battery (current I = 1700 mAh and voltage U = 1.5V) that is commonly used for EYESIFXv2 sensor nodes. The transmitting unit of these nodes in low power mode uses the following set of values for current I = $\{4.1\ 4.9\ 6.8\}$ mA, and I = $\{9.4\ 11.9\ 14.6\}$ mA in the high power mode. The available voltage values are U = $\{2.1\ 3\ 5\}$ V. The receiving unit of these nodes uses the current of I = $\{9\ 9.5\}$ mA and voltage of U = $\{3\ 5\}$ V. We set the path loss exponent γ to 3, which is a value commonly used the given environment. We assumed the packet length of 128 Bytes, and the link capacity of 250kbps. The bridge we observe is 1km long. The transmission power is adjusted for each x-hop connectivity case such that we achieve a given receiving SINR (and therefore uniform link capacity) value throughout the network. The proposed scheme was tested for different number of nodes and connectivity cases to understand how different factors affect the lifetime of the network. We assume that the battery drainage is the primary cause of early dying nodes.

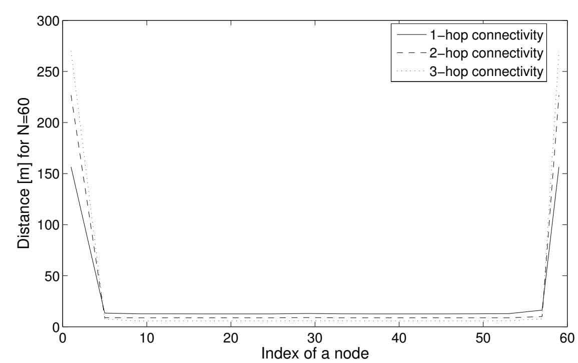

Fig. 3. Distribution of distances between adjacent nodes for a network of 60 nodes.

Figure 3 depicts the distribution of the distance between adjacent nodes in a linear network of 60 sensor nodes for different connectivity cases. The positioning of the nodes has been optimized given the underlying network coding algorithm and according to the proposed rules in order to maximize the network lifetime. We can observe that nodes located closer to the edges are mainly affected by the optimization and need to be placed far apart, while the distances between nodes towards the center are almost uniform and nodes are located closer to each other. This is because nodes in the middle of the bridge suffer of more interference and also need to encode/relay more data packets as compared to nodes towards the edges (due to the two way traffic). Figure 4 demonstrates the distribution of the distances between adja-

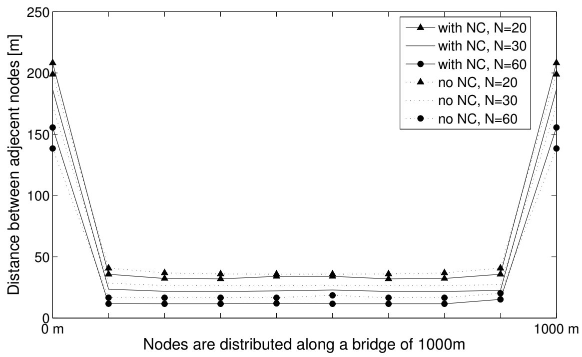

Fig. 4. Distribution of distances between adjacent nodes for networks of various numbers of sensor nodes.

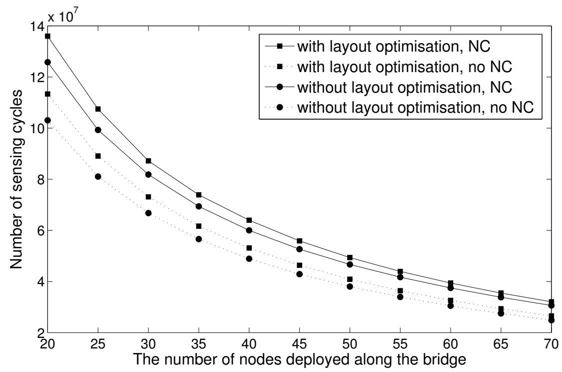

Fig. 5. Lifetime of a single-line, 1-hop network versus the total number of sensors in the network, with and without topology optimization.

cent nodes for different total number of nodes deployed in the network, when network coding or simple-data-relaying is considered. It is evident from this graph that in simple-data-relaying based networks, nodes towards the edges must be located closer and nodes towards the center more far apart, as compared to the corresponding positioning in network-coding based networks. This is because the overall number of packet transmissions is reduced when network coding is considered and the pattern of packet transmissions throughout the length of the linear network changes due to packet coding.

The main objective and contribution of our proposed optimization scheme was to maximize the life time of the linear sensor network. This is highlighted in Figure 5 where the lifetime (in terms of number of sensing cycles) of the 1-hop linear sensor network is presented as a function of the total number of nodes in the network, with and without network coding, and with and without optimized positioning. A sensing cycle includes the data collection and packet (re)transmissions, until the packet is received by both sinks. It is important to observe that the main saving in energy comes from the use of network coding, i.e., network coding with uniform node distribution will provide longer network lifetime compared to simple-data-relaying and optimized node positioning. Nevertheless, it is also become evident from this graph that our optimization scheme prolongs the network lifetime and that the combination of network-coding with optimized node positioning will provide the best performance in terms of energy saving. More specifically, for the 20-nodes network case, the combination of network coding with optimized node placement prolongs the network lifetime by 25%. This benefit becomes less obvious for denser networks. This is due to our assumption that all nodes operate as sensors and generate their own date. Therefore, in a denser network the amount of generated data packets increases linearly with the total number of nodes.

5. CONCLUSIONS

In this paper we presented a method for optimum sensor node placement in linear network-coding based networks that maximizes the operational lifetime of the network. More specifically we developed a numerical solution that calculates the required number of sensors and their optimum positioning of the sensors over a bridge given the length of the bridge and the required data throughput. Our numerical and simulation results indicate that he proposed method prolongs the network lifetime by up to 25% while at the same time eliminates and bottlenecks.

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