

Application of Network Coding in Wireless Sensor Networks for Bridge Monitoring

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Abstract— Wireless Sensor Networks (WSNs) have been deployed for the purpose of structural health monitoring (SHM) of bridges. SHM applications can potentially produce a very high volume of sensing data, which consumes much transmission power and thus decreases the lifetime of battery-run networks. We employ the network-coding technique to improve network efficiency and prolong its lifetime. By increasing the transmission power, we change the node connectivity and control the number of nodes that can overhear transmitted messages so as to hopefully realize the capacity gain by use of network coding. We propose here to control transmission power as a means to adjust the number of nodes that can overhear a message transmission by a neighboring node. However, too much overhearing by high power transmission consumes too much limited battery energy. We investigate the interplay between transmission power and network coding operations. We show that our solution reduces the overall volume of data transfer, thus leading to significant energy savings and prolonged network lifetime. We present the mathematical analysis of our proposed algorithm. By simulation, we study the tradeoffs between overhearing and power consumption for the network-coding scheme. Specifically, we consider a bridge with fixed length and sensor nodes are deployed at a uniform distance along one or both sides of the bridge. Our numerical results reveal that appropriate choices of transmission power can achieve the optimal extent of overhearing for network coding gain, while minimizing the overall power consumption for the WSN.

Index Terms— network coding, transmission power, structural health monitoring, wireless sensor networks

I. INTRODUCTION

Structural Health Monitoring (SHM) systems evaluate the reliability of civil-engineering infrastructures (e.g., bridges and high-rise buildings) and track their conditions in real-time. The purpose of SHM is to detect and localize damage, to evaluate the severity of damage, and to predict the remaining lifetime of the infrastructure. Recent developments in SHM led to the deployment of Wireless Sensor Networks (WSNs) instead of wired sensing systems. It is cheaper, easier and quicker to use WSN than wired sensor network. Nodes are not intrusive and they easily integrate with most structures. WSN systems are scalable to a large number of nodes as compared to the wired sensor networks which are restricted. This allows dense coverage of infrastructure systems; however the nodes' power supply is often internal and limited. In addition to limited power supply, WSNs introduce a variety of limitations for system designs such as limited bandwidth and high packet loss rate. The main objective of SHM systems is to provide high quality data. Based on those data, the structure

quality is assessed and further decisions concerning infrastructure safety are made by civil engineers. Data sampling should be performed simultaneously at all nodes. In addition, the sampling rate should be high because the measured vibrations in a structure change quickly. Due to the high sampling frequency, the traffic load of raw data is very high, and it is recommended to decrease the volume of data prior to transferring them to the data sink node. However, data processing should not harm the fidelity of data because that would directly degrade the sensitivity of SHM. The performance of a SHM system depends on the quality of data received at the sink and the packet loss rate. Thus, SHM's goal is reliable and lossless communication over potentially a large span network. It is essential to decrease data overhead as much as possible and carefully use scarce network resources. Data aggregation techniques are not the best solution for SHM. They are frequently based on averaging, minimizing or maximizing the value of all received messages. In monitoring infrastructure, it is important to deliver accurate information to civil engineers so they can make the best decision. In typical aggregation, some information is lost. A good way to preserve original sensed data yet decrease the volume of data is to deploy network coding. The idea of network coding is to allow the coding of data at intermediate nodes and forward coded packets, each of which is generated by combining and encoding more than one packets received from possibly multiple sources. The simplest encoding scheme is the XOR operation applied to each corresponding bits of two packets of the same size. In traditional routing schemes, nodes forward data packets from each neighboring node towards the sink separately. Let us observe the communication between nodes A and B, via relay node R (the top part of Figure 1). Firstly, node A sends its message (A) to the relay node R, which forwards the message (A) to the node B. In the third time slot, the message from node B, labeled as (B), is sent to the relay node R, and then it is forwarded to the node A in the fourth

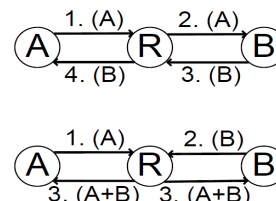


Fig. 1. Nodes A and B are exchanging messages via relay node R. a) Conventional forwarding requires 4 transmissions. b) Network coding based routing requires 3 transmissions.

time slot. The total number of the transmissions needed for this communication is four. However, if both nodes A and B send their messages to the relay node R, in respectively time instances 1 and 2, node R can XOR the received messages and broadcast the coded packet (A+B) in the third time slot (the lower part of Figure 1). Once nodes receive that message, they will be able to XOR it with their own message, and to decode the information sent from the other node. Thus, this approach requires 3 transmissions for the communication with only a small increase in the computation complexity.

The network coding is a useful technique for gaining network efficiency. In order to maximize the throughput of multicast networks, Ahlswede et al. [1] introduces network coding for the first time. They show how to decrease the traffic load by encoding the received messages in intermediate nodes before forwarding them.

II. MOTIVATION

SHM is a very active area of research. Safety and reliability of infrastructure is important for modern society. Collapse of infrastructure has extensive consequences on both finance and quality of life. One of the most vulnerable structures is bridge. We witnessed some recent collapses of bridges, e.g. Minnesota Bridge in 2007 and the Baihe Bridge in 2011 that caused loss of lives, huge financial damage and destruction of normal traffic flow for a long time.

Monitoring of bridges could help to avoid these misfortunate and costly events. Extensive work has been done in various applications of WSNs; however, their application in SHM still needs more attention. There are a number of solutions offered for SHM of bridges. Usually, vibrations are measured. Vibrations can change in the fraction of second, thus, in order to capture that moment, sampling rate must be very high. High sampling rate will cause a need to transfer a massive amount of data. Given the limitations of WSNs, any provided solution must deploy some technique to reduce the amount of data for transfer to the sink nodes. Applied solutions can make use of different forms of data aggregation. However, data aggregation is not necessary the best idea. Data aggregation indeed reduces data volume at the expense of degradation of data quality. In the case of SHM, it is very important to collect non-distorted data. Thus any sort of data aggregation that uses maximization, minimization or averaging is not desirable because the proper operation of SHM systems directly depends on the quality of collected and received data. In order to ensure the desirable operation and outcome of the SHM systems, we choose to apply network coding to reduce the data volume. At a small expense of added computation, we achieve a significant reduction in data volume, while transferring non-distorted data to the sink node.

Due to the specific linear layout of sensor nodes, the SHM of bridges should be studied on its own. In this paper, we present the algorithm that is designed especially for the SHM of bridges, based on network coding. We show that our algorithm achieves a significant improvement in terms of the number of transmitted messages and energy consumption. We show that the increase in transmission power can change not only the

network topology, but also the number of necessary transmissions. We provide the mathematical analysis of our proposed algorithm for different connectivity and layouts of sensor nodes. At the end, by extensive simulations we test the performance of our proposed algorithm.

III. RELATED WORK

Nagajothy et al. [2] investigate the benefits of network coding for enhancing the lifetime of nodes by decreasing the number of transmissions for grid and circular configurations. They study the interplay between the energy and the traffic rate, number and density of nodes. In [3], Hong et al. propose a distributed algorithm for data gathering based on network coding that maximizes the network lifetime. However, in their approach the energy spent for data reception is neglected, whereas they consider that only the energy consumed by transceiver modules contributes to depletion of the initial energy in nodes. Glatz et al. [4] study network coding with low computational power to the butterfly structure. Their method prolongs network lifetime and loosens resource constraints. Glatz et al. [5] design an independent and autonomous network coding layer that is overhead-free. The scheme can be applied to existing applications on the top of current routing mechanisms without changing the application or networking protocol. It is designed to work without centralized control and to conserve up to 29.3 % of the messages that need to be sent. Wang et al. [6] propose an algorithm based on network coding for the 2-hop information exchange in WSN. Their algorithm is tested on both grid and random topology networks, and it achieves better performance when compared to simple forwarding. Sikora et al. [7] consider a WSN with one source node, one sink node, and multiple relay nodes placed equidistantly between them. They optimized the number of hops so as to achieve the lowest total transmission power, under the constraints of total bandwidth and the end-to-end data rate. They perform the optimization with an additional constraint of the end-to-end delay.

To the best of our knowledge, existing research has not considered the joint use of power control and network coding in the WSN used for SHM. Specifically, using bridge monitoring as an example, this paper proposes and investigates the performance tradeoffs of power consumption (and thus network lifetime) and the network coding gain due to increased overhearing by high transmission power. Existing research work cannot be applied directly to bridge monitoring because of the very specific, linear topology of sensor nodes on the bridge.

IV. SCENARIO

It is expected that sensor nodes will be deployed on either both sides of the bridge or on only one side (which is enough for narrow bridges). Thus, nodes will appear in a single line or in double-line. Also, the sink node is likely to be installed at the end of the bridge because it is a convenient place to transfer collected data over the Internet. Since the most important feature of SHM systems is reliability, we consider that sink nodes are placed at both ends of the bridge. That way

we enhance the reliability. In the case of the link loss or strong interference at one of sink nodes, the other sink node will still receive a copy of the missing data. The cost of this is expected to be small when compared to a bridge failure.

We consider two different layouts of sensor nodes at the bridge: a single-line layout and a double-line layout as shown in Figure 2. In the first scenario, each node can communicate with its immediate (one-hop) neighbors on both right and left sides. For example, if node 3 transmits, nodes 2 and 4 receive its message in Figure 2.a. In the double-line scenario, in addition to the immediate neighboring nodes on the same line, each node can additionally communicate with neighboring nodes on the opposite line. We put sink nodes on both ends of each line to provide the redundancy for the SHM in the case of wireless link failures.

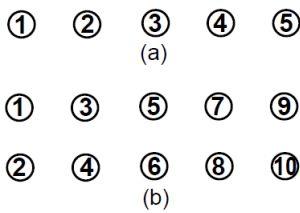


Fig. 2 a) Single-line layout of nodes. b) Double-line layout of nodes.

In addition, three sub-cases are discussed. We say that a node can communicate directly with its immediate neighbors if only one-hop neighboring nodes can be reached directly. For example, when node 2 transmits, and nodes 1 and 3 receive its message in Figure 2.a and correspondingly, nodes 1, 3 and 4 receive its message in Figure 2.b. In this case nodes transmit with the minimum power that is just high enough to maintain network connectivity. We say that nodes can communicate directly with the two-hop neighbors if each node can reach its neighboring nodes located two hops away. For example, when node 2 transmits, nodes 1, 3 and 4 can receive its message in the single-line scenario in Figure 2.a, or nodes 1, 3, 4, 5 and 6 can receive the message in the double-line case in Figure 2.b. If nodes further increase the transmission power, they can achieve three-hop connectivity. For instance, when node 2 transmits, nodes 1, 3, 4 and 5 can receive its message in the single-line scenario in Figure 2.a, or nodes 1, 3, 4, 5, 6, 7 and 8 can receive the message in the double-line case in Figure 2.b. We here propose a network coding algorithm for bridge monitoring. To present a routing algorithm with network coding, we consider the single-line topology (Figure 2.a). We assume that each node has its transmission power adjusted to

communicate only to its immediate (one-hop) neighbors. For simplicity at this point, we also assume that perfect transmission schedule is in use so that message transmissions do not collide and messages can be properly received by their intended receiving nodes. We use an example with a six-node network in Figure 3 to illustrate our routing scheme with network coding. As an initial step, each node performs sensing and creates one packet of sensing data that needs to be transferred to the sink nodes at both ends of the bridge.

The next step is that each node broadcasts its original message. Thus, at this point each node will be aware of its own message and the messages from its immediate neighbors. As shown at the top of Figure 3, each node (with index in boldface) is associated with six rectangles. Each rectangle belonging to a node (say k) shows the index of the source node associated with the message that has been received by node k after each round of message exchanges. For example, after the first round of message exchanges, node 3 has received messages from itself (node 3) and its immediate neighboring nodes 2 and 4, as indicated in the top row of rectangles in Figure 3. In the next step, each node XORs the two received messages just from its two immediate neighbors and broadcasts the coded packet. For example, node 4 XORs messages from nodes 3 and 5, and broadcasts the coded message to nodes 3 and 5. Since node 3 knows its own message, performing an XOR operation on the coded packet from node 4 and the original message of node 3 will enable node 3 to decode the original message from node 5. Similarly, node 3 receives and decodes the original message from node 1 as well. As a result, the original messages that each node now holds after two rounds of message exchanges are shown in the middle row of rectangles in Figure 3. For example, node 3 now holds the original messages of nodes 1, 2, 3, 4 and 5. In essence, after two rounds of message exchanges using network coding, each node possesses the original messages from two-hop neighboring nodes. In essence, each node, excluding the sink nodes, behaves like a relay node for its immediate neighbors, as in Figure 1.a. Each node XORs a broadcasted message received from its two neighbors with a message it already has, as a mean to decode new messages. This process continues until the last round of broadcasting when no node receives more than one coded (XORed) message. The rest of messages can simply be forwarded to the sinks via the nearby nodes. The number of transmissions can be reduced further, if we increase the transmission power. Figure 4 presents the messages possessed by each node after each round of message exchanges for the case of the single-line layout where each node can communicate directly with its two-hop neighbors. Contrast to the case of one-hop direct connectivity, after the initial phase, only nodes that receive the messages from two different two-hop neighbors behave like relay nodes in the first round of network coding. In the first round, they XOR the messages received from the two-hop neighbors. The algorithm continues in the same manner as for the one-hop connectivity. As for the double-line layout, the algorithm does not change. When the transmission power is low and nodes can directly communicate only with their immediate neighbors, each node

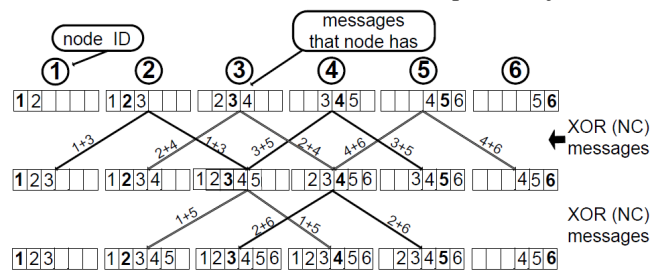


Fig. 3 Network coding based algorithm for the single-line layout, each node can reach its immediate neighbours.

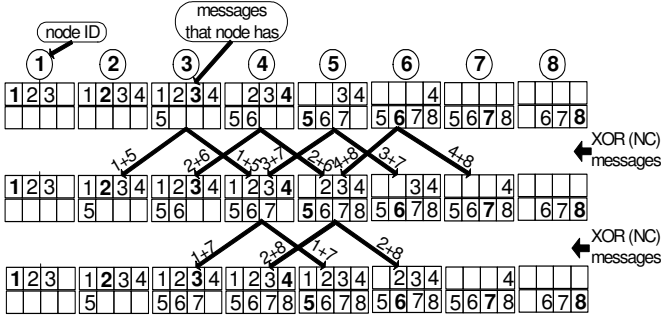


Fig. 4. Network coding based algorithm for single line layout, each node can reach up second immediate neighbor.

XORs and broadcasts messages received in the previous round from its immediate neighbors in the same line. Now, nodes on the other line are able to decode the coded message too due to the overhearing.

V. ANALYSIS OF CODING GAIN AND NUMERICAL STUDY

The total number of transmissions required until information reaches the sink nodes consists of two parts: transmissions of original and coded messages. The greater the proportion of messages is coded, the better the network performance. Not only that network coding reduces energy consumption, it can also improve capacity. Let N be the number of nodes in the network deployed in a single line. Consider that nodes can directly communicate only with their next hop neighbours. The total number of transmissions required to transfer data from all nodes to the sinks is:

$$N_{tr} = \sum_{i=0}^{\alpha} (N - 2i) + 2, \quad (1)$$

$$\text{where } \alpha = \left\lfloor \frac{N}{2} \right\rfloor \text{ and } \beta = \left\lfloor \frac{N-3}{2} \right\rfloor.$$

However, if network coding is not applied, for a transmission of every broadcasted XORed message in the above formula, two transmissions are required. Thus, when network coding is not used, the total number of transmissions increases exactly by the number of transmissions of coded messages. So, without network coding, the total number of transmissions is given by

$$N_{tr} = N + 2 \sum_{i=1}^{\alpha} (N - 2i) + 2 \sum_{i=0}^{\beta} (N - 3 - 2i). \quad (2)$$

However, if transmission power is increased, the number of necessary transmissions will decrease. This is caused by the fact that more nodes overhear others' messages and they do not need any more separate transmissions. However, in this case, a scheduling algorithm must be carefully designed to avoid excessive interference in light of increased transmission power. The increase in transmission power reduces the number of transmissions, but it also consumes more energy. The trade-off between these two factors should be carefully studied. Nevertheless, if network coding is used, and two-hop connectivity is achieved according to our algorithm, the total number of transmissions can be obtained as follows

$$\text{for } N = 4k, \quad N_{tr} = 3 \sum_{i=1}^{k-1} (N - 4i) + N + 2; \quad (3)$$

$$\text{otherwise, } N_{tr} = 3 \sum_{i=1}^k (N - 4i) + N, \quad (4)$$

where $\chi = \left\lfloor \frac{N}{4} \right\rfloor$. Similar to the previous case, the total number

of transmissions without network coding can be easily derived, by doubling the number of transmissions of coded messages:

$$\text{for } N = 4k, \quad N_{tr} = 4 \sum_{i=1}^{\chi-1} (N - 4i) + N + 2; \quad (5)$$

$$\text{otherwise, } N_{tr} = 4 \sum_{i=1}^{\chi} (N - 4i) + N. \quad (6)$$

If we increase the transmission power to the point where the 3-hop connectivity is achieved, the number of transmissions will decrease further. For $N = 6k$ in the case of network coding

$$N = 11 + 6k \quad N_{tr} = \sum_{i=0}^{\phi} (N - 6i) + 2 \sum_{i=0}^{\phi} (N - 6i - 5) + 2, \quad (7)$$

without network coding total number of transmissions is

$$N_{tr} = N + 2 \sum_{i=1}^{\phi} (N - 6i) + 2 \sum_{i=0}^{\phi} (N - 6i - 5) + 2; \quad (8)$$

where $\varphi = \left\lfloor \frac{N}{6} \right\rfloor - 1$ and $\phi = \left\lfloor \frac{N-5}{6} \right\rfloor$. Otherwise, $N_{tr} = N_{tr} - 2$.

Nodes can overhear more transmissions from other nodes in the double-line layout. However, since each node can get only one new packet from each XORed (coded) packet, coding gain will again be limited. Thus, each XORed packet received by the group of nodes must consist of a number of already known packets and one new packet - to be useful. If XORed packet contains two or more new packets for one node, that node is not able to decode any message. Ideally, all nodes from the group of packets that are receiving XORed message can decode a new packet. The coding is optimal when all nodes that overhear encoded message can extract new packet for themselves. If at least one node cannot decode any new packet for itself, coding is sub-optimal. A total number of transmissions in the case that any message can be received only by its immediate neighbours is

$$N_{tr} = \sum_{i=0}^{\alpha_1} (N - 4i) + 2 \sum_{i=0}^{\beta_1} (N - 4i - 6), \text{ for } N \geq 8; \quad (9)$$

If network coding is not applied, for $N \geq 8$, we have

$$N_{tr} = N + 2 \sum_{i=1}^{\alpha_1} (N - 4i) + 2 \sum_{i=0}^{\beta_1} (N - 4i - 6); \quad (10)$$

$$\text{where } \alpha_1 = \left\lfloor \frac{N}{4} \right\rfloor \text{ and } \beta_1 = \left\lfloor \frac{N-6}{4} \right\rfloor.$$

If nodes form two parallel lines and they increase transmission power so that they can directly communicate with neighbours two hops away (thus more overhearing of others' messages), the number of necessary transmissions further decreases. When network coding is used, for $N > 5$ and $N = 4k$, the number of transmissions is equal to

$$N_{tr} = \sum_{i=0}^{\chi_1} (N - 8i) + 2 \sum_{i=1}^{\chi_1} [(N - 8i) + 2]. \quad (11)$$

Otherwise, for $N > 5$, we have

$$N_{tr} = \sum_{i=0}^{\chi_1} (N - 8i) + 2 \sum_{i=1}^{\chi_1} (N - 8i), \quad (12)$$

where $\chi_1 = \lfloor \frac{N}{4} \rfloor$. If network coding is not applied, the total number of transmissions is, for $N = 4k$,

$$N_{tr} = N + 2 \sum_{i=1}^{\chi_1} (N - 8i) + 2 \sum_{i=1}^{\chi_1} [(N - 8i) + 2]. \quad (13)$$

Otherwise,

$$N_{tr} = N + 2 \sum_{i=1}^{\chi_1} (N - 8i) + 2 \sum_{i=1}^{\chi_1} (N - 8i). \quad (14)$$

Finally if nodes further increase the transmission power, so they can reach their third-hop neighbours, the number of transmissions decreases further. For $N = 12k$ and $N = 22 + 12k$

$$N_{tr} = \sum_{i=0}^{\eta} (N - 12i) + 2 \sum_{i=0}^{\mu} (N - 12i - 10) + 4; \quad (15)$$

where $\eta = \lfloor \frac{N}{12} \rfloor$, $\mu = \lfloor \frac{N-10}{12} \rfloor$. When network coding is not applied

$$N_{tr} = N + 2 \sum_{i=1}^{\eta} (N - 12i) + 2 \sum_{i=0}^{\mu} (N - 12i - 10) + 4. \quad (16)$$

For all other N , $N_{tr} = N_{tr} - 4$.

Figures 5.a and 5.b present the total number of message transmissions using our algorithm. We assume the length of the bridge is 2km and a given number of sensors are placed on one or two sides of the bridge uniformly. Depending on the transmission power, the sensor nodes have 1, 2 or 3-hop connectivity, as described earlier. To achieve a fair comparison, let us define the coding gain as the ratio of the total number of transmissions with network coding to that for the conventional routing method as follows.

$$\text{coding_gain} = \frac{\text{no. of transmissions with network coding}}{\text{no. of transmissions with conventional routing}}$$

With this definition of coding gain, we can evaluate the performance of our algorithm for different network topologies and connectivity. Figure 5.c shows that the best performance of the network coding algorithm can be achieved for the case when nodes can reach only their immediate (one-hop) neighbours. (Note that for a given degree of connectivity, results for the single and double-line layouts are very close to each other, as shown in Figure 5.c.) In the case of one-hop connectivity, each node receives the original messages (data) generated at its two-hop-away neighbours via the coded messages received from its immediate neighbours. In contrast, for the case of two-hop connectivity, a node receives the original messages directly from its two-hop-away connectivity, neighbours as data is transmitted at a higher power to maintain the two-hop connectivity. As a result, a higher proportion of messages will be conveyed via network coding for networks with one-hop connectivity, when compared with the case of two-hop connectivity where more original messages are received directly from neighbors. Therefore, coding gain will be higher for one-hop connectivity than for

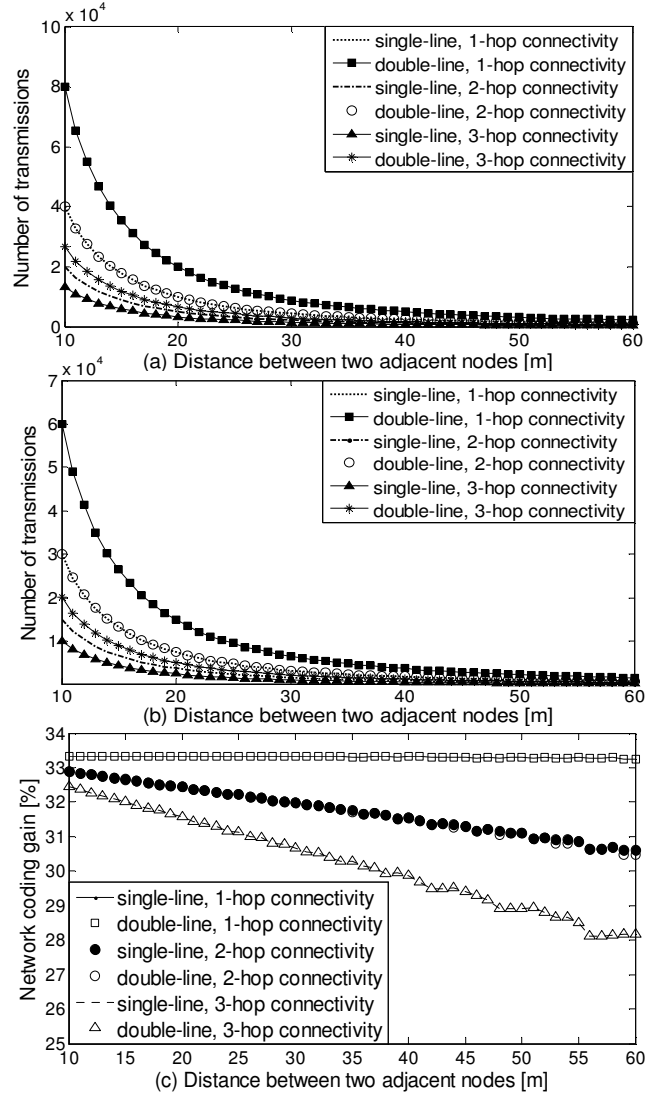


Fig. 5 Total number of transmissions with (a) or without (b) network coding (NC) for all four cases. (c) Comparison of the coding gains for all four cases.

two-hop connectivity in spite of the decrease (due to the overhearing capability) in the total number of transmissions. The same comment applies to the 3-hop connectivity. Our results in Figure 5.c reveal that our algorithm generates up to 33.3% reduction in the number of transmissions. The figure also suggests that we can achieve the maximum coding gain even for a small number of nodes, thus confirming that our proposed algorithm performs well for relatively small sensor networks. However, the proposed algorithm will yield better performance gain for bridges with a moderate and large number of sensor nodes.

VI. CONNECTIVITY AND PERFORMANCE STUDY

We use computer simulation to study the performance of improved connectivity and power consumption. We assume combined path loss, shadowing and Rayleigh fading for each radio link between any given pair of sensor nodes. Since radio link changes in time, we adjust the transmission power at each node such that its signal can reach its immediate neighbours with a received signal power level above a fixed threshold for

a given probability. We consider that a transmission is successful if the power level at the receiver is above the receiver sensitivity of -103 dBm (e.g., that for ZigBee Pro Module 2PM3570). We also consider 250 kbps data rate with packet (message) length of 128 Kbytes, as given in the 802.15.4 standard. As explained in Liu et al. [10], to receive k bits of data, a node consumes $k \cdot \alpha$ [nJ] where $\alpha = 50$ nJ/bit.

Due to the fading and interference, data transmission via wireless links is prone to error. We consider a radio link characterized by an exponential path loss, shadowing and fast fading. Since many vehicles are passing over a bridge, we consider the presence of fading and shadowing on the top of signal path loss. We obtain from the simulation the probability of successful transmission with various transmission power levels in dBm and distances between nodes, as shown in Figure 6.

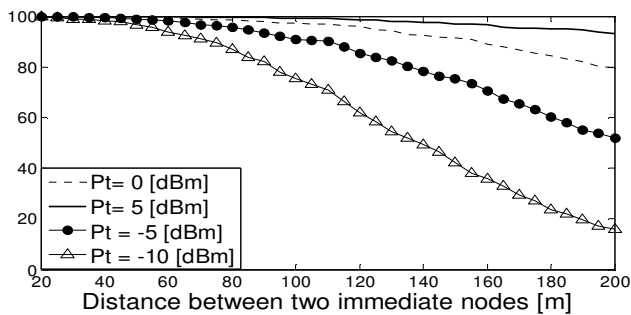


Fig 6. a) Probability of successful transmission for various distances between transmitter and receiver.

As expected, our results show that the higher transmission power leads to the higher probability of successful transmission. Specifically, Figure 6 shows that for transmission power of 5 dBm, the probability of successful transmission is higher than 95%, even if nodes are placed 200 m from each other.

We simulate the WSN performance for a 2 km long bridge under a constraint that 99% of transmissions should be successful. That means that each side of bridge has 40 nodes, for the spacing between two adjacent nodes of 50 m. For the case of the double-line topology, power consumption for nodes on both lines is symmetrical. We see that even though energy consumed per node in the case of one-hop connectivity is lower, the energy consumption in the case two-hop connectivity is better balanced among nodes. Figure 7 presents the case when we position nodes at 50 m from each other. Thus, a total of 40 nodes are deployed for the single-line scenario and 80 nodes are used for the double-line scenario. For one-hop connectivity, nodes should transmit at -5.35 dBm to assure 99% rate of success at a distance of 50 m, whereas for the two-hop connectivity, nodes should transmit at 4.52 dBm to assure 99% success rate at a 100 m distance. Finally to achieve three-hop connectivity with the same probability of success, nodes should transmit with 11.08 dBm. We observe how the energy consumption is balanced among nodes. Since nodes at the middle of the bridge send almost all messages by means of network coding, they save most of the power. On the other hand, nodes towards the ends of the bridge will send almost all their transmissions by means of regular message

forwarding, and hence they will spend more energy when compared with nodes at the middle of the bridge. We see that the lower degree of connectivity is, the longer lifetime of network will be. We plot power consumption for nodes along one side of the bridge.

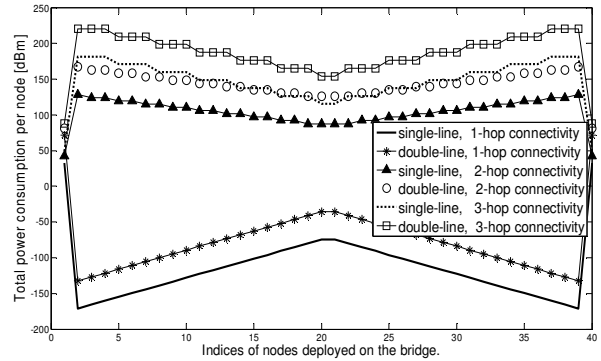


Fig. 7. Total power consumption per node for nodes placed 50 m from each other.

Figure 8 shows the total power consumption by all nodes in the network for various combinations of layouts and connectivity, when the distance between two adjacent nodes is 30 and 50 m, respectively. For a given distance, the number of nodes is twice higher in the case of the double-line layout as in the single-line layout. It is shown that the single-line layout with one-hop connectivity consumes the least amount of total energy by all nodes. Although not shown in the figure, if we allow two-hop connectivity for the same layout and nodes spacing of 100m, the total energy consumption triples. Clearly, for any combination of layout and connectivity, the figure reveals the use of network coding reduces power consumption. When compared with traditional forwarding, our algorithm achieves up to the 20% reduction of power consumption. We can also see from the figure that for a fixed node distance, the higher degree of connectivity requires higher power consumption to ensure proper reception. For a given degree of connectivity, we observe that half of the total power consumption for the double-line layout is still higher than that for all nodes in the single-line layout. This is so because relatively speaking, there are more direction transmissions for the double-line layout than that in the single-line layout, thus reducing the gain by the network coding. Combining all the effects, the single-line layout with one-hop connectivity among all combinations consumes the least amount of energy, thus producing the longest network lifetime.

VII. CONCLUSIONS

In this paper, we have proposed and analyzed the performance of a new algorithm that employs network coding for structural health monitoring of bridges. Wireless sensors are deployed on the bridges to take (sense) a variety of measurements. The key idea is to make use of network coding to reduce the number of transmissions needed in forwarding sensing data to the sink nodes. We have analyzed the performance gain of the network coding technique. We have also considered to adjust transmission power to cope with the propagation environment characterized by fading, shadowing and path loss to assure a

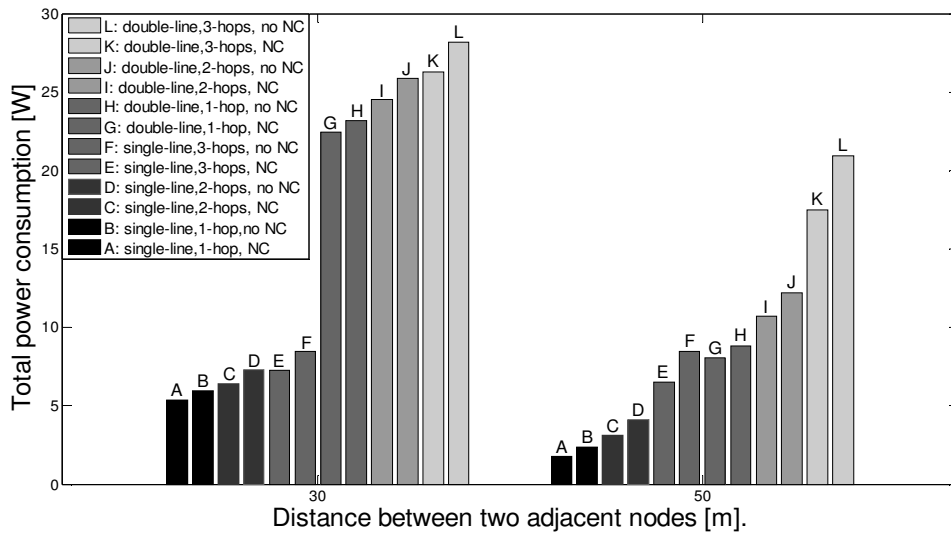


Figure 8. Total power consumption for WCN with and without network coding.

high probability of successful reception. We evaluated the power consumption by all nodes in the network. It has been found that the network coding method can always reduce power consumption for a given node layout and degree of connectivity. However, special attention has to be paid to the layout and connectivity if the objective is to minimize the overall power consumption (i.e., to maximize the network lifetime) when the network coding technique is applied. For the numerical examples considered, the scenario with the single-line layout, one-hop connectivity and network coding consumes the least amount of power. It is so because networking coding gain depends on the node layout and connectivity in some complicated ways. In terms of future work, we plan to design the medium-access protocol to support the proposed algorithm and to investigate interference cancellation techniques that could improve the algorithm performance as nearby sensor nodes may transmit data simultaneously.

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