Suspension Bridge Vibration Measurement Using Multihop Wireless Sensor Networks

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Abstract

Wireless smart sensor networks (WSSNs) have been expected to improve the capability to capture structural dynamic behaviors through dense instrumentation as well as to evaluate the current condition of structures. While the expectation for structural health monitoring using WSSNs has been high, among the key limitations are the limited radio communication range and communication speed. A multihop communication protocol addressing these issues has recently been proposed. Its throughput does not decrease as the hop number increase while similar protocols in the past suffer from significant decrease in speed. Employing this protocol, a wireless sensor network system has been developed to measure structural vibrations. This system first synchronizes all the sensor nodes using multihop RF communication. Based on synchronized clocks, each sensor node records structural vibration and save data on its local storages. The data is then transferred to the base station over multihop routes promptly. This system is installed on a suspension bridge and traffic induced vibrations of the main girder are measured. This monitoring campaign demonstrates quick and easy installation, measurements, and sensor removal as well as its capability to capture dynamic behavior of the bridge. This paper describes the developed monitoring system and the one-day monitoring campaign, which demonstrate the effectiveness of the multihop system.

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1. Introduction

Comprehensive understanding of structural behavior is fundamental to objective evaluation of structural performance which facilitates effective and efficient maintenance of aging infrastructure. Nevertheless, conventional approaches to capture structural dynamic behavior have limitations which current technological advances may overcome. Sensing devices are becoming smaller, less expensive, more robust, and highly precise. Wireless smart sensor networks (WSSNs) leverage these advances to offer improved capability to capture structural behavior.

Structural health monitoring (SHM) systems based on WSSN offer many advantages over conventional wired systems, particularly for large civil infrastructure (Nagayama and Spencer 2007; Rice and Spencer, 2009); however, WSSN implementation for such purposes has challenges. Radio communication on and around structures made of concrete or steel components is usually complicated due to radio wave reflection, absorption, and other phenomena that result poor reception. These facts, combined with the sheer size of typical civil infrastructure, often make direct communication with the base station impractical.

Multi-hop communication addresses these issues by successively routing the communication through intermediate nodes. Multi-hop communication is comprised of two main phases: (i) the routing phase discovers desirable path(s) between source and destination; (ii) the data transport phase uses the constructed path(s) to deliver data. Many routing and transport protocols have been proposed for ad hoc wireless networks; however, these protocols are not designed specifically for structural health monitoring applications and do not necessarily provide the desired functionality.

The remainder of this article is organized as follows. Multi-hop communication for WSSN is briefly reviewed. Subsequently, a reliable multi-hop communication is proposed, utilizing the AODV protocol (Perkins and Royer, 1999) and acknowledgement-based reliable communication (Nagayama and Spencer, 2007). This approach is described in detail and their advantage and disadvantages are discussed with evaluation on a full-scale bridge.

2. Multihop Communication Protocols

There have been a few attempts to construct reliable multihop systems for structural vibration monitoring. Xu et al. (2004) introduced a WSSN system called Wisden, the Reliable Data Transport component of which uses a combination of hop-by-hop and end-to-end methods to recover from packet loss. Intensive use of overhearing associated with packet loss recovery can be problematic; radio communication consumes a noticeable amount of energy even when nodes are in the listening state and furthermore nodes may be put into low-power mode for energy conservation purposes making the overhearing intricate. Kim et al. (2007) has designed and implemented a multi-hop wireless sensor network to monitor the Golden Gate Bridge. A reliable communication package was built on top of MintRoute (Woo et al 2003) and simple broadcast. The link quality metric for routing is packet loss and success events obtained through snooping methods; associated network cost is not small. They have also provided data reliability using selective NACKs while keeping network overhead as low as possible. Time required for the transfer of 512 KB data record from 64 nodes was reported to be more than 12 hours, which emphasizes the importance of communication speed improvement in addition to the reliability. Mechitov et al (2004) have designed a distributed sensing system for SHM applications that emulates the functionality of centralized wired sensing approaches. The system features a self-organizing tree structure for routing and an opportunistic data aggregation to tackle the problem of limited bandwidth while the communication speed issue remains critical in particular as the number of nodes increases.
Reliable multihop communication protocols which overcome the communication speed issue under the general limitation of WSSN, (i.e. limited resources including bandwidth and power) are hence needed. Multihop routing and data transfer methods are studied respectively hereafter.

3. Routing and Data Transport Customization

Multi-hop communication schemes that do not employ coordinated transmission control usually require long data collection times due to packet congestion and collision which slow data transport (Mechitov et al., 2004; Kim et al, 2007). Such approaches are impractical for applications that need prompt information about structural performance. Two cardinal solutions to the problem of long data collection times are decentralization and increasing data transfer throughput. A reliable multi-hop communication corresponding to the second solution is proposed in this section.

This multihop communication seeks to minimize the long times associated with single-sink data collection, frequently termed many-to-to-one or central data collection, by increasing data transport efficiency. Among the various communication patterns found in SHM applications, single-sink data collection takes the longest time. While decentralization of operation can reduce the need for central data collection, single-sink data collection is still employed within hierarchical groups (Nagayama and Spencer, 2007); fast single-sink data collection is undoubtedly vital. By taking into account the communication patterns of centralized data gathering applications and the RF communication characteristics of WSSNs, an efficient data collection approach is proposed.

The proposed multihop communication consists of two phases: shortest path search and efficient data transport utilizing the paths. The routing phase is prompt and congestion-free formation of the shortest-path (i.e., smallest-number-of-hop) routing-tree, which contribute to faster data collection. While searching routes to or from many nodes usually requires transmission of many packets resulting in packet congestion with a high probability of packet collisions, the proposed approach resolves these issues taking advantage of specific communication patterns involved. The data transport phase is conducted in a link-by-link manner over the established routes. The data collection time required in this phase is reduced by employing efficient and reliable link-by-link data transport protocol and allowing multiple neighboring pairs of nodes assigned with distinct frequency channels to transfer data simultaneously.

3.1. Shortest path search for single-sink data collection

The Ad hoc On-Demand Distance Vector (AODV; Perkins and Royer, 1999) routing protocol is customized to achieve efficient shortest path search for single-sink data collection. The AODV protocol, at the beginning, broadcasts a packet to search for the destination node. The receiver nodes broadcast again this packet if the nodes does not have routing path to the destination. This forwarding continues until the packet reaches the destination or the node having routing path to the destination. The maximum number of forwarding (Time To Live; TTL) is also predetermined. The destination or intermediate node having routing path to the destination returns back a route reply packet on reception of the routing request packet. The reply packet is sent back to the originator node through the path used in the request forwarding and informs the originator and intermediate nodes the next hop towards the target.

While the standard AODV protocol has a mechanism to choose the shortest path under any-to-any communication, the mechanism involves a large number of broadcasts. This broadcast packet traffic can be particularly heavy when many nodes initiate the route discovery process simultaneously and also when the Time-To-Live (TTL) value is large; such transmissions may cause numerous packet collisions. Also, the number of route table entries will be immense for large WSSNs wasting sensor node memory. The route discovery process is improved by assuming single-sink data collection scenarios and by
constructing routes in incremental steps. The details of the customized route discovery process are explained in the following paragraphs and illustrated in Figure 1.

TTL is always set to one hop and each leaf node repeatedly performs a route search toward the sink node until a route is found. First, all nodes within single-hop range from the sink identify the sink and establish single-hop routes; subsequently, all nodes within the two-hop range find nodes which already have routes to the sink. The process continues until all nodes set up routes.

After a waiting time, all the nodes except for those which have already established routes initiate the AODV route discovery process again with TTL = 1. Not only the sink node, but also the leaf nodes possessing routes to the sink (i.e., nodes in the single-hop range from the sink) are qualified to respond to the RREQ packets this time. On reception of a RREQ packet, the qualified nodes examine the RSSI value and return RREP packets. When the corresponding originator receives the RREP packet, the RSSI value check is conducted and a route is established. Because multiple nodes are qualified to return RREP messages and may reply, the originator might receive multiple RREP packets. When RREP messages with a smaller number of hops are received, the route table entry is updated. The table can also be updated when RREP with the same number of hops but a higher RSSI values is received. RSSI values of RREQ packets are included in RREP packets, and the smaller of RREQ and RREP RSSI values are compared to that on the table for update. In this manner, nodes in the two-hop range from the sink can establish routes. The process is repeated for a predetermined number of times.

![Incremental routing process](image)

Figure 1: Incremental routing process (for illustration purposes, a linear network topology is shown).

One drawback of this approach comes from link asymmetry. When a RREQ originator updates its route upon reception of a better RREP message, it does not reliably inform the previously-linked node of this change. Although the established routes are stable and with the minimum number of hops, both in the forward and backward directions, nodes on the routes do not know the backward paths. If backward paths are needed (e.g. one-to-many communication), subsequent actions should be carried out; for example, the originator can send a packet to the sink node informing all the intermediate nodes of the established route.

3.2. Link-by-link block data transfer using multiple RF channels

Sending multiple packets successively along multi-hop routes as in GPMH requires a clear time between packet transmissions to avoid packet collisions, which slows down multi-hop communication as compared with single-hop communication (Kim et al. 2007). To better understand why multi-hop data throughput is low and to prepare for a solution to this issue, consider the case where multiple packets are transferred through four nodes as shown in Figure 2. Node A initiates the data transfer by transmitting the first packet “p1”. If node B forwards this packet to C and node A transmits the second packet “p2”
immediately, the chance is high that node B is in the transmit mode when “p2” reaches node B. If node A waits until “p1” reaches node C to send “p2”, “p1” from node C and “p2” from node A interfere with each other at node B. Therefore node A needs to wait until “p1” reaches node D before the next transmission. Because of possible temporary fluctuation of communication range, variations in travel time due to packet processing time variation at each node, and other reasons, this clear time between two successive packet transmissions is typically set larger than the average three-hop travel time. In Figure 2, only one node is included in each hop range for the sake of clarity. If multiple nodes are in each hop range, these nodes may also cause RF interference and need to have appropriate clear time.

Figure 2: Example illustrating the need for a clear time between packet transmissions.

One problem with the packet collision avoidance through transmission time slot division, as described above, is that it slows down communication. Multihop data transfer protocols, such as MintRoute (Woo et al. 2003) and Collection Tree Protocol (Gnawali et al. 2009), utilizes transmission timers and their multihop throughputs, in principle, become much smaller than single-hop throughput; the transfer of large amount of data therefore takes impractically long time. An alternative approach to avoid collisions is through frequency slot division (i.e. the use of multiple RF channels); in this case, long clear times are not of absolute necessity. When a neighboring node is communicating using one channel, surrounding nodes can communicate using different channels. The Imote2, as well as many other smart wireless sensor platforms, employs a 2.4GHz IEEE.802.15.4 RF device with 16 user-selectable channels, each requiring 5MHz of bandwidth between 2405MHz and 2480 MHz. In contrast to 2.4GHz IEEE 802.11, the IEEE.802.15.4 channels do not have overlapping frequency bands; simultaneous communication over all 16 channels is possible. Most previous wireless sensor networks utilized only one channel in the network. However, data intensive applications such as structural health monitoring need higher throughput; use of multiple RF channels is a potential solution.

Channel switching is carefully integrated into data transfer so that the RF channel is switched only when needed. Simply having multiple groups of smart sensors with different RF channels results in multiple independent sensor groups which cannot communicate with each other; time synchronization becomes challenging and control packets cannot be easily spread over the entire network. Furthermore, splitting the entire network into multiple independent groups reduces redundancy in the network. Also, channel switching timing is important. Both the intended sender and receiver should collaborate and change their channels in concert. When the frequency is switched back, both nodes should collaborate again. If the RF channel switch notification packet is dropped, one node remains on a different RF channel and becomes unreachable. Implementation of such synchronized frequency switching is not
trivial and should be employed infrequently. In the proposed data transfer protocol, sensor nodes switch the channel for block-by-block (e.g., 1MB) data transport instead of switching the channel for packet-by-packet transmission. A pair of nodes switches the RF channel, transfers blocks of data, and then switches the channel back. The data transfer then moves to the next hop. The frequency switching approach is explained next.

**Static channel allocation:** This frequency switching approach employs static channel allocation (see Figure 3). Depending on the number of hops toward the sink node, nodes are divided into layers and each layer is assigned two channels in addition to the common communication channel; one corresponds to data transmit and the other corresponds to data reception. The data transmit channel of nodes in the n-hop layer is the same as the data reception channel of the upper-layer or n-1-hop layer (i.e., the layer closer to the sink) nodes. The data reception channel of the n-hop layer is the same as the data transmit channel of the lower-layer or n+1-hop layer (i.e., the layer farther from the sink) nodes (see Figure 3). While the number of available RF channels is limited (i.e., 16 for IEEE802.15.4), the RF channels are utilized in a circular manner, providing network scalability. For example, when there are more than 16 hop layers, the 17th hop layer uses the same RF channel as the 1st hop layer. Because these two layers are physically apart from each other, the chance of interference is negligible. Once data is ready to be transferred using the routing tables, all the nodes switch from the common communication channel to their own data reception channels. When each node starts data transfer, the sender switches its RF channel to its data transmit channel and examines whether the channel is used by other nodes. If the channel is used, the node waits for a random time. Note that even seconds, instead of milliseconds, of waiting time would not slow down the total network throughput significantly when each hop data transfer time is tens of seconds or longer. If not, the node sends an inquiry packet asking whether the receiver is ready. If the receiver is not involved in communication with another node, has available buffer space, and is not overhearing packets from other communication pairs, the data transfer begins; a large amount of data is transferred at a time. After the data transfer, the sender switches the RF channel to its data reception channel. If the receiver is not ready and does not respond, the sender waits for a random time before sending the inquiry packet again.

![Figure 3: Data transfer based on static RF channel allocation.](image)
While this approach has been explained assuming single-sink data collection applications, its extension to multi-sink applications is rather straightforward. When two or more clusters of sensor nodes have their respective destinations, nodes can start the route search process simultaneously toward their own destinations. Data transport can be performed utilizing the established routes if RF channels are appropriately assigned for each sink or if dynamically allocated. In situations where each node needs to make routes to more than one destination, the routing process is performed for each destination.

3.3. Preliminary results

This section presents preliminary results for the reliable multi-hop communication protocols. The efficiency of data collection was evaluated on a suspension bridge in Japan. Along the main girder of the bridge, 49 sensor nodes were installed. Two base station nodes formed route trees and collected all the vibration measurement data. When 24 nodes under one of the two base stations sent 108 kB of data from each node, the acknowledgement-based reliable data transport was completed in six minutes, which resulted in 7 kB/s or 58 kbps data collection speed. The number of hops was eight at maximum. Because laboratory experiments have determined that the maximum single hop data transport speed of the reliable communication protocol is about 10 kB/s, the multi-hop communication approach can be considered to be quite efficient. The achieved multihop throughput can be compared to about 0.5kB/s throughput of the MintRoute-based data collection (Kim et al. 2007); the throughput increase is more than ten-fold.

4. Conclusions

Reliable multi-hop communication is an essential functionality of WSSNs for full-scale structural health monitoring. Based on an analysis of application specific characteristics, routing and data transfer protocols based on the Ad-hoc On-demand Distance Vector (AODV) routing protocol were proposed. The multihop communication protocols focus on efficient collection of large amounts of data at a single sink node, concurrently exploiting multiple radio channels. The proposed approach has been implemented on the Imote2 platform and applied in a test deployment on a full-scale bridge. The fast data collection speed of the protocols has been demonstrated.

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