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Reliable multi-hop communication for structural health monitoring

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Abstract. Wireless smart sensor networks (WSSNs) have been proposed by a number of researchers to evaluate the current condition of civil infrastructure, offering improved understanding of dynamic response through dense instrumentation. As focus moves from laboratory testing to full-scale implementation, the need for multi-hop communication to address issues associated with the large size of civil infrastructure and their limited radio power has become apparent. Multi-hop communication protocols allow sensors to cooperate to reliably deliver data between nodes outside of direct communication range. However, application specific requirements, such as high sampling rates, vast amounts of data to be collected, precise internodal synchronization, and reliable communication, are quite challenging to achieve with generic multi-hop communication protocols. This paper proposes two complementary reliable multi-hop communication solutions for monitoring of civil infrastructure. In the first approach, termed herein General Purpose Multi-hop (GPMH), the wide variety of communication patterns involved in structural health monitoring, particularly in decentralized implementations, are acknowledged to develop a flexible and adaptable any-to-any communication protocol. In the second approach, termed herein Single-Sink Multi-hop (SSMH), an efficient many-to-one protocol utilizing all available RF channels is designed to minimize the time required to collect the large amounts of data generated by dense arrays of sensor nodes. Both protocols adopt the Ad-hoc On-demand Distance Vector (AODV) routing protocol, which provides any-to-any routing and multi-cast capability, and supports a broad range of communication patterns. The proposed implementations refine the routing metric by considering the stability of links, exclude functionality unnecessary in mostly-static WSSNs, and integrate a reliable communication layer with the AODV protocol. These customizations have resulted in robust realizations of multi-hop reliable communication that meet the demands of structural health monitoring.

Keywords: wireless smart sensors; multi-hop communication; structural health monitoring; reliability; dense instrumentation.

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1. Introduction

Objective evaluation of structural performance can facilitate effective and efficient maintenance of aging infrastructure. Comprehensive understanding of structural behavior is fundamental to such evaluation. 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, allowing collection of high-fidelity data with dense instrumentation employing multi-metric sensors. Wireless smart sensor networks (WSSNs) leverage these advances to offer the potential for dramatic improvements in the capability to capture structural dynamic behavior and evaluate the condition of structures. WSSNs can be employed for medium- and long-term monitoring of structural condition, as well as for shorter-term investigative structural monitoring campaigns to diagnose specific problems.

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 *et al*. 2010, Jang *et al*. 2010); however, WSSN implementation for such purposes has challenges. In addition to the sensing issues discussed in Nagayama and Spencer (2007), communication issues emerge which are not manifested in other WSSN applications that consider collection of small amounts of data in open environments, e.g., environmental monitoring and target tracking (Mainwaring *et al.* 2002, Luo *et al.* 2006). 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. Moreover, sensor nodes are frequently installed in partially- or completely- obscured areas, such as between girders. These facts, combined with the sheer size of typical civil infrastructure, often make direct communication with the base station impractical.

Multi-hop communication, together with appropriate packet-loss compensation, addresses these issues by successively routing the communication through intermediate nodes, which are sufficiently close to employ direct single-hop communication. 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. Application specific characteristics of multi-hop communication are first presented, and multi-hop communication application scenarios are discussed. Then, a brief survey of multi-hop communication approaches is presented, along with the rationale for selecting the AODV routing protocol. Subsequently, two complementary approaches for reliable multi-hop communication are proposed, both utilizing the AODV protocol and acknowledgement-based reliable communication (Nagayama and Spencer 2007). The first approach, termed herein General Purpose Multi-hop (GPMH), features flexibility to accommodate a variety of communication patterns involved in decentralization to reduce communication requirements, while the other approach, termed herein Single-Sink Multi-hop (SSMH), aims to achieve efficient data collection from a dense array of sensor nodes. These two approaches are described in detail and their advantage and disadvantages are discussed.

2. Communication requirements for SHM applications

In the design of large-scale SHM systems, application-specific characteristics and requirements must be considered. The WSSN deployment on the Jindo Bridge (Jang *et al.* 2010, Cho *et al*. 2010) has provided critical insight into the necessary design features for a reliable multi-hop communication protocol. Following a brief description of the Jindo Bridge deployment, these features, as well as possible communication usage patterns, are summarized.

2.1 Jindo Bridge SHM project

The primary goal of the Jindo Bridge SHM project has been to realize the first large-scale, autonomous WSSN for structural health monitoring, taking advantage of the advanced computational capabilities of the Imote2 nodes (Crossbow Technology 2009). The second Jindo Bridge, opened in 2006 and connecting the southwestern tip of the Korean Peninsula and the Jindo Island (see Fig. 1), is the target of this study. This three-span, continuous, steel box-girder cable-stayed bridge has a length of 484 (70 + 344 + 70) m and a width of 12.55 m. The two pylons are 89 m high. The acceleration responses of the bridge under traffic and wind loads are investigated employing the Imote2s and the SHM-A sensor boards (Crossbow Technology 2007, Rice and Spencer 2009).

The initial goals of this study were to investigate issues related to long-term monitoring, which

Fig. 1 First (right) and second (left) Jindo Bridges

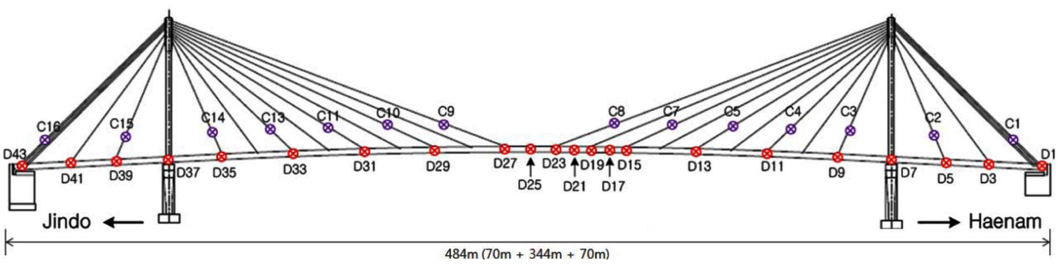

Fig. 2 Wireless sensor locations on the Jindo Bridge (side view)

involves permanent instrumentation and periodic monitoring. As shown in Fig. 2, 70 sets of Imote2s and sensor boards were installed on the girders, cables and pylons. Two gateway nodes are installed on the two pylons of the first Jindo Bridge and are connected to two base station computers, which are accessible through a wired Ethernet connection; remote users can send commands to the sensor network to start sensing, collect data and examine sensor node status. Also, sensors are installed with a set of autonomous monitoring software. Several sentry nodes monitor the vibration level and wake up the other nodes as needed. Sensor installation locations were selected so that all the nodes are in single-hop range from the two gateway nodes at the respective base stations. Changes in structural performance can be examined through modal, structural and statistical analyses performed automatically by the WSSN.

Short-term monitoring campaigns were also considered in this study, where quick and easy sensor deployment, measurement and removal are performed in one or a few days. Such monitoring campaigns are frequently employed for investigative studies, to examine chronological changes of structural performance, or to confirm structural behaviors after construction, structural retrofit, and extreme loading events such as earthquakes. To this end, from 21 to 34 Imote2s and sensor boards were deployed on the top side of the bridge deck over the three spans; acceleration responses were recorded, and forwarded to the gateway node connected to the base station computer. The wireless monitoring campaign was repeated by several people on a daily basis to gain insight into usability issues. While sensor installation on the top side of the bridge deck allows for quick deployment, handrails and other objects resulted in a complex communication environment and limited radio communication range; these tests informed the development of the multi-hop communication software described herein.

Further information regarding the Jindo Bridge SHM project can be found in Jang *et al.* (2010) and Cho *et al.* (2010).

2.2 WSSN application specific characteristics

A number of critical issues emerged in the course of the Jindo Bridge project. While many of the concerns were identified during the initial design phase, their relative importance and magnitude did not become apparent until the deployment and testing phase.

2.2.1 Large data size

Communication in most WSSN applications involves exchanging commands and limited amounts of data, both of which are typically small enough to be encapsulated in single packets. However, structural monitoring applications need to transfer large amounts of dynamic measurement data, which must be divided into a large number of packets. Each sample data point is typically 2 bytes and sampling frequencies can be as high as 1000 Hz. In addition, each sensor node usually has multiple sensing channels, increasing the data generated by each node. Such high sampling rates usually preclude real-time data collection, as even a small number of nodes can saturate the available network bandwidth. As a result, sensing and data collection take place sequentially in most SHM applications.

In the Jindo project, each node measures acceleration in three directions at 10-50 Hz and saves it in a 2 byte format. The sensing duration was from 2 to 17 minutes. Typically, the size of the acceleration records collected at each node was 60 KB. When the size of packet payload is 100 B, the 60 kB data is divided into 600 packets. However, the sensing duration for this deployment, and thus the size of the data generated, are not the maximum values for general SHM applications; requirement on data size can be much more severe.

2.2.2 Dense deployment of sensor nodes in large spatial regions

Civil infrastructure is typically extremely large; for example, the length of some bridges can exceed several kilometers. Because single-hop communication often cannot cover the entire structure, stable data transfer from nodes requires multi-hop communication. In addition, multi-hop communication is considered efficient and desirable; with proper scheduling, multi-hop can save power by using shorter links (Subramanian and Katz 2000). Moreover, local vibration characteristics and spatial distribution of dynamic properties are often of interest, which necessitates dense deployment. Therefore, the communication protocol needs to support large and dense multi-hop networks; design and implementation of such a protocol is generally challenging.

For bridge structures in particular, a unique characteristic is that the network topology is linear (i.e., the deployment area is long and in one dimension). Under this condition, a coarse deployment allows only a single chain-like multi-hop routing tree, leaving no alternate routes. On the other hand, dense deployments with multiple nodes in single-hop ranges allow for alternate routes as needed. For example, consider the 70 sensor nodes deployed on the Jindo Bridge; 16 were installed on the cables; with the balance installed on the deck or on the pylons (see Fig. 2). Most sensors on the cables were installed on every other cable on one of the two cable planes. Sensors were installed on the bottom side of the deck at a distance of approximately 25 m apart, corresponding to the distance between anchorage points of monitored cables. For the pylons, sensor nodes were installed only at the top of the pylons and a few meters above the deck. Although this topology is primarily linear, the dense nature of such deployment is beneficial to rapid and robust data collection.

2.2.3 Radio communication environment

The radio communication environment on the bridge can be complex due to RF reflection, refraction, absorption and other phenomena. Bridges consist of numerous components made from steel, concrete or other materials. Some bridge components may be between two WSS nodes, interrupting direct line-of-sight communication. Therefore, the communication range on a bridge will vary from place to place, and its estimation prior to on-site tests is challenging. In locations where communication range is limited, link asymmetry may prevent bidirectional communication between nodes at shorter distances than commonly seen in other applications. This problem is due to the combined effects of non-uniform antenna directionality and RF signal strength degradation due to the above-mentioned environmental factors. As a solution, multi-hop communication schemes that consider the bidirectional quality of each link are desirable.

As an example, consider the Jindo Bridge, which is comprised mainly of a steel box-girder, pylons and cables, as well as non-structural elements such as handrails, light poles and road pavement. For the long-term deployment, the gateway nodes were strategically installed on the pylons of the first Jindo Bridge, providing clear line-of-sight with most of 70 Imote2 sensor nodes. As a result, even the farthest nodes (>150 m) were within single-hop range of one of the two gateway nodes. In contrast, the campaign-type deployment of sensor nodes on the top side of the deck showed much shorter communication ranges, which is attributable to several reasons. First, sensor nodes installed on the top side of the deck do not necessarily have line-of-sight communication due to bridge deck camber. Non-structural elements on the top side of the deck, as well as cars and pedestrians, also affect the transmission range. Finally, communication distance varies significantly depending on exactly where the nodes are installed and their antenna orientation. For example, sensor installations on the pavement, at the bottom of handrails, and on top of the handrails showed significantly different communication ranges. In general, sensor nodes elevated above the ground improves communication range (Linderman *et al.* 2010, Kim *et al*. 2010).

2.2.4 Nodes at fixed locations

For most structural health monitoring applications, sensor installation locations are predetermined based on design drawings and structural considerations. These installation locations do not necessarily correspond with locations that are desirable with respect to RF communication. If the installation locations result in short communication range, countermeasures are needed. Separation of the sensing and communication (i.e., the antenna) components of the sensor node can be a solution. For example, ground-mounted sensors can employ elevated antennas (Jang *et al.* 2010, Kim *et al.* 2010).

Moreover, sensor nodes, including their antennas, seldom move, once installed. In this sense, structural monitoring applications do not need to account for frequent changes in the communication link quality; the routing tree topology should not need to change often. However, sporadic transmission interference may occur due to vehicles, pedestrians, workers, inspectors and birds; also, nodes may occasionally fail. Multi-hop communication needs to be robust in the presence of such events.

2.2.5 Need for prompt data collection/analysis

Structural vibration monitoring applications generally require prompt data collection and analysis, though data collection does not necessarily need to be in real-time. In particular, performance evaluation after extreme events such as earthquakes and typhoons must be done as soon as possible to address safety concerns. As for monitoring campaigns where operation time is limited, data collection must be done in a timely manner. When measurements involve stopping traffic, hourly workers, and/or rental equipment (e.g., exciters), minimizing long data collection times can result in significant cost savings. Moreover, shorter data collection time leads to shorter operation time resulting in extended battery life. Also, the time required for data transfer increases WSSN operational time, as leaf nodes in many systems need to transmit measurement data to the central computer and clear the local data buffer before starting the next measurement.

In the Jindo Bridge monitoring campaigns, the data collection time was significant, because the communication middleware used in the campaigns was not optimized for fast data collection. The data collection time for the monitoring campaigns was from one to a few hours, resulting in only a few sets of measurement data per daily campaign. The data collection time should be shorter to increase the amount of data obtained.

2.2.6 High requirement on reliability

Reliability of transporting acquired sensor data is vital. Most scenarios assume measurement data is available from all the nodes without intermittent loss. For example, many damage detection algorithms require sensing data from predetermined locations, while only a few algorithms (e.g., Gao and Spencer 2008) so far have been extended to provide robustness against node failure. Unresponsive nodes may impair the damage detection capability. For campaign tests, data is expected to be gathered from all of sensing locations. As for intermittent loss of data from certain nodes, the loss degrades the signal and limits the subsequent data analysis. Packet loss compensation is therefore required (Nagayama *et al.* 2007).

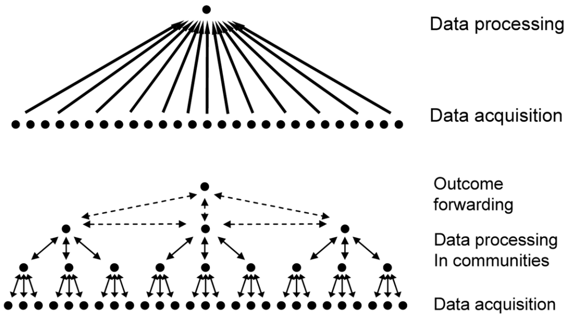

Fig. 3 Examples of communication patterns in WSSN applications: centralized data aggregation (top) and decentralized, cluster-based communication (bottom)

2.3 Multi-hop communication usage patterns in SHM

This section examines how multi-hop communication is utilized in SHM applications. To explore possible communication patterns, sensor network applications are classified into two categories (i.e., centralized and distributed) and characterized.

In centralized applications, a single node typically controls the behavior of the application and is often the root of a tree-like communication pattern in the network; that is, they emulate wired data acquisition systems (see Fig. 3). The communication patterns for these applications consists of configuration data being broadcast to the leaf nodes, followed by predetermined tasks such as time synchronization, sensing and data collection. All of the associated packet transfer is between the central node and the other nodes; usually data sharing among leaf nodes is not performed. Representative communication patterns are dissemination and many-to-one data sink. While in some cases local processing such as filtering and resampling may be utilized to reduce the amount of raw data generated by the sensors, the total volume of data that needs to be transferred from a large WSSN is expected to be significant. Thus, efficiency in data collection from multiple data sources is the key performance metric and a primary design goal for the application's data transfer protocol.

In decentralized or distributed applications (see Fig. 3), several loci of control reside within the network. These nodes may act independently, or coordinate their actions with other nodes. By exploiting the in-network computing capability of smart sensor nodes the overall volume of data transferred can be considerably reduced. The network is usually divided into local clusters, which perform much of the data processing and communication internally, without interaction with the rest of the network. The communication of such decentralized applications are usually varied and include data transfer within clusters, long-distance data transfer among cluster heads and the gateway node, and possibly information exchange between neighboring clusters. Dissemination, one-to-one data transfer, one-to-many multicast, and many-to-one data sink can all be utilized. With decentralization, the number of hops for each communication instance is expected to be small, as compared to centralized systems. However, multi-hop communication is still needed, and the combinations of originator and destination nodes is much more complex than in centralized systems; thus, requiring a flexible routing service.

Due to these application specific characteristics and communication patterns, the use of a multi-hop communication protocol that is fast, flexible and reliable is critical. Several multi-hop communication protocols have been proposed in the past for WSSNs, each targeting certain features of specific applications. To identify suitable protocols to be considered for structural monitoring applications, multi-hop communication protocols, as well as early research that employs multi-hop communication for structural health monitoring, are reviewed in the next section.

3. Survey of multi-hop communication

Multi-hop communication is comprised of two main phases, routing and data transport. This distinction follows the Open Systems Interconnection (OSI) reference model for data communication (Table 1), which is commonly used to classify network protocols. In the OSI model, routing and data transport belong to the network and transport layers, respectively. Protocols in the network layer are responsible for logical node addressing and determining desirable paths between source and destination nodes, while those in the transport layer uses the constructed paths to deliver data between nodes and provide features such as reliability. This section discusses the characteristics of several routing and data transfer techniques relevant to WSSNs and structural health monitoring.

Several routing techniques have been proposed for wireless smart sensor networks, most commonly distinguished by when and how route information is generated and how it is updated. Routing algorithms are also often specific to the network structure for which they are developed. Important properties expected from routing algorithms include loop freedom (i.e., a guarantee that a packet's route through the network will never contain loops) and finding the best route among several possibilities based on some routing metric.

Routing protocols for wireless ad-hoc networks, that is networks without a pre-defined topology, are usually classified as either table driven or on demand (Royer and Toh 1999). In the former, each node maintains routing information for every node in the network. Routing tables are kept up to date through the use of broadcast messages propagating changes in the network structure, and/or periodic update messages that aim to keep a consistent view of the network. Protocols within this category may differ in their policy for distributing changes in network topology and the number of routing tables required. Destination-Sequenced Distance-Vector Routing (DSDV) (Perkins and Bhagwat 1994), Clusterhead Gateway Switch Routing (CGSR) (Chiang *et al.* 1997), and Wireless Routing Protocol (WRP) (Murthy and Garcia-Luna-Aceves 1996) are representative examples of table-driven routing protocols. On-demand routing protocols, on the other hand, postpones route establishment until the routes are actually needed. The benefit of this approach is that nodes are not required to maintain up-to-date routing tables for all nodes in the network, whereas the main drawback is

Table 1 OSI reference model for data communications

Layer	Standards and Protocols
Application	HTTP, FTP, SMTP
Presentation	JPEG, GIF, MPEG
Session	AppleTalk, WinSock
Transport	TCP, UDP
Network	IP, ICMP, IPX
Link	Ethernet, ATM
Physical	RS232, T1, 802.x

increased latency for the first routing request. Ad-hoc On-demand Distance Vector routing (AODV) (Perkins and Royer 1999), Dynamic Source Routing (DSR) (Johnson *et al*. 2007), Temporally Ordered Routing Algorithm (TORA) (Park and Corson 1997), Associativity-Based Routing (ABR) (Toh 1996), and Signal Stability-based Adaptive routing (SSA) (Dube *et al*. 1997) are well-known examples of on-demand routing protocols. When the table-driven and on-demand approaches are compared in terms of power consumption and bandwidth, the omission of overhead related to periodic routing table updates is considered the main advantage of the latter approach. Tables 2 and 3 adopted from (Royer and Toh 1999) compare different table-driven and on-demand ad hoc routing protocols, respectively.

Routing protocols for wireless ad-hoc networks can also be categorized based on network structure as flat, hierarchical and location-based (Al-Karaki and Kamal 2004). In flat networks, all

Table 2 Comparison of the characteristics of table-driven ad hoc routing protocols

Parameters	DSDV	CGSR	WRP
Time complexity	$O(d)$	$O(d)$	$O(h)$
Communication complexity	$O(N)$	$O(N)$	$O(N)$
Routing philosophy	Flat	Hierarchical	Flat
Loop-free	Yes	Yes	Yes, but not instantaneous
Multi-cast capability	No	No	No
Number of required tables	Two	Two	Four
Frequency of update transmission	Periodically and as needed	Periodically	Periodically and as needed
Utilizes sequence numbers	Yes	Yes	Yes
Utilizes "hello" messages	Yes	No	Yes
Routing metric	Shortest path	Shortest path	Shortest path

Abbreviations: N = Number of nodes in the network, d = Network diameter, h = Height of routing tree

Table 3 Comparison of the characteristics of on-demand ad hoc routing protocols

Parameters	AODV	DSR	TORA	ABR	SSA
Time complexity (Initialization)	$O(2d)$	$O(2d)$	$O(2d)$	$O(d + z)$	$O(d + z)$
Communication complexity (Initialization)	$O(2N)$	$O(2N)$	$O(2N)$	$O(N + y)$	$O(N + y)$
Routing philosophy	Flat	Flat	Flat	Flat	Flat
Loop-free	Yes	Yes	Yes	Yes	Yes
Multi-cast capability	Yes	No	No	No	No
Beaconing requirements	No	No	No	Yes	Yes
Multiple route possibilities	No	Yes	Yes	No	No
Route table	Route table	Route cache	Route table	Route table	Route table
Utilizes route cache/table expiration timers	Yes	No	No	No	No
Routing metric	Shortest and freshest path	Shortest path	Shortest path	Associativity and shortest path and others	Associativity and stability

Abbreviations: N = Number of nodes in the network, d = Network diameter, z = Diameter of the directed path where the REPLY packet transits, y = Total number of nodes forming the directed path where the REPLY packet transits nodes have the same role, while in hierarchical networks nodes are assigned different responsibilities based on their position in the hierarchy. In location based protocols, the knowledge of the physical location of nodes is exploited, in that data is sent to the desired region of the network, instead of being propagated throughout the entire network. This classification is less useful in the SHM arena, where applications can fall into either of the three categories or a combination thereof, making development of a versatile routing protocol challenging.

Efficient, and reliable data transfer is an important feature of data-intensive applications such as SHM. Implementations of reliable data transfer can be classified into redundant transmission and acknowledgment-based approaches. While the former can be more efficient and simpler to implement, significant data loss due to the bursty nature of packet losses, cannot be completely compensated by this statistical approach. On the other hand, the acknowledgment based approach can be rather slow, particularly for transfer of large amounts of data. Nagayama and Spencer (2007) proposed a single-hop reliable communication protocol involving only a small number of acknowledgment packets. This protocol was tailored for densely deployed sensor networks used in SHM applications, with the aim of increasing the scalability and efficiency of the WSSN. While this protocol provides fast communication, together with packet loss compensation, it is limited to single-hop networks.

Several attempts to develop a reliable multi-hop framework for structural vibration monitoring have been reported. 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, where nearby nodes receive packets intended for one of their neighbors, associated with this approach to packet loss recovery can be problematic. Radio communication consumes a noticeable amount of energy, even when nodes are in the listening state. Therefore, nodes may be put into the low-power mode to conserve energy, making overhearing intricate. Mechitov *et al.* (2004) designed a distributed sensing system for SHM applications that emulates the functionality of a centralized wired sensor network. The system features a self-organizing tree structure for routing and opportunistic data aggregation to tackle the problem of limited bandwidth; in this approach, the communication speed issue remains unresolved, particularly as the number of nodes increases. Kim *et al.* (2007) and Pakzad *et al*. (2008) 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 and simple broadcast (Woo *et al*. 2003). The link quality metric for routing is packet loss and successful delivery events, obtained through snooping methods. Data reliability has been provided using selective negative acknowledgments (NACKs), while keeping network overhead as low as possible. The associated network cost of this method is not insignificant, however; the time required for the transfer of a data record stored on the 512 KB flash memory (e.g., 80 seconds of data for 3 channels sampled at 1000 Hz) from 64 nodes was reported to be more than 12 hours, for an effective data throughput of approximately 0.5-0.7 kB/s, which emphasizes the need for communication speed improvement in addition to maintaining reliable data transfer.

4. AODV routing protocol

Based on a careful comparison of the characteristics of the available routing algorithms against the requirements and constraints imposed by SHM applications, AODV is chosen to be the most suitable routing algorithm for multi-hop communication in SHM networks; it has favorable time and communication complexity, low overhead, and reasonable routing latency. It guarantees loop-freedom of routes by means of a destination sequence number, which is updated whenever new information about a destination is received. Additionally, the AODV route discovery packets are disseminated only when necessary, saving bandwidth and reducing congestion (Perkins and Royer, 1999). Using this protocol, general topology maintenance is not needed, i.e., only local connectivity information is retained. Another advantage of this protocol is that route information is stored only on nodes that are involved in the routing, thus providing greater scalability. Moreover, AODV is one of the most widely studied and popular routing algorithms and is the only on-demand routing protocol for which a simplified publicly available implementation is available for TinyOS, the operating system for Imote2-based wireless sensor networks. In what follows, this algorithm is first described and then the properties of AODV relative to SHM applications are discussed.

In the AODV protocol, when a node needs to communicate with another node in the network, it searches its route table for a route to the destination. If no such route is found, a route request (RREQ) message is initiated. The RREQ message is then advertised into the network. Route reply packets (RREP) originating at the destination or intermediate nodes knowing a path to the destination establish the route in the reverse order. Once receiving the RREP messages, the source node chooses a path with the minimum number of hops. Route freshness and loop freedom are guaranteed through the use of sequence numbers.

Fig. 4 shows an example of AODV route discovery method. Here, node *A* is the source, and node *I* is the destination. The source node disseminates a RREQ message. Nodes that receive the RREQ message rebroadcast; this process is repeated until the request reaches the destination node, or a node that has a route to the destination. At this point, a route reply message is sent back to the source, notifying it that the route was found. Among the received routes, the source node chooses the one with the minimum hop count for data dissemination.

The AODV protocol is designed to find a route connecting two nodes which may be many hops apart. As explained in the previous paragraphs, RREQ packets leave the originator node and diffuse in the network searching for the destination; intermediate nodes that receive RREQ packets re-broadcast. To prevent RREQ packets from traveling across the network indefinitely, the lifetime and therefore the maximum distance a RREQ packet can travel, is limited by a Time-To-Live (TTL) value. The TTL value is a mechanism to limit the scope the RREQ travels, which in turn reduces the overall power consumption of the network. In general, TTL is set via an expanding ring search; TTL is initially set as a small number and incremented if the destination is not reached. However, the appropriate TTL value can be configured based on the network and application. While large

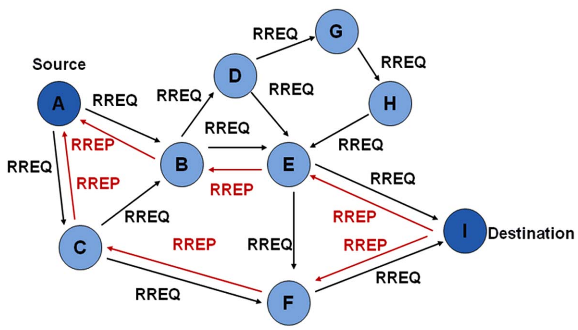

Fig. 4 An example of AODV route discovery, node A is the source and I is the destination, the source chooses the route with the shortest hop count

TTL values ensure full reachability, smaller values may be appropriate in some circumstances (e.g., for communication within a cluster or only with immediate neighbors).

The reason for choosing an on-demand routing protocol over a table-driven protocol comes from the unique requirements of SHM applications, where the network structure is predefined and mostly static. Therefore, imposing the overhead of periodic route table exchange is not rational. On the other hand, because the probability of node failures due to battery failure or other hardware problems is high, finding the routes once and maintaining fixed routing tables is inadequate. With respect to WSSNs deployed on bridges, the near-linear topology can be used to reduce significantly the overhead that is caused by route request message broadcasts in the AODV routing protocol. Moreover, the dense deployment and stability of the routing structure results in long-lived paths which in turn reduces the overhead of route discovery.

The flat routing philosophy of this protocol makes it a suitable choice for routing in SHM applications with linear network topologies. Moreover, the method of route discovery in AODV is very flexible, which makes it suitable for diverse SHM applications and allows it to support new applications with different communication patterns. AODV supports a wide variety of communication patterns, including multicast transmission, which is highly desirable as the network size increases (although not available now, future implementation of AODV for TinyOS can include this feature). As mentioned in Section 2.2, one characteristic of SHM applications is the deployments are typically large-scale and dense; providing multicast capabilities will allow efficient scaling up to large network sizes.

As a result, AODV is adopted as the routing protocol for the reliable multi-hop communication approaches presented in this paper. However, some adjustments to the AODV routing metric are required, as the hop count routing metric can lead to selection of paths with long and unreliable links. This problem will be further appraised in the next sections, and an approach proposed to address this difficulty.

5. Routing customization and data transport

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. Correspondingly, two complementary approaches to reliable multi-hop communication are proposed in this section.

The first implementation focuses on any-to-any communication needed for decentralized SHM applications. This flexible implementation contrasts well with multi-hop communication implementations for SHM applications reported in the past, which focus on specific data flow patterns such as central data collection and dissemination, and are not easily extended for decentralized applications. A common networking infrastructure to support these diverse communication functionalities, termed herein as General Purpose Multi-hop (GPMH), is proposed and implemented.

The second implementation, on the other hand, seeks to minimize the long times associated with single-sink data collection, frequently termed many-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, Sim and Spencer 2009); 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, termed herein as Single-sink Multi-hop (SSMH), is proposed.

5.1 Flexible general purpose multi-hop (GPMH) communication

This section describes GPMH, a flexible and adaptable approach for reliable multi-hop communication. SHM applications for large-scale WSSNs are quite complex, typically including several stages of operation, such as initialization, sensing, data processing and aggregation. Different applications, and even different parts of a single application, require different types of communication and data transfer (e.g., unicast or multicast from a single source, aggregation from multiple sources, peer-to-peer data exchange). This inherent complexity impacts significantly the design of WSSN-based monitoring systems, including multi-hop routing protocols. The Illinois SHM Project (ISHMP) Services Toolsuite (Rice and Spencer 2009), taken as the basis of this implementation, seeks to surmount the complexity problem using service-oriented architecture (SOA). The Toolsuite features a basic applications such as centralized data acquisition and decentralized data aggregation, as well as higher-level SHM applications that can perform modal analysis, system identification, and damage detection. A variety of utility services and applications for interacting with the deployed WSSN are also included. In SOA, an application is comprised of software components, called services that are linked together to form the application (Rice and Spencer 2010). As illustrated in Fig. 5, SOA allows for the application-specific logic and control structures to be decoupled from the low-level mechanics of sensing, data processing and communication. Because internal details are encapsulated into each service, one service can be replaced with another without changing other parts of the application.

GPMH is designed as a flexible reliable multi-hop routing service within the ISHMP Services Toolsuite; therefore, all applications built using the Toolsuite can enable reliable multi-hop communication simply by replacing the single-hop reliable data transfer service with the GPMH implementation. GPMH provides a common networking infrastructure, including multi-hop data transfer, which enables diverse communication functionality and avoids unnecessary code duplication, compatibility issues, and poor extensibility and maintainability. In the remainder of this section, changes made to the baseline AODV routing algorithm for implementation in GPMH are presented first, followed by a description of the associated data transfer service.

5.1.1 Modifications to the routing protocol

This section describes changes made to the baseline AODV routing protocol to meet SHM

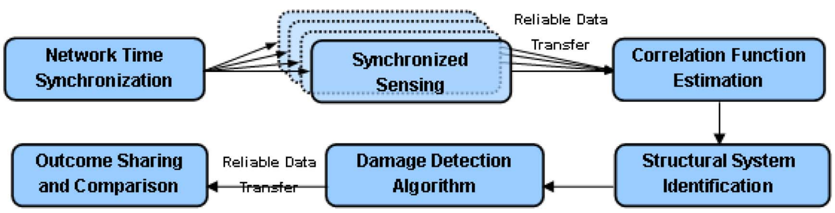

Fig. 5 A damage detection application composed from services in the ISHMP Services Toolsuite

application requirements. Deployment of a WSSN monitoring system for full-scale civil infrastructure is a challenging task that needs to take into account several structural and environmental factors that are difficult to address prior to deployment and are not often encountered in traditional wireless networks. As such, measuring, evaluating and monitoring the performance of the network during the deployment and operation phases are critical; data collection is not the only task involved in the deployment and operation of a WSSN monitoring system. On-site measurement of radio signal strength and link quality between sensor nodes, network status and performance auditing, and periodic monitoring of node battery levels are among the tasks that must be performed alongside data collection.

Communication patterns within these tasks may have different requirements for routing than those dictated by the application scenario. For instance, while radio signal strength measurement must take place along the same routes as data collection, which would depend on whether the latter is centralized or distributed, communication patterns for the battery measurement service need not follow the same routes, as it only involves point-to-point communication between the gateway node and the sensors. This situation prevents using the same routing topology that may be eventually employed for data collection. Moreover, the topology may change frequently as additional nodes are deployed or existing ones moved to different locations. These considerations indicate that a flexible, application-independent multi-hop communication service is required under these circumstances.

The original design of the AODV routing protocol specifically considers packet exchange among mobile nodes and thus includes mechanisms to update routing information frequently. In particular, the AODV protocol uses periodic probe packets for route maintenance. However, node mobility is not commonly an issue in structural vibration monitoring. Moreover, this method of update propagation consumes significant power. For these reasons, the proposed approach omits periodic probe messages. To cope with the problem of route maintenance which is caused by exclusion of AODV's local connectivity mechanisms, each entry of the routing tables is associated with a time-stamp that is updated whenever the route is updated or used. Route entry not used or updated for a specific period of time is deleted. The elapsed time before deleting an entry depends on the scale of the network, as well as the topology's stability. This procedure is deployed to keep the nodes from using out-of-date routes while avoiding costly update messages.

In the proposed implementation, RREQ and RREP packets with a signal strength indicator lower than a threshold are discarded to ensure high-quality links. The primary reason behind adopting the Received Signal Strength Indication (RSSI) threshold is that its use imposes no additional overhead to the network, it is easy to obtain, and it gives a reasonable estimate of link quality. However, the threshold should be specified carefully, because the only route to some nodes may include links with low RSSI packet values. If the chosen threshold is too low, the network may suffer from a flood of unnecessary messages, while if too high, the network may become partitioned.

In SHM applications, keeping the routing delay as small as possible is important. To reduce the delay caused by the routing protocol, RREQ messages are not regenerated when route discovery is unsuccessful; thus, the request for repeated route discoveries is initiated from the higher layers. In GPMH, this task is handled by the reliable data transfer service. This method transfers the control over the delay imposed by routing to the higher level service (reliable data transfer) and simplifies the adjustment to application needs in terms of latency.

The GPMH implementation of AODV employs an alternative to the standard hop-count routing metric used for evaluating different paths. The major drawback of the hop-count routing metric is that it may lead to the selection of long links, which in turn result in an increase in the loss ratio and power consumption, as well as a decrease in signal strength indicator for the received packets. GPMH implements a new route metric based on the link quality indicator (LQI), which is a measurement included in the header of each received packet characterizing the quality of link over which the packet was transmitted. The LQI value is calculated for each received packet by the CC2420 radio, and measures the received energy level and/or SNR (Chipcon Products 2004).

LQI is designed to be a better estimate of overall link reliability (packet reception rate), whereas RSSI is only a measure of maximum signal level, as mentioned above. However, Srinivasan and Levis (2006) have concluded, based on empirical evaluation, that an RSSI-based link quality indicator is a superior predictor of link reliability compared to LQI. There are two notable exceptions to this finding: (i) environments with asymmetric link quality and (ii) communication near the limit of radio sensitivity. These conditions are rare in many WSSN deployments; however, they are precisely the conditions encountered in SHM deployments similar to those on the Jindo Bridge (see Section 2.2). LQI is expected to have a higher correlation with link reliability when the network topology is sparse, and poor-quality links are prevalent. Moreover, preliminary testing of GPMH deployments on civil structures has provided empirical support for this observation. In GPMH, each RREQ packet carries a route metric, which is calculated on each intermediate node. The new route metric is a linear combination the hop count and the LQI value for the received packet. This routing metric is similar to the metric presented in (Moinzadeh *et al.* 2010), except that the link quality indicator is used herein instead of the signal strength. Other routing metrics, such as the four-bit link estimation (Fonseca *et al.* 2007) or a hybrid implementation may provide superior performance under certain conditions; however, a detailed evaluation is beyond the scope of this paper. The proposed routing metric provides a sufficiently reliable assessment of path quality, while not adding significant overhead to the protocol. Moreover, the simplicity of using this metric along with the built-in metric of AODV is attractive.

5.1.2 Modifications to the reliable data transfer service

In what follows, the reliable multi-hop data transfer service is briefly introduced and its important features are discussed. This data transfer service has been designed as a natural extension to the Illinois SHM Project Services Toolsuite, which employs a service-oriented architecture to manage the intrinsic complexity in large-scale WSSN applications. The GPMH communication protocol is implemented underneath the reliable communication protocol developed by Nagayama and Spencer (2007). As a result, the multi-hop data transfer functionality can be added transparently to all applications built using the Toolsuite simply by replacing the single-hop reliable data transfer service with its multi-hop counterpart.

This reliable data transfer service is implemented on top of the routing protocol in an end-to-end manner. Packets are sent to the destination node over multi-hop links without intermediate checks. If missing packets are detected, the destination node requests for the missing packets, and the originator sends them again. To minimize packet overhead, NACK packets are utilized. Here, short messages and long data records are treated separately. Moreover, based on whether the communication is unicast or multicast, a different procedure may be applied (Nagayama and Spencer 2007). For long data records, the sender breaks the data record into smaller packets and then sends them. Once all the packets are transmitted, the sender returns a message to the receiver, indicating the end of data transmission. Subsequently, the receiver responds to the sender with the packets that are missing. Only the missing packets are retransmitted. For short messages, because only one packet is sent, an acknowledgment is returned from the receiver to the sender for each packet. This method of end-to-end reliability support alleviates the need for large buffers on intermediate nodes as packets need little or no processing on these nodes. Moreover, if packet loss for each link is expected to be negligible, the end-to-end reliability check can reduce communication related to acknowledgment packets and allow for fast and efficient data transfer. In the case of high quality intermediate links, this approach can also result in a reduction in power consumption.

Several changes to the existing single-hop reliable data transfer service were required to extend it to exploit the AODV routing protocol. First, all transmissions of this service were replaced with the modified TinyAODV send and receive interfaces. To use the reliable data transfer service coupled with the AODV multi-hop routing, delays were added between consecutive transmissions to accommodate the additional time required for multi-hop data transfers. These delays allow for the underlying routing protocol to stabilize before a new request is generated or before more data is sent. Moreover, the send and receive timeouts in this service were increased relative to the delays in the routing algorithm. Although these changes slow down the applications, they allow route discovery to be performed without interruption. The resulting service allows for reliable multi-hop transmission of data packets that is made possible through the use of the AODV routing protocol.

5.2 Efficient single-sink multi-hop (SSMH) communication

This section describes SSMH, which is a multi-hop communication protocol designed for efficient collection of large amounts of data from arrays of sensor nodes. 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 transfer 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.

5.2.1 Shortest path search for single-sink data collection

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. SSMH improves the route discovery process 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 Fig. 6.

In this proposed customization, 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 two-hop range find nodes which already have routes to the sink. The process continues hop-by-hop in this manner until all nodes set up routes.

To establish the single-hop routes, each leaf node initiates route search toward the sink node after

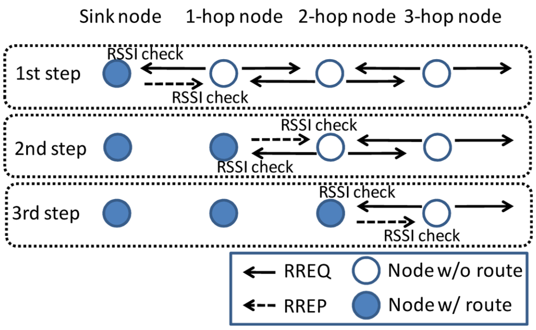

Fig. 6 Incremental routing process (for illustration purposes, a linear network topology is shown)

receiving a command packet that was disseminated over the network. The AODV routing process with TTL = 1 starts by each node broadcasting a RREQ packet. To reduce packet collision, the RREQ packet is sent after some random waiting time. The transmission is repeated multiple times to compensate for packet collisions; this repetition can practically eliminate the possibility of missing the RREQ packet due to collisions. Because the TTL value is one, only RREQ packets from nodes in a single-hop range reach the sink node. On reception of these RREQ packets, the sink node examines the Received Signal Strength Indication (RSSI) value and disregards packets with RSSI values lower than a specified threshold. Note that RSSI is employed as the link quality metric, but other metrics may be used in its place. The sink node then returns the RREP packets only to the certified nodes; the RREP packets are sent multiple times to compensate for packet collisions. When each originator of route search in single-hop range receives the corresponding RREP packet, its RSSI value is examined and single-hop route is established if the value is larger than the threshold. Created routes are clearly of the shortest path (i.e., one hop), and the quality of the links, whose RSSI values are greater than the threshold, is considered satisfactory.

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. When this process is conducted again, nodes in the three-hop range establish routes. The process is repeated for a predetermined number of times.

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.

5.2.2 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 presentation of a solution to this issue, consider the case where multiple packets are transferred through four nodes as shown in Fig. 7. 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 Fig. 7, 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.

One problem with the packet collision avoidance through transmission time slot division, as described above, is that it slows down communication. Multi-hop data transfer protocols, such as MintRoute (Woo *et al*. 2003) and Collection Tree Protocol (Gnawali *et al.* 2009), utilize transmission timers, which in principle, results in a much smaller throughput than for single-hop. As a result, the transfer of large amounts of data may take an 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 2.4 GHz IEEE.802.15.4 RF device with 16 user-selectable channels, each requiring 5 MHz of bandwidth between 2405 MHz and 2480 MHz. In contrast to 2.4 GHz 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

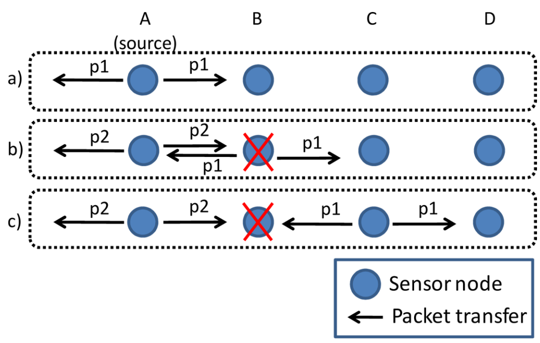

Fig. 7 Example illustrating the need for a clear time between packet transmissions

channels is a potential solution.

Channel switching is carefully integrated into SSMH 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 single-hop reliable communication middleware service (Nagayama and Spencer 2007), which can transfer data quickly with packet loss compensation, is utilized for each link. Two frequency switching approaches are explained next.

5.2.2.1 Dynamic channel allocation

One approach for frequency switching is dynamic channel allocation. Prior to the link-by-link data transfer, the sender searches for an available wireless channel by changing its RF channel to a tentative channel and listening to RF packets. A TinyOS function which counts the received RF packets over the last one-second is utilized to determine channel availability. If the overheard packet number is small, the sender considers this channel as available. If the number is large, the node examines another RF channels. Once an available channel is found, the RF channel is switched back to the original channel and one packet including information about the available channel number is sent to the receiver asking whether the receiver is ready to receive a new data set via the channel. The receiver responds only if ready. If the sender does not receive a reply from the receiver, it repeats this process at a certain interval. Before the receiver responds, the available channel is also examined by the receiver in the same manner. In the receiver response packet, the channel availability is included. If the channel is not available, the sender repeats the process of searching for an available channel and then notifies the receiver again. If the channel is available, the sender reliably notifies the receiver that these two nodes should then switch to the available channels after a certain time delay. Using the new channel, the two nodes perform data transfer.

Two pairs of nodes in a given neighborhood may begin the above-mentioned channel search at the same time; as a result, they both will be in the listening mode to monitor RF activity and cannot find each other's activity. If the two pairs begin data transfer in the same channel without knowing each other, packet collisions will frequently occur. To reduce possible occurrence of such collisions, the RF channel search is performed after a random wait time. Nevertheless, the chance of two pairs switching frequency to the same channel simultaneously cannot be eliminated. When such collisions occur, link-by-link data transfer takes much longer than usual. Therefore, a timeout for link-by-link data transfer is utilized to detect such collisions. If link-by-link data transfer times out, then the data transfer is halted, and resumed after a random wait time.

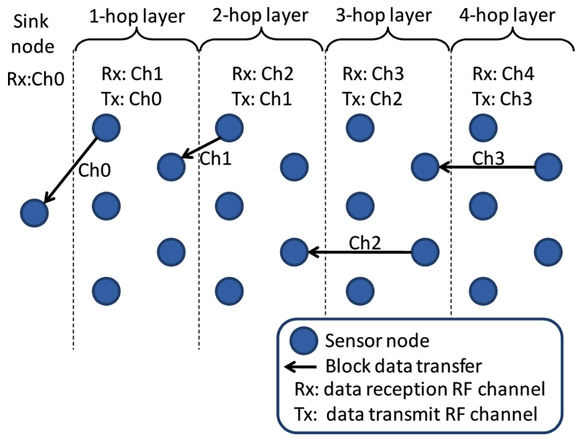

Fig. 8 Data transfer based on static RF channel allocation

5.2.2.2 Static channel allocation

The second approach employs static channel allocation (see Fig. 8). 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 Fig. 8). 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 minimized. 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; large amounts of data are transferred for each instance. 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.

To eliminate bottlenecks at nodes which have many children (i.e., nodes directly under the node of interest), as compared to the other nodes in the same layer, on-demand rerouting is employed. When an upper-layer node is not able to receive data from the lower-layer because the upper-layer node is forwarding data to an upper-layer node or because the buffer is full, the lower-layer node can start searching for a new parent node by initiating the route discovering process and then send data using this new route. In this way, channels are well utilized and bottlenecks created at a node with many children can be resolved.

Because the static channel allocation approach is simpler, and simplicity usually results in fewer programming bugs and fewer sensor network hang-ups that are typically unforeseen before full-scale deployment, the second approach was employed in the SSMH implementation on the Imote2 platform. However, if a WSSN is used in environments where interference with other RF devices is severe and/or varies with time, the dynamic channel allocation approach better suits the problem.

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.

5.3 Preliminary results

This section presents preliminary results for both the GPMH and SSMH reliable multi-hop communication protocols.

The GPMH reliable multi-hop communication protocol has been evaluated on several test beds. Initial tests were carried out in an office building with 5 to 15 nodes. Subsequently, experiments with 24 nodes were performed in an open parking garage, where the distance between nodes was between 5 m and 8 m. In these experiments, the average route discovery time was approximately 50 seconds. To balance prioritization of stable, high-quality routes with the need to communicate in situations where the signal strength is adversely affected by the environment, an LQI threshold of 60 was determined empirically. The maximum observed hop count for the deployment was 3. In all of the experiments, a linear topology was employed to aid measurement and performance evaluation. For the range of experiments considered, the only change required for integration of GPMH into the various applications was to change from the peer-to-peer communication interface to the interface provided by GPMH, confirming the flexibility, and adaptability of GPMH. Moreover, these experiments played an important role in optimizing the implementation.

The efficiency of data collection employing the SSMH communication protocol 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 multi-hop performance provides approximately a ten-fold improvement on the throughput of the MintRoute-based data collection strategy (Kim *et al.* 2007).

6. 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 protocol customizations are proposed. The Ad-hoc On-demand Distance Vector (AODV) routing protocol was adopted with customizations of the routing metric and exclusion of unnecessary functionality. Additionally, two data transfer services utilizing AODV routing are proposed. The GPMH service features sufficient flexibility to accommodate a broad range of communication patterns, suitable for centralized and distributed data collection, as well as application-independent communication tasks. The SSMH service, on the other hand, focuses on efficient collection of large amounts of data at a single sink node, concurrently exploiting multiple radio channels. Both of the proposed approaches have been implemented on the Imote2 platform and applied in laboratory tests as well as test deployments on full-scale bridges.

Acknowledgments

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