Agility of Wireless Sensor Networks for Earthquake Monitoring of Bridges

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***Abstract*— Applying wireless sensor networks (WSNs) for bridge monitoring has received considerable interests over the past few years. In this paper two WSN-agility problems are identified based on the deployment experiences of WSNs in earthquake monitoring of bridges: (i) timely capturing the earthquake response of bridges and (ii) quasi-realtime processing of the measured data for bridge modal identification in monitoring the features of the structure. This paper also presents solutions for these problems: a pulse-based media access control scheme for the first problem and a distributed approach to modal identification by spectral methods for the second problem to address the combined agility issues. Results show the effectiveness of the proposed approaches.**

Keywords-wireless sensor networks; network agility; media access control; modal identification; distributed algorithm

I. Introduction

Bridges are critical to the national economy and public safety [1]. There are considerable interests over the past few years in the application of wireless sensor networks (WSNs) for cost-effective bridge monitoring [2-6]. However, deployment experiences of WSNs in earthquake monitoring of bridges reveal that further investigation is needed on the agility of WSNs. Agility is defined as the capability of a WSN in timely capturing the event response of the monitored bridge, processing the measured data and extracting the relevant features, and interpreting the results. The importance of WSN agility in the context of earthquake monitoring of bridges is described as follows.

1. *The need of an agile WSN in capturing the bridge's responses to earthquakes*. In May 2006, a group of researchers from the University of California, Berkeley, installed a WSN on the main-span and a tower of the Golden Gate Bridge (GGB), which consisted of 256 accelerometers. After the initial installation phase, the network operated on the bridge from June to September 2006, periodically collecting acceleration and temperature data and transmitting them to a base-station located inside the south tower. During this period, at least three earthquakes occurred in Northern California, the Glen Ellen shaking of magnitude 4.4 on August 2, 2006 being the largest amongst them. The sensor network on the bridge did not collect data during any of these earthquakes [7] because it was not alert for their arrival: the network was either asleep or transmitting ambient vibration data collected prior to the arrival of the earthquake.
2. *The need of an agile WSN in processing the sensor data for bridge modal identification, extracting important features of the data and interpreting the results*. During an earthquake the bridges have significant non-linear behaviors and many of their extreme-condition design provisions are reached. The owners, engineers as well as the general public are interested in knowing how each element of the bridges performed during the strong motion, take that information into consideration in responding to the event, and remedy the possible failures in the future retrofits/design of that and other bridges. This can be done by relating the structural condition of the bridge to features of the response data, and monitoring changes in those features.

These two problems are complementary in a system's design perspective as they can be viewed as two sides of one coin: the former deals with the data capturing agility and the latter with processing agility for a bridge monitoring system. Here low energy-consumption is an important design factor as the WSNs need to be deployed for bridge monitoring for long periods of time.

In this paper, we present a pulse-based media access control (PB-MAC) approach in Section II to address the communication agility aspect of the first problem. A distributed approach to modal identification of dynamic systems is presented in Section III to provide an example for distributed timely feature extraction. Two variations of the spectral method and their performance are described and compared.

Based on the proposed approaches, a trigger message from a nearby observation site can be timely propagated across a WSN to preempt current tasks such as energy-saving sleeping and scheduled data transmissions so that the sensor network can be forced into a record ready state before the earthquake waves reach the monitored bridge. Then the distributed approach to modal identification provides timely in-network analysis results based on distributed sets of sensor data, rather than waiting for all the data to be collected at a base station, which is the common approach to characterize the dynamic properties of a structure, identify possible damage and update mathematical models of the bridge. It is critical that these tasks be completed as quickly as possible, and thus the updated status of the structure is available for post-earthquake disaster response. In this paper, we address distributed and timely identification of select features of data (modal properties). Consequent tasks in relating the modal properties to the possible damage are beyond the scope of this paper and are extensively discussed in the literature [8].

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II. Pulse-Based Media Access Control

The successful dissemination of trigger messages in WSNs can make a difference between capturing a bridge's response to an earthquake and missing the opportunity to do so. To achieve this goal to enable a WSN to capture the critical information, *trigger message* dissemination needs timely and lossless medium access in WSNs.

To solve the communication agility problem in a large scale WSN deployment, i.e. a WSN of tens of hops in the network diameter as in the Golden Gate Bridge case, we introduce a preemptive MAC to preempt existing low-priority communication by the high-priority trigger messages. In fact, the experience described in Section I shows that existing non-preemptive MAC without priority support has failed to capture earthquake signals in practice, and using a reset message flooding based on the existing MAC protocols will take a long time to propagate through a large WSN due to hidden terminals [9], which may also lead to the loss of the opportunity of capturing earthquake signals by the WSNs.

A. Related Work

In the literature there are media access control (MAC) protocols that support priority medium access [10-13]. However, these protocols focus on providing *statistical priority for unicast flows* instead of *strict priority for individual packets*. Packets may experience unpredictable delays in media access due to deferrals and back-offs. Long medium access delay is, however, intolerable for trigger message dissemination because of the short lifetimes of trigger messages in earthquake scenarios. Moreover, a WSN may generate different types of messages with different priorities or delay tolerance. As a result, a MAC scheme must be able to ensure that a message with a longer delay tolerance yields to a message with shorter delay tolerance. This paper presents a MAC scheme [14] that addresses this issue. With its novel pulse-based control mechanism, the distributed scheme realizes multiple levels of strict priority scheduling for various types of packets, e.g. trigger-message, time-sync and data packets.

B. PB-MAC

PB-MAC is an out-of-band MAC in which the control channel only carries *pulses* and the data channel only carries *packets*, such as trigger-message, time-sync and data packets. A regular pulse consists of an active part of a coded length in a single-tone wave and a random pause part in two sub-parts, i.e. a contention window of a fixed size and a residual pause of a random length, where the contention window is cut into equal-size contention sub-windows. A node transmits regular pulses in the control channel when it is transmitting a packet in the data channel. The active part of a pulse signals a busy data channel, while the pause part is mainly for collision detection. Any transmitting node hearing a pulse aborts its transmission. The length L of the active part of the pulse indicates the priority level P of the data packet in transmission; a longer active part indicates a higher level of priority for the data packet [14-15].

When a node detects a pulse in the control channel, it measures the length of the pulse's active part. If the active length is a valid coding length for priority level information, the information L is decoded. Thus every receiver of the pulse has the knowledge of the priority level of the packet in transmission L_r. When a packet source S_i detects a busy control channel but finds that the priority levels L_i of its packet is higher than the priority level L_r of the packet in transmission, the source S_i starts a random backoff timer as soon as the pulse in the control channel pauses. A packet source with a lower priority packet will defer and check the control channel status later. The random backoff delay d_i of the source i is drawn in a contention sub-window that is determined by the priority level L_i of the source's packet. A higher level of priority acquires a smaller sub-window and thus a shorter delay. The source with the shortest backoff delay (i.e., of the highest level of priority such as the trigger message's priority level) acquires the medium before other sources do, and this source becomes the winner source S_v in this round of contention. When the backoff timer of the winner source S_v expires, S_v starts to transmit pulses in the control channel. The packet source S_o, then owning the channels, is still in its pause in the control channel because its random backoff delay d_i is of a larger value due to the relatively lower packet priority. Therefore, S_o can detect the pulse of S_v and releases both channels. In the PB-MAC design, a relay scheme of pulses by the intended packet receiver is also designed to suppress hidden terminals [14-15].

C. Simulation Results

In the ns-2 simulations testing the competition among packet sources, five sources S_1 to S_5 compete with each other. Source S_4 is assigned the highest level of priority called level 3 for trigger messages, S_5 a priority level 2 for time-sync control packets, and others have level 1 for sensor data packets. As shown by the simulation results in Fig. 1, S_1 successfully accesses the medium first because its packets arrive at its MAC sub-layer first. However, before it finishes transmitting its first packet, it is interrupted by S_5, which has higher priority than S_1. Similarly and again, S_5 is interrupted by S_4, which has the highest priority among all of the five sources. Source S_4 successfully finishes transmitting its packets after interrupting S_5. Source S_5, with the second highest priority, then transmits its packets. After S_4 and S_5 finish sending their packets, other sources transmit their packets in sequence, although S_1 and S_3 have an immediately-resolved collision at about the 31 ms. The results show that PB-MAC can preempt low-priority events by high-priority ones and thus enable timely trigger message dissemination [15].

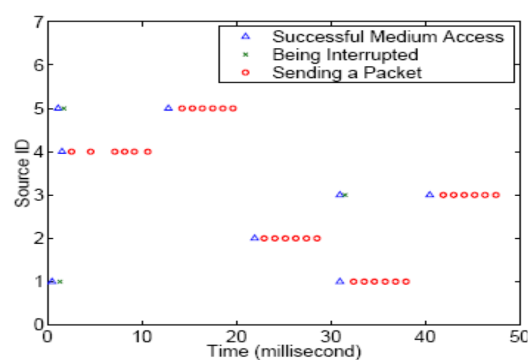

Figure 1. An event map of 5 competing packet sources of 3 priorities [15].

III. Algorithms for Distributed Modal Identification

There are two main challenges in the structural monitoring application compared with other applications of WSNs: fast sampling rates which result in large volume of data in a scalable network, and nature of monitored features of interest whose identification depends on cross-correlation information between different nodes. Distribution of identification algorithms in network is an essential aspect for a scalable WSN for bridge monitoring applications. It is important from two critical points of view: energy consumption and network agility. Transmitting one bit of data over a wireless network consumes about four orders of magnitude more energy than performing a local computation on the same bit, so replacing trans-network communication with in-network computation is critical in maintaining a low-power WSN. Communication bandwidth saving is also a critical consideration for bridge monitoring using WSNs because the transmission time of a large volume of data generated by the network could significantly affect its performance, as responding to an earthquake needs timely analyses of the data.

Condition monitoring of structures depends on monitoring specific features of the measured response and translating its changes to the health state of the structure. The existing paradigm of tethered networks, which requires collection of all measured data, is sufficient but not necessary in extracting the appropriate features. Examples of such features are the modal properties of a dynamic system, which change as structural damage occurs. In this section an example of distributed modal identification algorithms is presented and implemented to estimate the modal properties of a long-span bridge.

A. Related Work

The existing research on modal identification of dynamic systems (both input-output and output-only) is almost exclusively devoted to algorithms processing the entirety of the measured data [16-19]. The exceptions include in-network processing such as hierarchical classification [20], progressive transmission [21], and a class of spectral methods, also known as peak picking methods, which allows for partial distribution of computation within the network [22].

In all of the spectral methods, the computation of the modal properties of the system depends on the estimation of the cross-correlation matrix of the measured response quantity. The vibration frequencies and damping ratios are related to the eigenvalues of this matrix (or a matrix derived from it) and the mode shapes are related to its eigenvectors. This process requires the computation of full cross-covariance matrix to feed the modal identification algorithms. Another class of such algorithms is developed for the free-vibration response of dynamic systems, which again requires computation of Markov parameters from the cross-correlation matrix for the case when only the forced vibration response is available.

B. Spectral Methods

The spectral methods (also known as peak picking methods) are simple ways to estimate modal properties of a system using the power spectral density (PSD) of output-only data. These methods are based on the property that for a linear system with a white or nearly white noise excitation, the PSD at each degree of freedom is peaked at the resonant frequencies and the peak values are proportional to the corresponding mode shape. These two conclusions can be used to identify the mode shapes of the system using either the auto PSD (diagonal elements of the PSD matrix), or the cross PSD (each column of the PSD matrix) of the signals recorded at each degree of freedom. The advantage of using the diagonal of the PSD matrix is that the required elements can be computed without the need to communicate the entire signals over the network, i.e. local computation of the auto PSD is sufficient for identifying the mode shapes. Once the auto PSD is estimated at the node level, only their peaks will be communicated through the network.

This distributed modal identification algorithms work as follows: At each node, the system parameters are estimated using the spectral method based on the available data at that node. The estimated parameters are then passed over to the neighboring node closer to the base station to repeat this process until converged. By pushing the computation in-network and reducing the communication load of the network, this approach achieves two main goals of the distributed system identification. It saves energy, which results in longer battery life and lowers the maintenance cost of the network. It also speeds the identification process, since the bottleneck is the delay due to the communication time for all of the data from the network to be collected at a base station. A reduced communication load provides quasi-realtime estimates of the modal properties of the structure, which are available immediately. This initial estimate is improved in accuracy and resolution as the estimated parameters travels through the network and iterates.

C. Performance Evaluations

Ambient acceleration data from the deployment of a large WSN on GGB is used to evaluate the performance of both variations of the spectral methods. For detail specification of the sensors and deployment plans refer to [7]. Fig. 2 shows the first three vertical mode shapes of the bridge, identified using auto-PSD (APSD) and cross-PSD (CPSD) spectral methods, as well as their 95% confidence intervals estimated using ARMA models which consider the full correlation information. The identified modes using the CPSD method lie within the confidence intervals for all three modes. The results from APSD method are also within the confidence interval with a few outliers, especially near the modal nodes. The superior performance of CPSD is due to partial consideration of cross-correlation information, but both methods perform exceptionally well for the low modes of this long span bridge.

Note that for the APSD method, the single-hop communication load of a network of m nodes where each node collects p data samples is only $O(m^2)$, compared with $O(pm)$ for the CPSD estimate and $O(pm^2)$ for the complete non-distributed models. This is a significant saving in communication, since m and p are large for a scalable WSN, and p can be up to three orders of magnitude larger than m. Note that this communication saving is critical for the WSN-based bridge monitoring system responding to an earthquake with timely analyses of data.

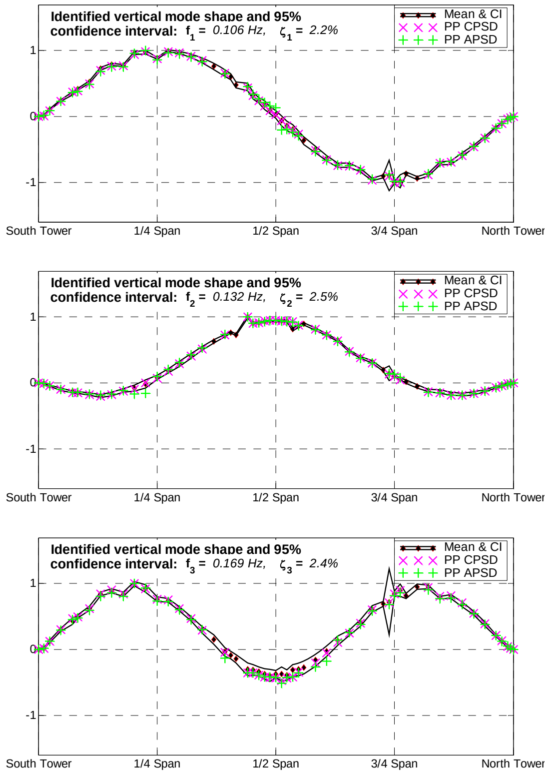

Figure 2. Comparison between third identified vertical mode shapes using Peak Picking methods, and the confidence intervals.

IV. Conclusions

In this paper we present approaches that address the agility issues of WSNs in timely capturing the earthquake response of bridges and distributed processing of the sensor data for bridge modal identification.

1. Using a controlled flooding on top of the PB-MAC, a trigger message from a nearby observation site can be timely disseminated to preempt current tasks in the WSN deployed at a bridge so that all sensor nodes can be forced into a record ready state before the earthquake waves reach the bridge.

2. Using both variations of spectral methods, the algorithms provide in-network analysis results based on distributed sets of sensing data that can be used to characterize the dynamic properties of the structure, identify possible damage and update mathematical models of the bridge.

Results show the effectiveness of the proposed approaches in addressing the agility issues in WSNs for earthquake monitoring of bridges. Our future work includes implementing the PB-MAC scheme and the algorithm for distributed modal identification in a practical WSN and deploying it on testbed bridges.

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