Sensor Network Issues in the Sustainable Bridges Project

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I. INTRODUCTION

The proliferation of sensor network research in the past years has lead to an increase on the number of applications developed for the most diverse areas. Some projects like Hogthrob or Floodnet deal with the monitoring of animals, habitats or environmental conditions in a cost-effective way. Others, like Ubicare are health monitoring applications, whereas Odyssey or WINS allows the U.S. military to perform underwater surveillance and terrain exploration. Finally, applications such as intelligent traffic systems and smart room environments provide the necessary infrastructure to allow users to interact with their environment (cars or buildings) in a more sophisticated and efficient way. In the case of vehicular networks, for example, the user is assisted in the process of driving by allowing important information like traffic jam or road conditions data to be distributed to other cars immediately.

In this paper, however, we concentrate on Sustainable Bridges, an Intelligent Building Monitoring application, being developed as part of the 6^{th} Framework Programme from the European Union [1]. Sustainable Bridges is a project with 32 partners from all over Europe which assesses the readiness of railway bridges to meet the demands of the 2020 scenario and provides the means for upgrading them in case they fall short. The 2020 scenario requires increased capacities with heavier loads to be carried and bigger forces to be absorbed due to longer faster trains and mixed traffic. An important part of this project is to provide efficient monitoring of bridges using MEMS and wireless technology.

As we will see in the following sections, the Sustainable Bridges application exhibits some interesting characteristics that make it the ideal place to investigate and test canonical problems related to the field of sensor network research.

The remainder of this paper is structured as follows. Section II gives a brief overview of the Sustainable Bridges project and identifies the characteristics related its sensor network architecture and application domain. Section III identifies the research issues related to the project, provides some insights about related work and gives a list of some of the challenges that need to be solved within the project. Finally, section IV concludes this paper.

II. OVERVIEW OF THE SUSTAINABLE BRIDGES PROJECT

Traditional monitoring of civil structures, like bridges and buildings, has been performed either by visual inspection or by the installation of collections of sensors that communicate with each other using some kind of cable technology. In the first case, the interpretation and assessment of the structure is based on the experience of the expert, whereas the second method requires the expensive installation of kilometers of cables to cover the object subject to observation.

Therefore, one of the main goals in the Sustainable Bridges project is to develop and provide the necessary infrastructure and algorithms to allow for the cost-effective detection of structural defects and to better predict the remaining lifetime of these structures. The project is committed to the use of wireless sensor network technology in order to reduce the costs involved in the installation and maintenance of a cabled system so that, as a side-effect, a number of sensor network challenges need to be solved.

For this purpose, some of the researchers involved in the project are working in developing the necessary algorithms to detect structural defects based on the audible information emitted by the structure itself [6], [5]. Using these algorithms, it will be possible to determine whether or not a crack in the structure has been produced and, if so, where it is located. If needed, a specialized team of engineers will then inspect the affected zone knowing in advance where to look for the problem, thus reducing the time needed to repair it. Also some other research is going on in the field of modal analysis and stress, strain and displacement measurement using the same wireless sensor network. However, this paper will focus only on audible information (acoustic emission) due to the highest requirements the sensor network has to fulfil.

Sensor Network Architecture

The sensor network functionality required for the Sustainable Bridges project has a number of characteristics which are important from the point of view of sensor network research. In this particular setting, the network is composed of several types of sensor nodes: temperature and humidity, vibration, material stress sensors, etc., located at specific points within and outside the bridge. We are, therefore, dealing with a static network topology, where several types of nodes cooperate with each other.

As shown in Fig.1, each individual sensor is affixed to the structure, communicates ad-hoc with its neighbors and, depending on its location, might be part of a cluster of nodes, whose purpose is to coordinate the decision process involved in determining whether or not a structural defect has occurred or a change of structural behavior becomes obvious. The network user (in most cases a civil engineer) has a global view of the network and specifies which nodes form part of a cluster and which ones are simply needed to forward data.

Finally, the sensor network is connected to one or several sinks, that is, one or more desktop computers located inside or nearby the bridge whose purpose is the collection of data and the interfacing of the sensor network with the user. Therefore, the Sustainable Bridges application has a hybrid network architecture with possibly a multitude of sinks.

III. RESEARCH ISSUES

Let us now describe some of the more relevant research issues that need to be successfully solved within the Sustainable Bridges project from the perspective of computer science and sensor network research. Unless otherwise noted, we assume that the typical resource limitations of sensor networks such as energy, code size, etc. apply. Further assumptions are listed in their respective sections.

A. Network Configuration

The problem of network configuration involves two main challenges: the assignment of roles within the network, and the provision of optimal routes so that all nodes can talk to each other efficiently.

The first problem is solved in the Sustainable Bridges project by human intervention, since the user is able to determine what kinds of roles should be assigned to each node. In order to assist the engineer in doing this assignment in an efficient way, one could think of the usage of a role distribution language, as described in [11], although this method still would need to be optimized.

Using this particular role assignment, code distribution algorithms can also leverage the knowledge of differences in role assignment to route code updates only through the set of nodes that really need it, that is, belong to a specific role. This issue is addressed in [8].

Finally, wireless monitoring civil structures require optimal (power efficient) network configuration, because the monitoring system must be able to function several month or years before requiring the exchange of batteries. For example, a detailed bridge inspection has to take place at an interval of three or six years in Germany. Therefore, it is desired, that the lifetime of the monitoring system also lasts at least three years. Although there is a number of research approaches proposing different techniques to optimize network configuration [14], this issue needs proper modeling that takes into consideration the adjustment of transmission ranges [12] and the choice of the most efficient path to forward the data to the sink node. A solution for both, the case where global and local knowledge is available still needs to be addressed.

B. Cluster Management

As explained in Section II, part of the network is composed of clusters of nodes that communicate with each other. The need for cluster formation and management is motivated in the Sustainable Bridges project by the necessity to decide whether or not an event (noise, for example), is related to a structural defect. In order to reduce the number of false positives, all members of a cluster that might have detected some noise "debate" whether or not that event needs to be reported to the user. For such purpose, clusters need to organize themselves and determine the cluster head based on the current conditions of the network.

Even though there are general techniques for leader election in distributed systems and MANETs [3], these solutions cannot be used in our sensor network setting,

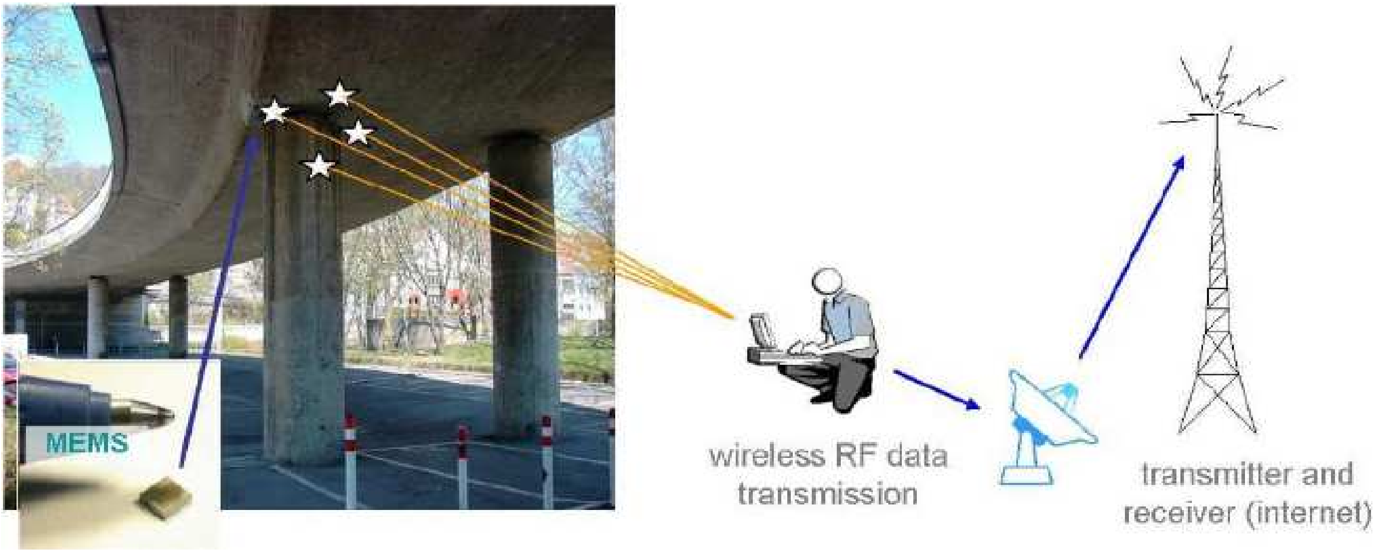

Fig. 1. Network Architecture of Sustainable Bridges

because they are too inefficient. In our case, application knowledge, such as node IDs and/or cluster IDs, as well as the fact that a global view of the system might be stored at the sinks, could be used to manage the available clusters without using as much communication as in the traditional case.

C. Event Localization

Most sensor data is associated with the physical context of the phenomena being sensed. Hence event localization, that is, the determination of the position of specific events, is an important problem that needs to be solved efficiently for the application at hand. In our application, this is one of the main tasks of a cluster.

The use of signal strength techniques for event localization and tracking of moving objects is well-known [10]. But this event localization uses the position of the sensor itself, which is different from the origin of the acoustic event we are looking at in the Sustainable Bridges project. In our case, the application contains a static network topology, which simplifies the problem in a certain way, because we can integrate some sensor nodes to a cluster. Such clusters or sensor arrays are well known for the localization of earthquakes or other seismic events and could be used to localize damage processes in structural parts as well.

The use of the measured transient acoustic event and its onset time with the combination of knowledge about the specific positions and the sensing ranges of all nodes in the network would allow us to locate events very precisely, while at the same time being able to transmit this information using a very low number of packets. Therefore time synchronization of the nodes in the specific cluster is of particular importance for event localization.

D. Time Synchronization

Nodes within a cluster need to compare their readings of the complex data that encodes the observation of an event. In order to do this, each sensor has to be able to compare a transient acoustic wave with its neighbors in order to discard data that does not need to be forwarded. It is this in-node and in-cluster data analysis that allows the network to reduce the amount of information that needs to be forwarded to the sink, thus reducing the number of packets sent over the radio link.

In order to perform this comparison and to localize the damage zone, time synchronization techniques at least as precise as $60\mu s$ are needed. The algorithms available in the MANET literature and others developed for sensor networks [4], [9], [7], are not able to achieve these levels of accuracy. Therefore, new efficient time synchronization algorithms need to be developed and, if this is not possible due to some of the resource-limiting constraints of sensor networks (energy considerations, for example), it will be necessary to design new techniques for the comparison of complex sensor data in the presence of (possibly) shifted time series.

E. Data Aggregation

In addition to the local signal processing techniques used within clusters, the information that gets sent through the network can be aggregated in intermediate nodes and forwarded as needed in compound packets that save energy. Furthermore, aggregation functions like MIN, MAX, COUNT, etc. can be used for certain types of sensor data in order to further minimize the amount of transmitted data.

Even though several data management frameworks such as TinyDB [13] and COUGAR [2] can be found in the literature, in the Sustainable Bridges project it should be possible to leverage application knowledge to provide better in-network data aggregation. For this purpose, topological and role information can be used and will certainly lead to more efficient algorithms tailored to the specifics of the Sustainable Bridges project.

IV. Conclusion

The Sustainable Bridges project, an Intelligent Building Monitoring application developed as part of the 6^{th} Framework Programme from the European Union, provides a perfect setting for the testing, validation and real-world simulation of algorithms that leverage cross-layer information in topologies where nodes are static and the network has a hybrid structure.

Research in the areas of network configuration, cluster management, event localization, time synchronization and data aggregation has just started, but it seems clear that many interesting ideas related to sensor network research can be implemented and tested within the project.

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