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Wireless Sensor Network Architecture for Monitoring Large Physical System in Cyclic Mobility

Abdellatif Chafik *,** **Vincent Lecuire** *,** **Francis Lepage** *,**

* *Université de Lorraine, CRAN, UMR 7039, Campus Sciences,*
BP 70239, Vandoeuvre-lès-Nancy Cedex, 54506, France
(e-mail: firstname.lastname@univ-lorraine.fr)
** *CNRS, CRAN, UMR 7039, France*

Abstract: This paper addresses a sensor system dedicated to monitor a large mechanical machine. This sensor system is based on a wireless sensor network whose special feature is the mobility of one or more nodes following an invariant path traveled repeatedly. In the study described here the path is a circle. The topology chosen is that of locating relays on the mobile system that has appropriate geometric characteristics. A new dynamic routing algorithm is proposed. It uses the location and moving speed of mobile nodes to choose the optimal route of the packets forwarded to the fixed sink. Network performance is evaluated in terms of delivery time and packet loss rate and compared to this obtained by using flooding routing protocol. The results show that the proposed architecture and mechanisms deliver the appropriate quality of service for the monitoring of large physical systems.

Keywords: monitoring, mobile wireless sensor network, routing algorithms, cyber-physical system, measuring transmitters.

1. INTRODUCTION

Monitoring a large mobile mechanical system from a fixed host is a great challenge at information sensing level. This one must indeed capture data in many places and transmits them in long distance while crossing a link mobile to fixe. Instrumentation can be designed either to monitor continuously the installation to diagnose malfunctions and to ensure its safety or to make measurements during a verification - certification phase. For the second purpose Wireless Sensor Networks (WSNs) and more precisely mobile WSNs are well suited for rapid instrumentation of existing installations with moving parts without large investments. The sensor or sensors board can measure parameters specific to the mobile part (e.g., vibrations, forces acting on a mechanical part) or environmental parameters throughout the trajectory of the mobile (e.g., wind speed, temperature) or a combination of both. Mobile WSNs are a subtype of mobile ad-hoc networks (MANETs). They are distinguished mainly by their sensors and their low power. Among the large mobile mechanical systems, we address those moving in an invariant way over a fixed path travelled cyclically. This specificity is expected to optimize the sensor network topology and two essential functions: localization of the moving sensor node(s) and mainly routing. Examples are transfer lines of products in industry, material ropeways in cement factory or a great ride, a chairlift or gondola in a leisure park or a resort.

1.1 Scenario and assumptions

Let us consider an observation wheel like the Singapore Flyer with a diameter of 150 meters and a total height of 165 meters. Passengers take place in 28 capsules moving at the speed of 0.24 m/s. The safety of such outstanding leisure equipment is fully mandatory. Wind speed is measured permanently but at one point only. Although the lateral movement and vibration of capsules have been carefully studied to be reduced at very low level it will be a safety improvement to easily measure them time to time and their variation with wind speed and capsule load. The corresponding system must perform measurements on the mobile part and send them to a fixed station for data analysis and storage. The sensor must be able to send its data immediately after sampling the information independently of its position. This is a requirement for a monitoring application. For a measurement application for a technical certification or for checking by a safety committee, a recording of measurements and a deferred processing is possible. However, a live processing has two major advantages for this application: one is saving time and second is the possibility of changing operating measurement scenario (e.g., other mobile speeds, other stimuli) if measures approaching some thresholds or if artifacts are detected. For multiple reasons, it is necessary to place the control station in a room on the ground: power supply, station environment, operator comfort. A wireless sensor network with mobile nodes seems well suited to carry out such a measurement system. It enables rapid deployment thanks to its two major advantages: lack of infrastructure and self-configuration.

1.2 Research objectives

The overall objective of our research is to design the sensor network system capable of capturing information in the right places, at suitable time, with sufficient precision, and of transmitting data to the control station in real time and without loss. For economic reasons and for easy maintenance, a constraint is to use a wireless sensor network available off the shelf. Thus processing resources, characteristics of the radio links and medium access protocol are predefined. WSN have the already mentioned quality of installation facilitated by the lack of infrastructure and by self-configuration. But their performance is limited in terms of bit rate, reliability of communications and message delivery delay. This performance is closely related to the topology of the network and the routing algorithm. This is why these two essential features must be designed making best use of geometry of the mechanical system and its movement with the aim of meeting the required performance. The topology should ensure permanent connectivity between the sensor(s) and the sink. The transfer from sensor to sink is not straightforward in the general case where the two nodes are not always linked by a direct radio channel. So the packet needs to be relayed by intermediate nodes according to the principle of ad-hoc networks. Whatever the route is used it includes a wireless link between the mobile part and the fixed part located at ground. The place of the mobile-ground connection defines two types of topology:

- A topology with mobile-ground connection at level of the sensor, the rest of the topology being fixed ground relays;
- A topology with mobile-ground connection at level of the sink, the rest of the topology being relays embbeded in mobile nodes.

The second type of topology is the only one considered in this paper. It is well suited to mechanical systems consisting of spatially distributed subsystems moving together like materials ropeways. Routing determines the path of the data packet from the mobile sensor node to the fixed sink. Because topology is constantly changing, dynamic routing is required. The used routing criterion is the minimum of delay with the constraint of very low packet loss ratio. The proposed routing algorithm takes into account not only the location but the speed of the mobile too.

The rest of the paper is organized as follows. Section 2 describes the related works. The methodology and algorithms of dynamic packets routing in the network are described in Section 3. The performance of the proposed solutions is evaluated by simulations. The results are reported and discussed in Section 4. A conclusion and some perspectives complete this paper.

2. RELATED WORKS

2.1 Monitoring using Wireless Sensor Network

The use of WSN for monitoring is well known in several fields like military forces, environment, civil infrastructures often as an add-on on existing wired sensor networks. For example a WSN for Structural Health Monitoring has been designed, implemented, deployed and tested on the 4200 ft long main span and the south tower of the Golden Gate Bridge [Kim et al. (2007)]. WSN are used in the same manner in house monitoring and human heath monitoring [Akyildiz et al. (2002)]. These scenarii are very different from this of our research because almost the whole monitored system is static as well as all network nodes. Monitoring scenarii with mobile nodes connected using wireless technology are targeted by Cartel project at MIT [Hull et al. (2006)] and MobEyes at UCLA [Lee et al. (2006)] using VANET (Vehicular Adhoc Network). But this monitoring is adapted to a Delay Tolerant Network with non permanent link from a node to a sink and the nodes are powerful compared with those of the MWSN used in the architecture proposed in this paper. Machine monitoring using WSN are not frequently investigated in research papers. But some specific WSN dedicated to industrial automation have been developed by industry network manufacturers [Christin et al. (2010)]. They are based on WSN protocol standards but focus on quality of service and security. Major contributions focused on application and used very simple WSN. Some uses the wireless capability to monitor electrical motors [Lu and Gungor (2009), Lima-Filho et al. (2012)] but some address more global systems in order to optimize energy [Salvadori et al. (2009)] or to monitor machines-tools especially the wear of the tools [Tan et al. (2009)]. Due to the low number of hops in these networks most contributions improving QoS requirements for industrial uses focused on MAC layer [Yigitel et al. (2011)]. According to this survey, we observe that majority of the protocols follow a service differentiation approach. Packets are treated according to their class and the corresponding requirements by tuning the associated network parameters at the MAC layer. WSN sensor nodes defaults could occur and so affect the monitoring. The localization of the faulty sensors has been addressed by Chen et al. (2006). Finally no contribution has been found addressing especially big machines monitoring by WSN.

2.2 Mobile WSN routing

Any network routing is based on one or several metrics. Position with respect the sink and residual energy are the main metrics used in WSN routing. Energy is not a critical issue in our scenario because the installation is temporary and the nodes are limited in number and are accessible. So batteries can be renewed and recharged. Among the routing using position metric geographic routing is an attractive routing protocol for WSN due to its simplicity and scalability. In geographic routing [Mauve et al. (2001)], a node simply forwards a packet to be closer to the sink in terms of geometric distance, so this position based routing named Greedy Routing is simple and scalable since it does not require global topology information. However, due to the lack of global information, greedy routing can fail at voids or obstacle where there is no neighbor node that is closer to destination than this node. This is well known as the local maximum (or minimum) problem. This can be easily avoid when all node locations are known. Mobility of one or more nodes creates a fully dynamic topology and routing strategy must be adapted. Various geographic information based routing could be used. Zhao and Cao (2006) improve geo-routing using predicable vehicle mobility, which is limited by the traffic pattern and road layout. This concept of using expected next location in routing is interesting for our research.

In the same way Bertaux (2013) uses localization of the vehicle-node in order to anticipate the handover and thus avoid disruption of the information flow due to time to set protocols.

2.3 Mobile WSN localization

The location of a node is often required by the application in order to associate this location with value(s) measured by the sensor(s). It is also useful in geographic routing when this type of routing used. Localization of a WSN node can be done by various strategies [Li et al. (2010)]. These can be divided regarding the information processing into centralized or distributed methods, regarding the type of used signal into range-based or range-free methods and regarding the obtained position into absolute or relative methods. GPS is the most popular tool for outdoor localization but in the case of WSN mobile nodes, an efficient and accurate method has been proposed by [Chen et al. (2013)]. However a proven manner for mobiles is the use proprioceptive sensors such as low cost accelerometers [Hsu and Yu (2009)], gyroscopes, gyrometers, magnetometers, inclinometers or Doppler radar. We used one or other localization method up to now.

3. A NEW GEOGRAPHIC DYNAMIC ROUTING

3.1 Problem statement

Let us consider a wireless sensor network consisting of N mobile nodes equally distributed around a circle of radius R, as shown in figure 1. All the nodes move together around the circle so that they always remain at the same distance from each other, whatever the variation of the angular speed with time. A static sink node, which collects sensed data from the mobile nodes for the end user, is located slightly outside of the circle. Sensor nodes use radio-frequency communications to transmit data packets to the sink.

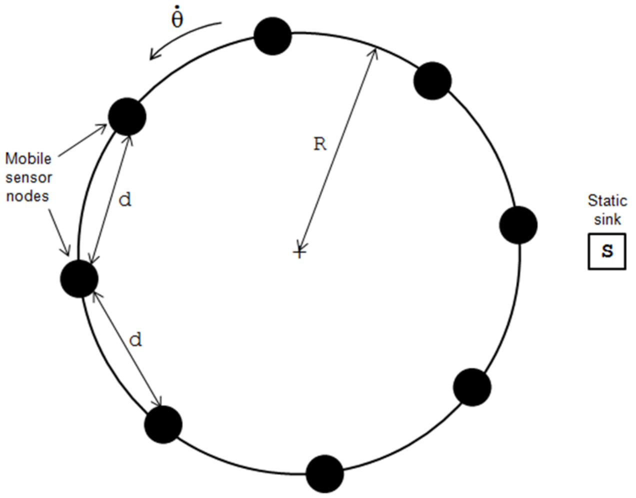

Fig. 1. Topology of the wireless sensor network with N mobile sensor nodes and one static sink.

The radio transmission range depends on the transmission output power. If the transmission output power is large enough to that sensor nodes can always reach the sink in one hop only, then the routing problem does not occur. However, using a single-hop communication model can be impossible when R is too large compared to the maximum transmission distance, or even undesirable especially for energy conservation purposes when sender nodes are battery-powered (see Monks et al. (2001)). In the case where a multi-hop communication model is adopted, it suffices that sensor nodes are able to transmit data packets to their two nearest neighbors for that a route to the sink exists. Let d be the distance between two consecutive nodes around the circle. We have:

$$d = 2R \sin \frac{\pi}{N} \tag{1}$$

Consequently, sensor nodes need to have a radio transmission range slightly higher than d for the wireless sensor network works normally. Under this condition, indeed, sensor nodes which are far away from the sink have two possible routes to reach the sink using multi-hop communications: a forward route following the rotation direction of mobile nodes and a backward route following the reverse direction.

We assume that each mobile sensor node is able to monitor the dynamic variations of its angular position and speed in real time (see section 2.3 which explains how this hypothesis can be tested). Therefore, the sensor-to-sink routing problem can be addressed locally, at the sensor node level. For the source sensor node, the problem is to find the best route to the sink as a function of its current position and speed, or, in other words, how to alternate between the single-hop route, the backward route and the forward route.

3.2 Route selection algorithm

Let O be the center of the circle and let S be the location of the static sink. Location of mobile nodes can be conveniently described in the polar coordinate system with pole O and polar axis $\overrightarrow{OS}$. Consider any mobile node, for example the one with polar angle θ which is labelled A in figure 2. Node A has two neighbor nodes that are candidates for next hop selection, node C in the rotation direction (forward route) and node B in the reverse direction (backward route).

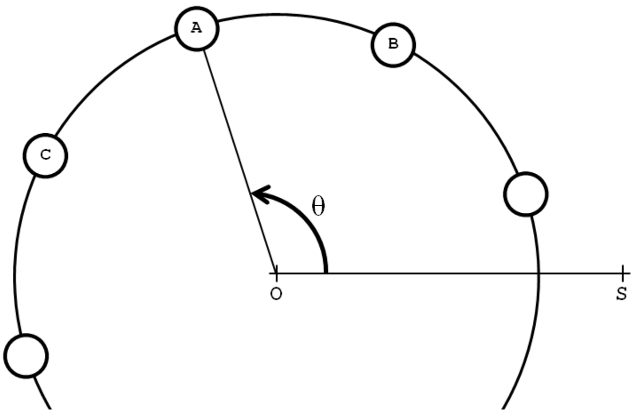

Fig. 2. Location of mobile sensor nodes in polar coordinates.

Let T be the one-hop transmission delay to send a data packet. If node A at position θ selects the forward route, then node C will receive the packet at position $\theta + \frac{2\pi}{N} + \dot{\theta}T$ due to mobility of sensor nodes, where N is the number of sensor nodes and $\dot{\theta}$ is the angular speed. In the same way, if the reverse route is selected, node B will receive the packet at position $\theta - \frac{2\pi}{N} + \dot{\theta}T$. Generally speaking, after k hops, the data packet reaches the node located at $\theta + k(\frac{2\pi}{N} + \dot{\theta}T)$ and $\theta - k(\frac{2\pi}{N} - \dot{\theta}T)$ by forward and reverse routes, respectively. Of course, the route having the lowest end-to-end delay, and hence the shortest hop count, is preferable. The choice between the forward route and the reverse route depends on the position θ of the source node.

The number of hops, k_f, to reach the mobile node closest to sink by the forward route is given by:

$$\lim_{k_f \in \mathbb{Z}+} \left[\theta + k(\frac{2\pi}{N} + \dot{\theta}T)\right] = 2\pi \tag{2}$$

Similarly for the reverse route, we have:

$$\lim_{k_r \in \mathbb{Z}+} \left[\theta - k(\frac{2\pi}{N} - \dot{\theta}T)\right] = 0 \tag{3}$$

From (2) and (3), the equilibrium point, i.e., the position of source node where $k_f = k_r$, is given by:

$$\theta_0 = \pi - \frac{N\dot{\theta}T}{2} \tag{4}$$

As a result, in the general case, the source node will select the forward route when its current position is higher or equal to θ_0, and the reverse route otherwise. If no neighbor node is closer to sink than itself, then the source node directly transmits data packet to the sink. This particular case appears when $\theta > \frac{2(N-1)\pi}{N} - \frac{T\dot{\theta}}{2}$ or when $\theta < \frac{\pi}{N} - \frac{T\dot{\theta}}{2}$.

Let us note that T, the one-hop transmission delay, depends on the nominal data rate of the radio transceiver and the protocol used at the MAC layer. The value of T needs to be known *a priori* and registered as an input parameter of our geographic routing algorithm.

4. PERFORMANCE EVALUATION

4.1 Method

The performance of our routing protocol is evaluated by simulations using WSNet network simulator [Chelius et al. (2007)] and considering the scenario of the Singapore Flyer. Consequently, 28 mobile nodes and a static sink are deployed over an area of size 170 × 170. The center of the circle is at coordinates (85, 85) and its radius is 75. The static sink is located at (85, 5). Mobile nodes are equally distributed around the circle: The initial coordinates of node 1 are (85, 10), those of node 2 are (101.69, 11.88), those of node 3 are (117.54, 17.43), and so on. Mobile nodes move around the circle at speed of 0.0032 rad/s. The radio model adopted in simulations complies with the RF CC2420 transceiver which is used on real wireless sensing devices such as the well-known MicaZ, TelosB and Imote2. It operates in the 2.4 GHz frequency band using O-QBSK modulation and provides a nominal data rate of 250 kbps. At the MAC layer, the famous B-MAC protocol (Polastre et al. (2004)) is selected. B-MAC can work in low-power listening (LPL) mode, i.e., node periodically sleeps, wakes up to check briefly for channel activity, and then returns to sleep if no activity is detected. B-MAC is configurable with some parameters which, last but not least, can be dynamically adjusted. Especially, the check interval (i.e., the period between consecutive wakes-up) is one of the parameters. Moreover, LPL mode can be enabled or disabled. Obviously, the one-hop packet delay (i.e., the input parameter T in our routing algorithm) depends on the configuration parameters of B-MAC. Especially enabling LPL mode has an influence on the packet delay, and packet delay increases as the check interval increases.

Simulation parameters are given table 1. Simulation duration is 4000 seconds, this time being equivalent to two rounds of the wheel. Simulation results are shown for both cases where LPL mode is either enabled and disabled. When LPL mode is enabled, the check interval is 10 ms.

Table 1. Simulation parameters

	Parameter	Value
Radio models:	Propagation range	20 meters
	Modulation	O-QPSK
	Data rate	250 kbps
	Interferences	orthogonal
	Antenna	Omnidirectional
Protocols:	MAC layer	B-MAC
	Routing layer	Our, flooding
	Application layer	CBR (20 bytes of payload)

For comparison purposes, the same simulations are done again with a flooding protocol replacing our geographic protocol. Two performance criteria, namely, end-to-end packet delay and packet loss rate, are used for the comparison.

4.2 Results

A synthetic view of various simulation results is given in figures 3 and 4 and in tables 2 and 3. As explained before the two main criteria useful for monitoring application are delay and packet loss. Indeed bandwidth could be considered but it is directly obtained by traffic load when packet loss begins to increase.

Figure 3 shows the variation of end-to-end delay when the wheel turns two rounds. This is the delay of a packet sent by the node 1 and received by the sink. Node 1 is the closest to the sink at $t = 0$. All 28 nodes send packets during simulation time but only those sent by node 1 are tracked. In order to avoid additional delay due to bandwidth bottleneck CBR (Constant Bit rate) application is set with a period of 30s. This figures shows that delay is directly related to the number of hops between source and destination. So it is a minimum when the sink is inside the radio propagation radius that is for t about 0 or 2000 or 4000s. It is a maximum when the node is in farthest location from the sink that means packets make 15 hops. In order to quantify the influence of duty cycle at MAC layer performance measurements are made in two cases: always-on (LPL disabled) and sleep-wakeup (LPL enabled) with a check interval of 10ms. Sleep-wakeup mode increases dramatically the delay as it was expected.

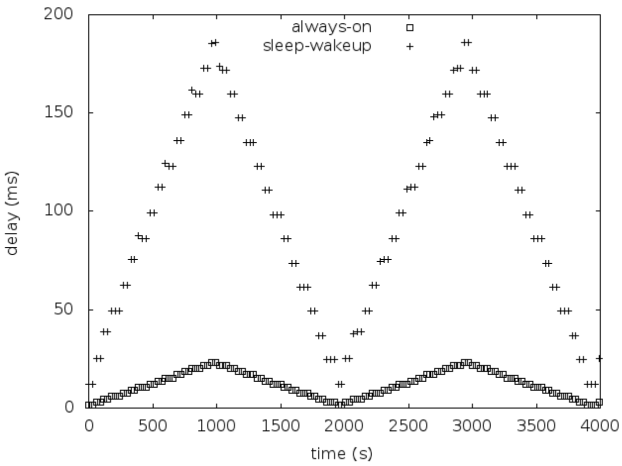

Fig. 3. End-to-end packet delay as a function of time for node 1.

Table 2 gives a statistical analysis of this delay with minimum, average and maximum values. Comparisons are not only with both B-MAC configurations but are extended to two routing algorithms: the simple flooding and our geographic routing. In all cases delay is a little lower with flooding than with our protocol. This can be explained by the fact that flooding is simpler than geographic routing and does not require computing before sending any packet. But the difference is not great and cannot be compared with that resulting from the use of the MAC protocol with LPL mode. The maximum remains very low, about 23 ms, with always-on MAC protocol.

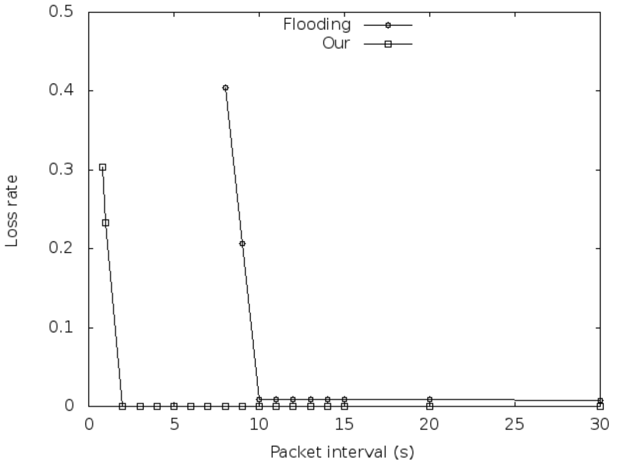

Fig. 4. Packet loss rate as a function of packet sending period.

Packet loss rate as a function of packet sending period is plotted on figure 4 for the two experimented routing protocols. Both protocols are effective when packet interval is greater than 10 s and packet loss rate is virtually nil (less than 1%). But when the period decreases below 10 s packet loss increases sharply in the case of flooding routing. The network works until a period of 2 s in the case of our routing protocol virtually without packet loss. This is an important result that the threshold of the sampling period is significantly lower when using our geographic routing protocol.

Table 2. Delay comparison (in ms)

	Min.	Avg.	Max.
Our (always-on)	1.536	12.036	23.041
Flooding (always-on)	1.408	10.027	19.713
Our (Sleep-Wakeup)	12.288	97.017	186.040
Flooding (Sleep-Wakeup)	12.160	87.406	170.241

Table 3. Minimum packet interval for CBR application

LPL mode	Our
disabled (radio always-on)	175 ms
enabled (check interval of 10 ms)	1.350 s
enabled (check interval of 20 ms)	2.450 s
enabled (check interval of 50 ms)	5.850 s

It could be necessary to monitor some specific parameter with a very short sampling period during a test. Table 3 gives the minimum packet interval or sampling period with the always-on MAC protocol and with 3 values of the check interval with LPL mode. Our protocol is always used. These values are lower limits that guarantee a packet loss rate less than 1%. That means they can be used in monitoring application. It can be deduced from the values in table 3 that LPL mode is not suitable for short sampling period.

5. CONCLUSION

In this paper we have proposed a wireless sensor network architecture for monitoring large physical system in cyclic mobility. We have especially studied its deployment on a big wheel. The performance evaluation was obtained by simulation. The experimental results shown that the lower period of data acquisition on the 28 sensor nodes with low packet loss ratio is short enough to monitor very dynamics physical phenomena. The proposed geo-routing protocol shortens the minimum sampling period in comparison with a general use flooding routing protocol. It could be noticed that the architecture chosen to test our physical system is very slow. In such a case the speed parameter has no influence in the path selection algorithm which then depends only on the location. Other result is the limited packet transfer delay that matches with online monitoring. Therefore this wireless system is not only easy and inexpensive to deploy but also delivers a high quality of service.

Some monitoring applications require that samples must be accurately time-stamped in order to correlate readings from different sensors. Sensor network time synchronisation schemes like this proposed by Ganeriwal et al. (2003) are sufficient to solve this problem. We have to implement and test such synchronization.

More ambitious future works are to study other large physical systems moving on non circular trajectories. We plan to adapt the architecture to systems such as chairlifts or material ropeways which move on two parallel linear paths in opposite directions. We are also looking for partners in order to experiment our architecture on a real working system.

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