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A SAW wireless sensor network platform for industrial predictive maintenance

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Abstract Predictive maintenance predicts the system health, based on the current condition, and defines the needed maintenance activities accordingly. This way, the system is only taken out of service if direct evidence exists that deterioration has actually taken place. This increases maintenance efficiency and productivity on one hand, and decreases maintenance support costs and logistics footprints on the other. We propose a system based on wireless sensor network to monitor industrial systems in order to prevent faults and damages. The sensors use the surface acoustic wave technology with an architecture composed of an electronic interrogation device and a passive sensor (without energy at the transducer) which is powered by the radio frequency transmitted by the interrogation unit. The radio frequency link transfers energy to the sensor to perform its measurement and to transmit the result to the interrogation unit—or in a description closer to the implemented, characterize the cooperative target cross section characteristics to recover the physical quantity defining the transducer material properties. We use this sensing architecture to measure the temperature of industrial machine components and we evaluate the robustness of the method. This technology can be applied to other physical parameters to be monitored. Captured information is transmitted to the base station through multi-hop communications. We also

treat interferences involved in both interrogator to interrogator and sensor to interrogator communications.

Keywords Predictive maintenance · Surface acoustic wave · Wireless sensor network

Introduction

Maintenance is an important activity in industry. It is performed either to revive a machine/component, or to prevent it from breaking down, and aims at increasing system availability, readiness and enhancing safety.

We focus our work on a particular type of industrial maintenance, the predictive one. Based on the current machine state, one can induce possible future faults and anticipate machine deterioration. Condition monitoring data need to be extracted to enable adequate maintenance decisions. Our proposal is based on the use of a wireless sensor network made of several battery-free, temperature sensors, installed around and inside the monitored machine (Fig. 1).

Its scope is to acquire data on the monitored units of a particular industrial machine and transmit it to a final user. Battery-less sensors remotely interrogated are of interest when no maintenance is possible once the sensor is installed, e.g. buried in a polymer or concrete, or installed on rotating parts such as motor rotors. Alternative technology include chipless RFID (Preradovic and Karmakar 2012) in which resonating coils provide the identification mechanism—yet no sensing capability is included in such an approach—and a few attempts at including sensing capability to silicon based RFID (Beriain et al. 2014), yet limited in the temperature range of CMOS doped silicon. Piezoelectric transducers naturally provide sensing capability through the acoustic velocity dependence with temperature or strain (selected with

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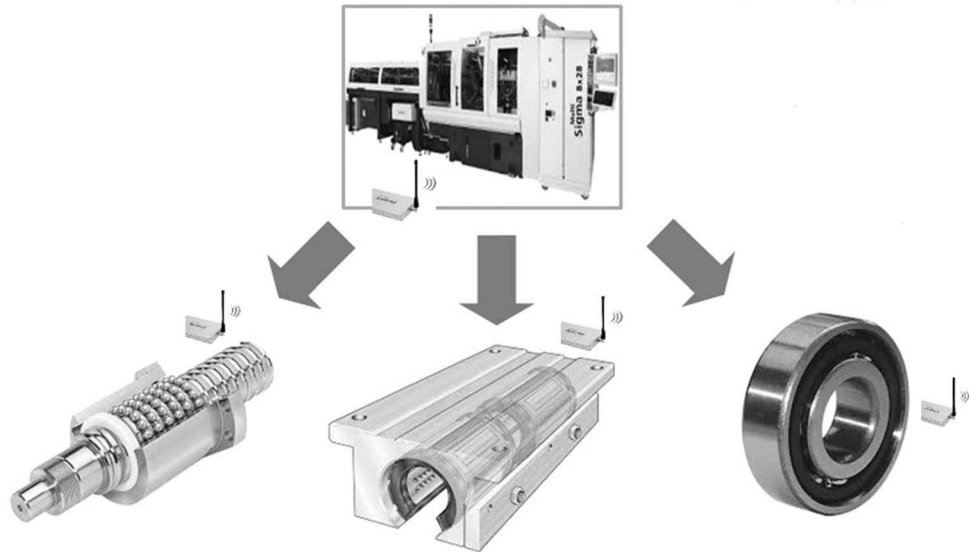
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Fig. 1 Example of industrial machine to monitor



the appropriate material orientation) in addition to identification and sensor signature with respect to background clutter.

The temperature sensors are dispatched optimally to capture the health state evolution of the machine, detect and anticipate its potential faults and take appropriate decision accordingly. Being wireless and battery-free, the sensing element of the network can be installed inside the machine and on rotating devices. Data acquisition is achieved by an electronic interrogation device, called interrogator. The sensing principle is based on the surface acoustic wave technology. Specifically, the sensing transducer is made of a piezoelectric substrate patterned with electrodes. When illuminated by an electromagnetic wave (emitted by the interrogator), the backscattered signal is characteristic of the sensor and carries a signature representative of the physical quantity being monitored.

The main contribution of this work concerns the design of a network (in the computer science meaning) of battery-free sensors/interrogators which make use of the wireless communication to transmit data in several hops to an end user. The measurement unit makes a dual use of the radiofrequency electronics, on the one hand for short range radar measurement to collect sensor values, and on the other, to route the processed information through a multi-hop digital wireless link. This kind of network enables monitoring of industrial systems, assess their health state, detect and diagnose their faults and predict their remaining useful life. The originality of the sensing technique (based on the SAW technology) is its battery-free functioning. The originality of the measurement technique is the use of interrogators to both probe sensor response and ensure multi-hop communications. Being passive, and wireless, the sensors can be deployed on rotating devices (wind turbines, train motors, turbofans, etc.) or in inaccessible and harsh areas (contaminated systems, machine

tools, ovens) to collect relevant, reliable and representative data. These data are then processed to perform condition monitoring and predictive maintenance of the targeted industrial applications.

The remainder of the paper is organized as follows. Section “Motivating context” presents the motivating context of the predictive maintenance for the use of sensors wirelessly connected to monitor health state of industrial machines. In section “The SAW sensors: technology and interconnection” we present the surface acoustic wave (SAW) technology based on an interrogator and a passive sensor and the sensor interconnection. In section “SAW-sensor based data acquisition”, we describe data acquisition mechanism based on SAW-sensor interrogation and data validation. In section “Interrogator-based data transfer”, we present the proposed network architecture and the challenges of data communication: multihop transfer and collision avoidance. Section “Data exploitation” points out the use of the collected data in the process of industrial maintenance. We conclude in section “Conclusion and perspectives”.

Motivating context

Different maintenance strategies have evolved through time, bringing maintenance to its current state. This evolution was due to the increasing demand of reliability in industry. Nowadays, plants are required to avoid shutdowns while offering safety, availability, and reliability, all while reducing the costs.

The first form of maintenance is the corrective one. In this strategy, actions (repair or replacement of components) are only taken when the system breaks and can no longer perform the intended tasks. The second form of maintenance

is preventive or time-based. In this case, the maintenance interventions (Hu et al. 2012) are planned independently of the real health state of the machine and the components are replaced each time period or each number of cycles or kilometers of utilisation—it is a periodic activity. Condition based maintenance (CBM) was proposed and developed in early nineties (Heng et al. 2009). CBM is based on real-time observations to assess the machine’s health and decide whether maintenance actions are needed or not.

A new maintenance has recently emerged: predictive maintenance (PM). It predicts the system health, based on the current condition, and defines the needed maintenance activities accordingly. This way, the system is only taken out of service if direct evidence exists that deterioration has actually taken place. This increases maintenance efficiency and productivity on one hand, and decreases maintenance support costs and logistics footprints on the other hand.

To perform and implement PM on real industrial systems, one needs to identify the critical components, define the physical parameters to monitor and choose the appropriate sensors to collect relevant and representative data about the health state of the system. The collected data are then processed to extract features and build models which are used to continuously assess the health state of the system, detect and anticipate its faults and take appropriate decisions accordingly. Thus, PM is a process composed of different tasks. Its implementation on real industrial systems should be decided by the managers and considered as a priority within the company, without which its success can not be guaranteed.

Condition monitoring data can be provided by conventional sensors (wired) or by wireless sensors. In some applications where the environment is harsh and the operating constraints are strong (rotating machines, drones, large scale systems, etc.), wireless sensors network (WSN) can be a good alternative to conventional sensors. WSNs allow a diversity of sensors, and reducing the deployment complexity thanks to the reduction of wires. Its utilisation in PM can then be advantageous as it allows to cover more components and provide more useful data. However, to be used efficiently in PM, some issues regarding WSN should be solved. These issues, which are tackled in this paper, concern the precision and reliability of the information provided by the sensors, the interrogation of the sensors and the data transfer (or communication) protocol.

The SAW sensors: technology and interconnection

Presentation

In the proposed monitoring application the sensing element is made of a passive transducer probed through a far-field

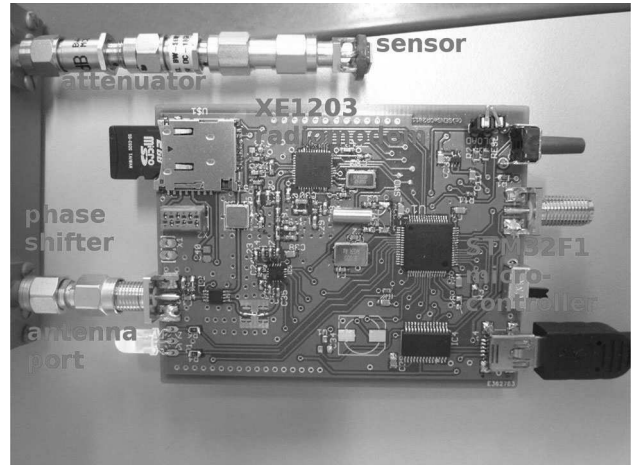


Fig. 2 Measurement platform, including the sensing element and the interrogation unit. Here the varying distance between the reader unit and the sensor is simulated with a phase shifter and an attenuator

radiofrequency link, while data acquisition is performed by an associated interrogation unit (see Fig. 2).

Intrinsic transducer material property changes with the environment—stress or temperature—which allows for probing such physical quantities by characterizing the RADAR cross section of the transducer acting as a cooperative target. Since the magnitude of the returned power is strongly dependent on the radiofrequency link budget, it is considered as a poor indicator of a physical quantity, and will here focus on the resonance frequency of a narrowband transducer. In order to shrink the dimensions of the cooperative target with respect to an electromagnetic energy confinement mechanism, we shall consider the use of acoustic waves for storing the energy in an acoustic resonator, following the conversion of an electromagnetic wave to an acoustic wave using a piezoelectric substrate. Such a technology is widely used in analog radiofrequency signal processing and is well known in the field of surface acoustic wave devices (SAW). This technology is widely described in the literature Morgan (2007) and Hashimoto (2009) with the dedicated application to wireless probing reviewed in Plessky and Reindl (2010). Although the SAW sensor does not require local power, the interrogation unit is battery powered. Piezoelectric surface acoustic wave (SAW) transducers (Droit et al. 2012) have additionally been used as passive (no local energy source) wireless sensors either to measure physical quantities such as temperature (Buff et al. 1994; Pohl et al. 1994; Reindl et al. 1996), pressure (Scherr et al. 1996), or for identification of goods (Hartmann 2009). Despite apparent similarities with silicon-based Radio Frequency Identification tags (RFID), SAW devices underlying physical principles differ vastly, requiring only linear processes in the electromagnetic to mechanical sensing wave conversion and thus improving interrogation ranges (Hartmann and Claiborne 2007). SAW

sensors are probed using active interrogation units operating on principles similar to RADAR. Amongst the classes of SAW devices, two main families include the resonators (narrowband device, characterized by a resonance frequency dependent on a physical quantity under investigation) (Beckley et al. 2002) and the delay lines (wideband devices, characterized by a propagation delay dependent on a physical quantity under investigation) (Pohl et al. 1999; Bulst et al. 2001; Kuypers et al. 2006).

Hardware architecture

The widespread availability of wireless communication interfaces provides embedded chips with most functionalities needed for probing a SAW sensor: tunable radiofrequency source, power amplifier, low noise amplifier on the reception stage, I/Q demodulator and low pass filters.

Our aim is to use such a transceiver not only for its original purpose of transmitting digital data through a wireless link, but also for probing the frequency-dependent response of SAW resonators. Hence, we select transceivers which provide the I and Q demodulated analog outputs, and analyze the needed signal processing steps for extracting the relevant information.

Many RADAR architectures have been demonstrated, meeting various requirements such as mobility (Ground Penetrating RADAR), speed detection (e.g. for sports application such as baseball and tennis), target identification using the second harmonic generated by a non-linear cooperative target (insect tagging), and most commonly ranging of targets with a resolution inversely proportional to the emitted pulse bandwidth (Skolnik 1990). When considering the RADAR equation link budget, the sensor insertion loss, multiplied by the characteristic dimension of the wavelength λ , replaces the RADAR cross section classically found in the RADAR equation. The received power detection limit is given by the thermal power fed by the receiver antenna to the RADAR reception stage: at equivalent temperature T a receiver operating on a bandwidth B will produce thermal noise with power $P_r = k_B T B$ with k_B the Boltzmann constant. A numerical application of such considerations applies to SAW delay lines operating on a $B = 20$ MHz bandwidth close to $f = 2400$ MHz ($\lambda = 300/2400 = 12.5$ cm) and exhibiting 30 dB losses: the interrogation range cannot exceed 5 m with isotropic antennas. Hence one limitation of the passive sensor, due to its returned power decaying as the fourth power of the distance, is the short range. A second limitation is the reduced number of sensors meeting the ISM regulations: considering the quality factor of resonators (10,000 at 434 MHz or a 43 kHz width at half height) and the measurement resolution, in addition to manufacturing variations, only allows to include a single sensor in the narrow European ISM band ranging from 433.05 to 434.79 MHz. The higher 2400 MHz

ISM band is wide enough to accommodate more sensors, with a number still limited by the linear response of the passive transducers preventing the use of complex modulation schemes or active communication approaches as used for active sensors. Again the complementarity of the active and passive sensor network is emphasized.

Software architecture

In the context of wireless meshed network, a significant factor in system reliability and average power consumption is related to software. While a low-level language implementation of the reader and point to point communication is readily achieved, such an implementation does not meet the requirement of routing the messages from sources to a sink through a wireless meshed network. Implementing such a routing protocol is not only a challenging programming task but also a significant theoretical endeavor in order to demonstrate the validity of the routing protocol. We have thus decided to rely on existing routing protocols, and most significantly those readily implemented in programming environments dedicated to wireless sensor networks.

One such environment is TinyOS (Levis et al. 2005), an executive environment widely used as operating system for sensor networks, characterized by a memory footprint compatible with low power microcontroller architectures, modularity, real-time oriented and moreover, supporting multiple wireless sensor routing protocols once the low level radiofrequency layer has been implemented. Well-suited for wireless radio communications, the software implementing the RADAR-like probing of acoustic devices is additionally ported to this environment to provide the best of both worlds—wireless passive sensing and long-range multi-hop wireless digital communication. The complementarity of both approaches is emphasized by considering the radiofrequency link budget: on the one hand, the RADAR equation describing the interrogation of the passive transducer, acting as a point like source at distance d from the reader, hints at a returned power decaying as $1/d^4$. On the other hand, the active node communication—one way trip of the message—exhibits a link budget with a received power decaying as $1/d^2$, but with the need of a battery source on the receiver which reduces life expectancy.

TinyOS has been ported to the microprocessor selected for this application—ST Microelectronics STM32 as described in Goavec-Merou et al. (2012). This implementation integrates the functionality of probing a passive acoustic sensor. We need to define low level functions to provide low-level communication with the selected radiofrequency (RF) interface—Semtech XE1203F radiomodem operating in the 434 MHz European Industrial, Scientific and Medical ISM band.

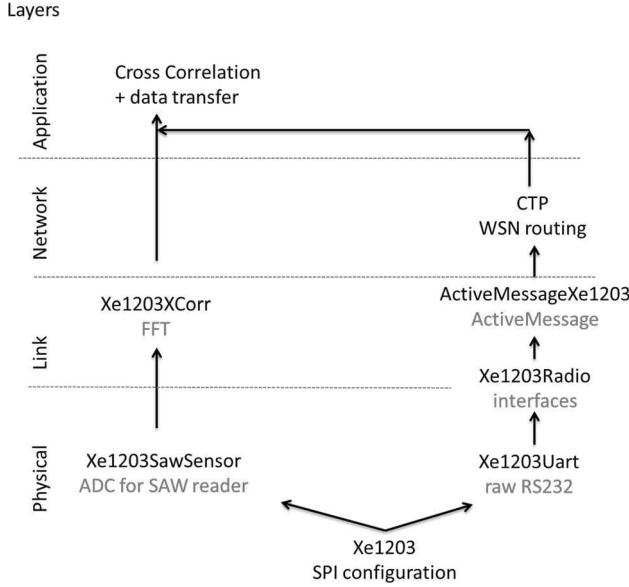


Fig. 3 Layering of the software developed in TinyOS-2.x for XE1203F radio modem usage

Thus, the hardware level aims at porting in the XE1203 library the low level functions needed to access the radiomodem (Fig. 3).

It is supported by the SPI access functionalities of the core implementation of TinyOS-2.x (configuration of the chip, either as a modem for digital communication or as a flexible RF source for interrogating SAW sensors, definition of the emitted frequency and emitted power). Having configured the radiomodem, the most common activity of digital data transfer is handled by XE1203Uart. The hardware performs pattern matching as included in all transfer headers to validate that the received RF signal actually includes digital data. This pattern is detected at the hardware level by the radiomodem in lower power receive mode, and is used to trigger a wake up interrupt of the STM32 microcontroller (EXTI) which was left otherwise in a low power consumption mode. Interfaces between these low-level functionalities and the higher level routing functionalities provided by TinyOS-2.x are described in ActiveMessageXe1203, thus reaching access to the dynamic routing capabilities as already implemented in the CTP protocol (Fonseca et al. 2006a). All this software is portable to architectures other than the STM32 willing to take advantage of the XE1203F radiomodem.

SAW-sensor based data acquisition

Temperature measurement

Some of the parameters which need to be monitored, having an impact on the health of an industrial machine, are: temper-

ature, pressure, humidity. We focus on the critical measure which is the temperature, which can potentially help fault detection and diagnosis. More particularly, increased temperatures may be consequence of early wear of critical pieces as for the ball bearing units.

The SAW technology used to sense temperature values is structured in four steps:

- monitor the radiofrequency band used for the interrogation to assess if another measurement or communication is occurring;
- acquire the SAW transducer backscattered transfer function and identify relevant characteristics (resonance frequency) using the analog capabilities of the RF component;
- send the response signal to the interrogator using the digital communication functionality of the RF component;
- convert the frequency to the physical quantity through calibration coefficients.

SAW sensors are powered by the energy of radio waves emitted by the associated transceiver unit of the interrogator when the latter interrogates remotely the sensor. All operations are restricted to the European 434MHz Industrial, Scientific and Medical (ISM) band. The pulse is converted into a surface acoustic wave (SAW) on the sensor by the piezoelectric material. The acoustic wave velocity is dependent on the substrate temperature: a second order dependence of the velocity with temperature provides an accurate description of the SAW temperature dependence of the mode propagated in the sensor used throughout this work, hence inducing accordingly a resonance frequency since the acoustic wavelength remains constant and defined by the geometrical patterns of the electrodes on the substrate.

Figure 4 shows how the input electrical signal is received and transformed into acoustic wave on the SAW sensor.

Following the assumption of a quadratic dependence of the velocity, and hence the resonance frequency f_r , with temperature T

$$f_r = \alpha T^2 + \beta T + \gamma \Leftrightarrow \alpha T^2 + \beta T + (\gamma - f_r) = 0$$

we derive the numerical value for the sensed temperature out of the frequency measurement by identifying the roots of the second order polynomial, yielding a relationship

$$T = A_0 + \sqrt{A_1 + A_2 f_r} \quad (1)$$

where $A_0 = \frac{-\beta}{2\alpha}$, $A_1 = \frac{\beta^2}{4\alpha^2} - \frac{\gamma}{\alpha}$ and $A_2 = \frac{1}{\alpha}$ are calibration coefficients individually assessed for each sensor.

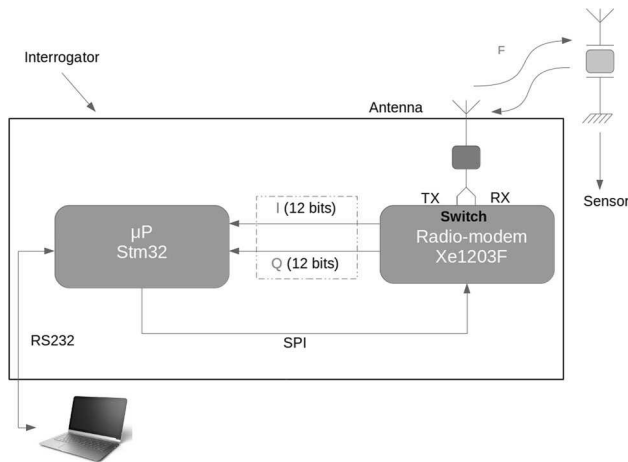


Fig. 4 SAW sensor interrogation system architecture: both transmission and reception channels are provided by the radiomodem, with a monostatic RADAR pulse triggered by a switch. The passive sensor returns a signal if the emitted pulse lies within the sensor transfer function

Measurement quality

Being an analog sensor characterization dependent on the signal to noise ratio and hence RF link budget, some quality of service information must be associated with each measurement for the user to assess the validity and accuracy of each measurement. Each measurement is the result of averaging multiple sensor interrogations, since each RADAR frequency sweep of the ISM band lasts a few (7 ms) milliseconds and digital communication (4800 bauds asynchronous link) lasts at least 45 ms, averaging on the reader prior to data transmission is more efficient than averaging as a post-processing step. Averaging is associated with the ability to compute a standard deviation on the averaged samples. Hence three levels of quality of service are provided to the user:

1. excessive standard deviation (as defined by the requirements of the user) allows to reject measurements that occurred during excessive radiofrequency interferences,
2. assuming a low enough standard deviation, a feedback loop aimed at keeping the received power within optimum operating conditions of the analog to digital converter controls the emitted power. Keeping the emitted power within feedback loop bounds and preventing the bounds of the emitted power (+10 to -22 dBm) from being reached provide optimal conditions for recording accurate measurements,
3. if the emitter power reaches its boundary (positive if the sensor is too far, negative if the sensor is too close and the receiver stage saturates), analyzing the returned power provides a last hint at the quality of the returned signal, with bounds that should not be brought too close to the boundaries of the analog to digital converter.

As an example of such an analysis, if the standard deviation is below a preset threshold defined by the user measurement accuracy, we use the mean frequency value in order to compute the sensed temperature.

Because the standard deviation on multiple measurements is used as a quality of service indicator, the number of samples used to compute the standard deviation is a mandatory property of the validity of the analysis; obviously, if a single acquisition was possible before a timeout is reached when the value is transmitted to the user, the standard deviation is null but has no relevance as to the quality of service. Hence, one last indicator provided to the user is the number of measurements needed to achieve the targeted number of averages, or whether a lower number of valid measurements was acquired before a timeout was reached.

Figure 5 chart exhibits the raw data prior to the application of the calibration coefficients to convert the resonance frequency measurement to temperature. On top of the figure is one sample of the frequency records: this raw dataset exhibits some significant divergence from the average trend, observed here as vertical lines. Data validation requires automated procedures for getting rid of such artefacts. The middle and bottom graphs in the same Fig. 5 demonstrate two such indicators. The middle graph displays the power emitted by the reader to probe the sensor signal. Since a feedback loop on the emitted power—whose maximum value is +10 dBm (as indicated by an emitter indicator value of 31) and minimum value is -21 dBm—aims at keeping the measured power returned by the sensor at mid-range of the analog to digital converter, sharp drops in emitted power indicate external radiofrequency disturbance. Indeed, all values of 0 on the transmitted power are representative of saturation of the receiver stage, most commonly associated with another emitter jamming the radiomodem embedded on our reader. If the coarse data link indicator of transmitted power is valid, then a more detailed data validity analysis focuses on the standard deviation over multiple repeated records which are averaged before a processed value is transferred to the user (typically 8–64 samples). The bottom graph in Fig. 5 shows the evolution of such an indicator, with sharp rises indicative of poor link budget, either because of jamming interferences or obstacles between the reader and the sensor. A threshold on this standard deviation efficiently removes outliers. The resulting processed dataset will be displayed in Fig. 10.

On a static sensor, most sensor RADAR cross section properties will be either successful if the cooperative target is within range, or fail if the sensor is out of range, and the two scenarios are either completion of the targeted number of averages or no sample acquisition, the latter being qualified on returned signal level comparison with threshold values. The case of sensors located on rotating parts is more interesting, since the sensor is only viewed intermittently by the

Fig. 5 Raw measurements over a duration of one year (Oct. 20 2011–Sept. 17 2012) exhibiting from *top to bottom* the frequency, representative of the temperature, the transmitted power—whose drop is representative of interfering emissions—and standard deviation on eight successive measurements

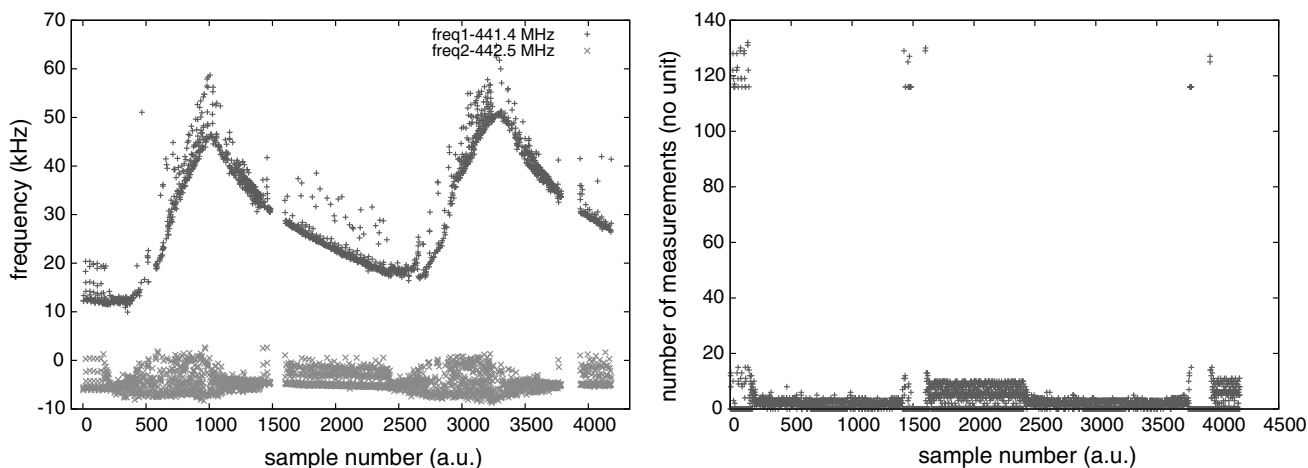
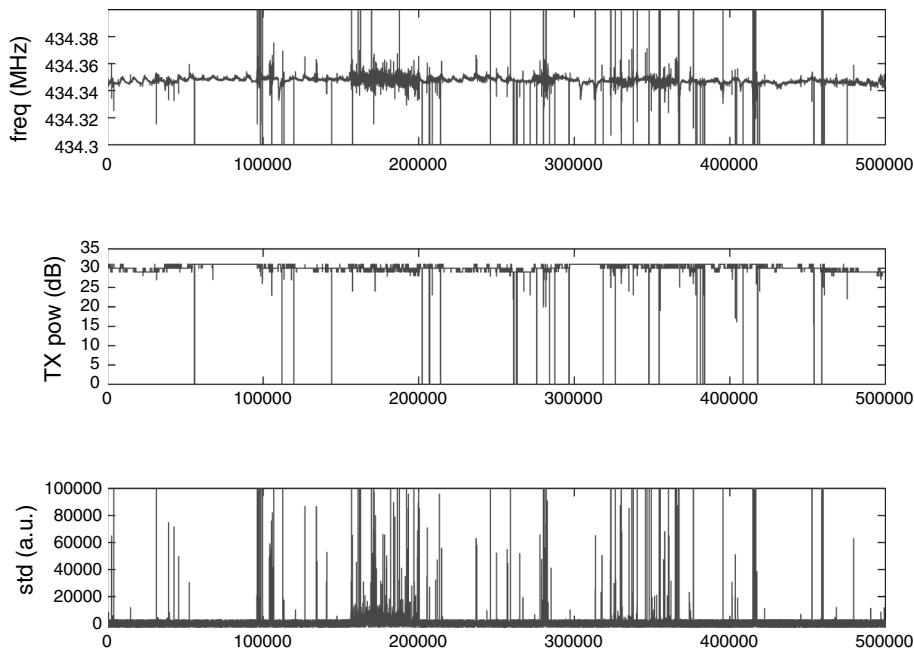


Fig. 6 *Left* sensor resonance frequency measurements, representative of the wheel temperature. *Right* number of samples acquired, with a targeted number of averages of 16. Most measurements yield fewer samples than the targeted number of averages: when the targeted number of averages has been reached, the user is provided with the number

reader as the monitored part rotates. As shown in Fig. 6 in which a sensor is located on a wheel, the targeted number of averages of 16 is rarely met when the wheel is rotating, even when attempting up to 160 measurements before transmitting to the user whatever data was collected by the time the timeout is reached. When few data are collected, the validity of the standard deviation quality of service is questionable, and might yield data rejection even if a low standard deviation is observed.

Having validated the quality of the temperature information remotely recorded by a given measurement node, the information must now be transferred through the meshed net-

work and the risk of data loss associated with the data transfer assessed. Digital communication provides a new framework based on the medium access control (MAC) for sharing the RF spectrum, on the cyclic redundancy checksum for assessing data corruption during transfer, and on routing protocol for the multi-hop communications.

Interrogator-based data transfer

The core novelty of the hardware discussed throughout this document is the use of a radiomodem as a peripheral of

Fig. 7 Wireless sensors/interrogators network

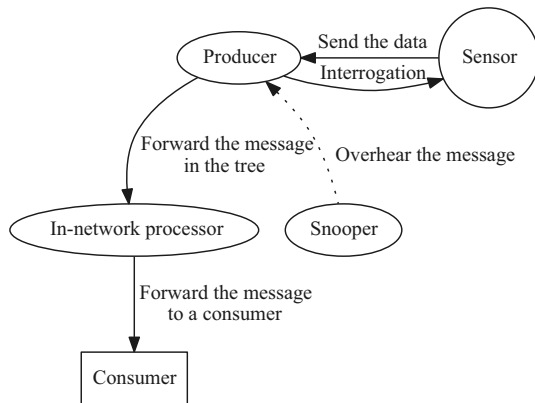
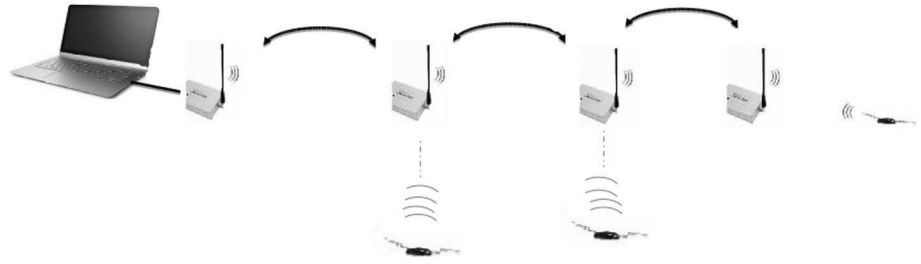


Fig. 8 Four kinds of nodes

the central processing unit for probing the passive sensor response in a RADAR-like strategy. Having acquired the necessary information, the radiomodem is reconfigured for its original digital communication purpose. In this point to point configuration, which does not require TinyOS support, little energy constraint lie on the data sink which is always awake, while the data source, which might be battery powered, aims at saving energy by switching to sleep mode and switching off all peripherals when interrogation or communication are not taking place. However, such a strategy requires some sort of synchronization if all nodes are to participate in a multi-hop network—beyond the basic point to point communication—as will be discussed below (Fig. 7).

Interference resolution

Managing simultaneous emissions

When interrogators emit at the same time, a collision occurs. Most of the time, the packets are lost or corrupted. In practice, interferences occur often enough to significantly decrease the network efficiency and reliability.

The network is composed of four kinds of nodes (Fonseca et al. 2006b). Each node type acts differently within the network to forward packets to a root node (Fig. 8).

- The producer generates the data to be sent to a root node.
- The snooper only overhears forwarded packets.

- The in-network processor intercepts the forwarded packets and updates them.
- The consumer is a root node that receives and collects the forwarded data.

Interferences can happen in two types of situations. It can first happen when a node probes a sensor response while some nearby nodes are communicating together. In that case, the emitted radiofrequency pulses can interfere with the neighboring nodes. Moreover, a collision can also occur when several nodes want to emit some communication packets at the same time. In these situations, the packets are corrupted and most of the time lost.

The Xe1203 radiomodem does not implement hardware collision detection to avoid this kind of collisions. Therefore, a software layer must be implemented to manage the access to the medium in order to avoid interferences in the network.

The listen before talk approach

To allow nearby nodes to emit simultaneously, we need to design a mechanism to control their use of the medium. In a wired communication, the medium would be the wire that links the nodes, but with a wireless local area network, our medium is the electromagnetic environment. Similarly to the wired communication, the medium cannot be used by more than one entity of the network for a given frequency.

We use the listen before talk (LBT) approach where each node first listens to the medium to detect other node activity before emitting. Practically, the I/Q demodulator provides the in-phase and quadrature signals at the output of the mixers used to convert from radiofrequency to baseband (see Fig. 4): RF spectrum use is assessed by measuring the power computed as the magnitude of the complex value $A = I + jQ$ with $j^2 = -1$. The collision detection is implemented as a comparison between $|I^2 + Q^2| - baseline$ and a threshold value experimentally determined to be associated with excessive risk of interferences.

If the medium is free, the node can immediately emit, otherwise emission is delayed by a randomly selected duration.

In the case two nodes emit exactly at the same time, medium use cannot be detected and collision should still occur: such a condition is handled by upper networking

layers, for instance using an acknowledgement system that would request retransmission of lost packets.

Designing the MAC layer

The software part that should control the access to the medium is the medium access control (MAC) layer.

The implementation of the MAC layer makes a large use of the event and of component oriented design provided by the network embedded system C (NesC) language. In order to split the detection part of the algorithm and its medium control part, two components have been implemented and wired together.

First, the detection part of the LBT approach is done by a component named `Xe1203DetectMediumAccess`.¹ This component has the responsibility to listen to the medium and indicate whether or not another network entity is already emitting.

Then, another component called `Xe1203MediumAccessControl`² contains the logic of the MAC layer. This component uses the previous one to detect the medium availability. It provides a function to request an access to the medium and in return it signals a callback when the medium is free.

Using the MAC layer within TinyOS

Since the communication part and the sensor interrogation module can create interferences in the network, both of them use the previously described MAC layer. In fact, the nodes willing to interrogate a sensor should wait for the medium availability, and so do the nodes that want to communicate through the network.

TinyOS is designed to encapsulate the platform dependant components so that we can add a MAC layer at the `Xe1203` level without adapting the upper layers.

Interrogator network communication

The previously described MAC layer is aimed at being used in the context of a collection network. Such a network is designed to carry measurements taken from sensors by interrogators to one collection point of the network (also named *root node* or *sink*). More than one collection point can collect the data since the routing protocol is address-free.

The collection tree protocol (CTP) (Fonseca et al. 2006a) allows to make a tree based collection network in which data from interrogators are forwarded to collection points. We use the implementation of CTP provided by TinyOS.

¹ Available at <https://sourceforge.net/p/tinyosnstm32/code/ci/for-next/tree/tos/chips/xe1203/Xe1203DetectMediumAccessP.nc>.

² Can be found at <https://sourceforge.net/p/tinyosnstm32/code/ci/for-next/tree/tos/chips/xe1203/Xe1203MediumAccessControlP.nc>.

Evaluating node quality and link quality

Route construction is based on particular network metrics. We define the quality of a network's node, established using an estimation called ETX (expected transmissions).

The quality of a node is the sum of the quality of its parent and the quality of the link between them. If the node's parent is itself (i.e. the node is the root of the routing tree), then the ETX value is 0.

$$\begin{cases} ETX_{root_node} = 0 \\ ETX_{node} = ETX_{parent} + ETX_{link_to_parent} \end{cases}$$

In order to compute the ETX of a node we have to make an estimation of the quality of the link to its parent. Since the link between two nodes is assumed to be asymmetric, in-bound and out-bound link evaluations are estimated separately. The quality of the link between node A and node B is the probability of a successful packet transmission from the node A to the node B. This probability is the packet reception rate (PRR) of the link.

$$PRR_{A \rightarrow B} = \frac{N_{received}}{N_{total}}$$

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The various quality of service indicators discussed earlier are evaluated on this dataset. Two processing steps are considered: because probing the SAW sensor is an analog measurement, the data quality is directly linked to the signal to noise ratio. Because in this experiment the aim was to maximize the interrogation range, the received signal is at the threshold of the detection limit and any obstacle (e.g. person walking between the interrogation unit and the sensing transducer) will increase the measurement standard deviation. Any active interference (e.g. external radiofrequency

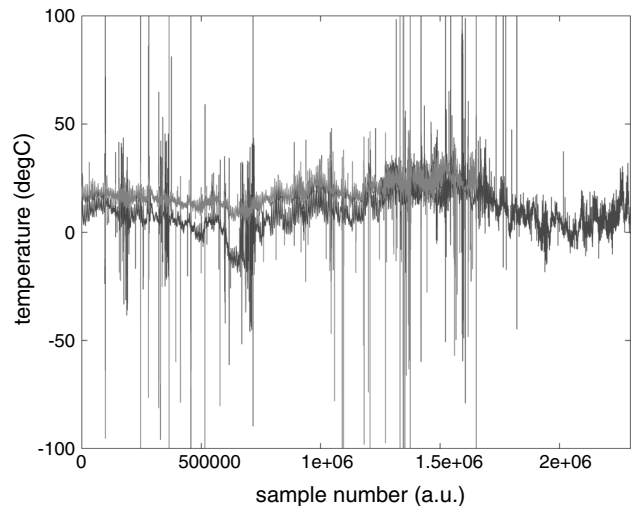


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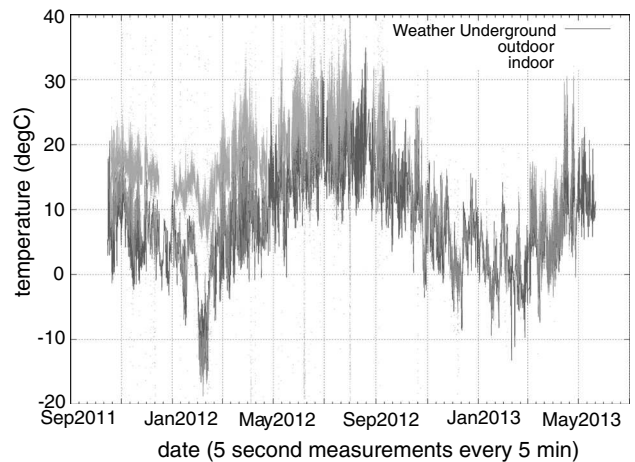


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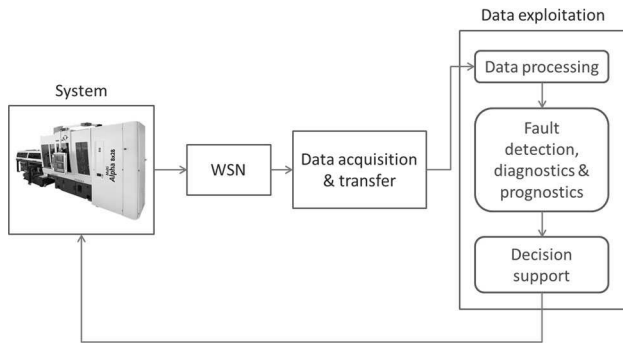


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From the resulting dataset, users can then define various filters on the resulting temperature aimed at keeping only data within “reasonable” bounds to prevent false alarms (Fig. 10). This is the step of pre-processing in data exploitation in the scope of monitoring the health state of the system, detecting and diagnosing its faults, predicting its future health state and taking appropriate decisions regarding its operation (Soualhi et al. 2015). Data should be complete, free of errors and noise and not corrupted. This step is very important as any wrong data used in the implementation of the algorithms will lead to wrong estimation, prediction and decision results. This is known as garbage in, garbage out. Indeed, the data gathered by the sensors carry relevant and useful information about the system and its environment and this should be preserved. Once this step is achieved, the next step is to process the data to extract relevant features and build health indicators which can be used to model the health state of the system. These features are then used as inputs of dedicated fault detection, fault diagnostics and fault prognostics algorithms to inform the user about probable faults the system can undergo and estimate its remaining useful life (RUL) (Medjaher et al. 2012). This information is finally exploited to take appropriate decisions about the operation of the system. The decision can consist of stopping the system, changing the control law, modifying its mission, reconfiguring the utilization of its components, etc. The entire process is illustrated in Fig. 11.

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Information captured by the sensors is routed to the platform to enable monitoring of industrial systems, assess their health state, detect and diagnose their faults and predict their remaining useful life.

The main limitation of interrogation range, reduced to a couple of meters to 10 m under best conditions, is emphasized in the link budget calculation. This limitation is hardly met in most industrial environments (switch gear, motor rotor or wind mill rotor, tire for some of the examples we met) but is a limitation in outdoor environmental monitoring.

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References

- Beckley, J., Kalinin, V., Lee, M., & Voliansky, K. (2002). Non-contact torque sensors based on SAW resonators. In *IEEE international frequency control symposium and PDA exhibition* (pp. 202–213).
- Beriaïn, A., Berenguer, R., Jimenez-Iratorza, A., Farsens, S. L., Montiel-Nelson, J. A., Sosa, J., & Pulido, R. (2014). Full passive RFID pressure sensor with a low power and low voltage time to digital interface. In *Conference on design of circuits and integrated circuits (DCIS)* (pp. 1–6). IEEE.
- Buff, W., Plath, F., Schmeckebier, O., Rusko, M., Vandahl, T., Luck, H., et al. (1994). Remote sensor system using passive SAW sensors. *Proceedings of IEEE Ultrasonics Symposium, 1*, 585–588.
- Bulst, W.-E., Fischerauer, G., & Reindl, L. (2001). State of the art in wireless sensing with surface acoustic waves. *IEEE Transactions on Industrial Electronics, 48*(2), 265–271.
- Droit, C., Friedt, J.-M., Goavec-Merou, G., Martin, G., Ballandras, S., Breschi, K., Bernard, J., & Guyennet, H. (2012). Radiofrequency transceiver for probing SAW sensors and communicating through a wireless sensor network. In *SENSORCOMM 2012, the sixth international conference on sensor technologies and applications* (pp. 48–52).
- Fonseca, R., Gnawali, O., Jamieson, K., Kim, S., Levis, P., & Woo, A. (2006a). The collection tree protocol (CTP). *TinyOS TEP, 123*, 2.
- Fonseca, R., Gnawali, O., Jamieson, K., & Levis, P. (2006b). TEP 119: Collection. <http://tinyos.net/tinyos-2.x/doc/html/tep119.html>.

- Gnawali, O. (2006). TEP 124: The link estimation exchange protocol (LEEP). <http://tinyos.net/tinyos-2.x/doc/html/tep124.html>.
- Goavec-Merou, G., Breshi, K., Martin, G., Ballandras, S., Bernard, J., Droit, C., & Friedt, J.-M. (2012). Multipurpose use of radiofrequency sources for probing passive wireless sensors and routing digital messages in a wireless sensor network. In *eWise workshop, at IEEE iThings conference*.
- Hartmann, P. R. (2009). A passive SAW based RFID system for use on ordnance. In *IEEE international conference on RFID* (pp. 291–297).
- Hartmann, C. S., & Claiborne, L. T. (2007). Fundamental limitations on reading range of passive IC-based RFID and SAW-based RFID. In *IEEE international conference on RFID* (pp. 41–48).
- Hashimoto, K.-Y. (2009). *RF Bulk Acoustic Wave Filters for Communications*. Artech House Microwave Library.
- Heng, A., Zhang, S., Tan, A. C. C., & Mathew, J. (2009). Rotating machinery prognostics: State of the art, challenges and opportunities. *Mechanical Systems and Signal Processing*, 23(3), 724–739.
- Hu, C., Youn, B. D., Wang, P., & Yoon, J. T. (2012). Ensemble of data-driven prognostic algorithms for robust prediction of remaining useful life. *Reliability Engineering and System Safety*, 103, 120–135.
- Kuypers, J. H., Tanaka, S., Esashi, M., Eisele, D. A., & Reindl, D. A. (2006). 2.45 GHz passive wireless temperature monitoring system featuring parallel sensor interrogation and resolution evaluation. In *5th IEEE conference on sensors* (pp. 773–776).
- Levis, P., Madden, S., Polastre, J., Szewczyk, R., Whitehouse, K., Woo, A., Gay, D., Hill, J., Welsh, M., & Brewer, E. (2005). TinyOS: An operating system for sensor networks. In W. Weber, J. M. Rabaey, & E. Aarts (Eds.) *Ambient intelligence* (pp. 115–148). Berlin, Heidelberg: Springer.
- Levis, P., Patel, N., Culler, D., & Shenker, S. (2004). Trickle: A self-regulating algorithm for code propagation and maintenance in wireless sensor networks. In *Proceedings of the 1st conference on symposium on networked systems design and implementation*.
- Lanter, M. (2011). Collection tree protocol. http://www.vs.inf.ethz.ch/edu/FS2011/DS/slides_talks/2011-03-22_marin-lanter_collection.pdf.
- Medjaher, K., Tobon-Mejia, D., & Zerhouni, N. (2012). Remaining useful life estimation of critical components with application to bearings. *IEEE Transactions on Reliability*, 61(2), 292–302.
- Morgan, D. (2007). *Surface acoustic wave filters with applications to electronic communications and signal processing*. Amsterdam, Boston: Academic Press.
- Plessky, V. P., & Reindl, L. M. (2010). Review on SAW RFID tags. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 57(3), 654–668.
- Pohl, A., Seifert, F., Reindl, L., Scholl, G., Ostertag, T., & Pietsch, W. (1994). Radio signals for SAW ID tags and sensors in strong electromagnetic interference. *Proceedings of IEEE Ultrasonics Symposium*, 1, 195–198.
- Pohl, A., Steindl, R., & Reindl, L. (1999). The 'intelligent tire' utilizing passive SAW sensors measurement of tire friction. *IEEE Transactions on Instrumentation and Measurement*, 48(6), 1041–1046.
- Preradovic, S., & Karmakar, N. C. (2012). *Multiresonator-based chipless RFID. Barcode of the future*. New York: Springer.
- Reindl, L., Scholl, G., Ostertag, T., Ruppel, C. C. W., Bulst, W. E., & Seifert, F. (1996). SAW devices as wireless passive sensors. *Proceedings of IEEE Ultrasonics Symposium*, 1, 363–367.
- Scherr, H., Scholl, G., Seifert, F., & Weigel, R. (1996). Quartz pressure sensor based on SAW reflective delay line. *Proceedings of IEEE Ultrasonics Symposium*, 1, 347–350.
- Skolnik, M. (1990). *Radar handbook* (2nd ed.). New York: McGraw-Hill.
- Soualhi, A., Medjaher, K., & Zerhouni, N. (2015). Bearing health monitoring based on Hilbert–Huang transform, support vector machine, and regression. *IEEE Transactions on Instrumentation and Measurement*, 64(1), 52–62.

layers, for instance using an acknowledgement system that would request retransmission of lost packets.

Designing the MAC layer

The software part that should control the access to the medium is the medium access control (MAC) layer.

The implementation of the MAC layer makes a large use of the event and of component oriented design provided by the network embedded system C (NesC) language. In order to split the detection part of the algorithm and its medium control part, two components have been implemented and wired together.

First, the detection part of the LBT approach is done by a component named `Xe1203DetectMediumAccess`.¹ This component has the responsibility to listen to the medium and indicate whether or not another network entity is already emitting.

Then, another component called `Xe1203MediumAccessControl`² contains the logic of the MAC layer. This component uses the previous one to detect the medium availability. It provides a function to request an access to the medium and in return it signals a callback when the medium is free.

Using the MAC layer within TinyOS

Since the communication part and the sensor interrogation module can create interferences in the network, both of them use the previously described MAC layer. In fact, the nodes willing to interrogate a sensor should wait for the medium availability, and so do the nodes that want to communicate through the network.

TinyOS is designed to encapsulate the platform dependant components so that we can add a MAC layer at the `Xe1203` level without adapting the upper layers.

Interrogator network communication

The previously described MAC layer is aimed at being used in the context of a collection network. Such a network is designed to carry measurements taken from sensors by interrogators to one collection point of the network (also named *root node* or *sink*). More than one collection point can collect the data since the routing protocol is address-free.

The collection tree protocol (CTP) (Fonseca et al. 2006a) allows to make a tree based collection network in which data from interrogators are forwarded to collection points. We use the implementation of CTP provided by TinyOS.

¹ Available at <https://sourceforge.net/p/tinyosstm32/code/ci/for-next/tree/tos/chips/xe1203/Xe1203DetectMediumAccessP.nc>.

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Evaluating node quality and link quality

Route construction is based on particular network metrics. We define the quality of a network's node, established using an estimation called ETX (expected transmissions).

The quality of a node is the sum of the quality of its parent and the quality of the link between them. If the node's parent is itself (i.e. the node is the root of the routing tree), then the ETX value is 0.

$$\begin{cases} ETX_{root_node} = 0 \\ ETX_{node} = ETX_{parent} + ETX_{link_to_parent} \end{cases}$$

In order to compute the ETX of a node we have to make an estimation of the quality of the link to its parent. Since the link between two nodes is assumed to be asymmetric, in-bound and out-bound link evaluations are estimated separately. The quality of the link between node A and node B is the probability of a successful packet transmission from the node A to the node B. This probability is the packet reception rate (PRR) of the link.

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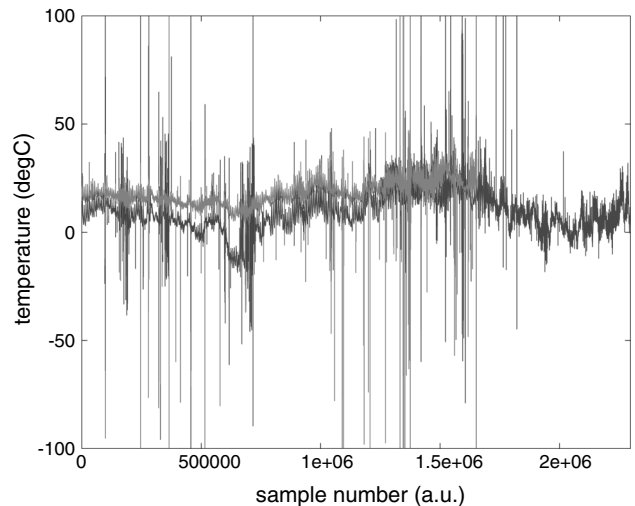


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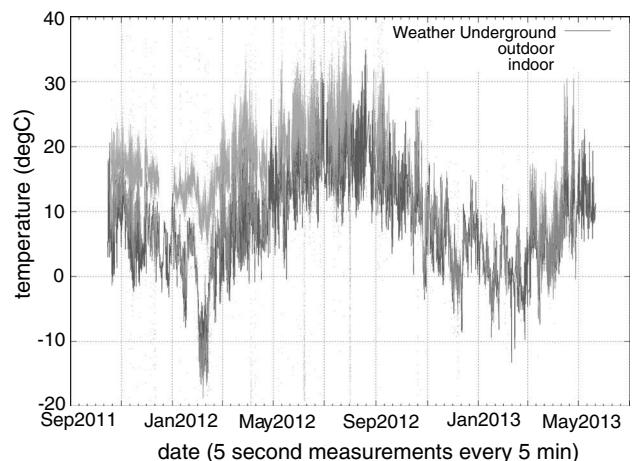


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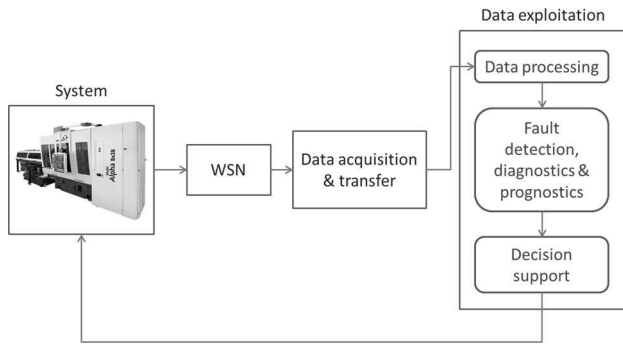


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References

- Beckley, J., Kalinin, V., Lee, M., & Voliansky, K. (2002). Non-contact torque sensors based on SAW resonators. In *IEEE international frequency control symposium and PDA exhibition* (pp. 202–213).
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- Fonseca, R., Gnawali, O., Jamieson, K., & Levis, P. (2006b). TEP 119: Collection. <http://tinyos.net/tinyos-2.x/doc/html/tep119.html>.

- Gnawali, O. (2006). TEP 124: The link estimation exchange protocol (LEEP). <http://tinyos.net/tinyos-2.x/doc/html/tep124.html>.
- Goavec-Merou, G., Breshi, K., Martin, G., Ballandras, S., Bernard, J., Droit, C., & Friedt, J.-M. (2012). Multipurpose use of radiofrequency sources for probing passive wireless sensors and routing digital messages in a wireless sensor network. In *eWise workshop, at IEEE iThings conference*.
- Hartmann, P. R. (2009). A passive SAW based RFID system for use on ordnance. In *IEEE international conference on RFID* (pp. 291–297).
- Hartmann, C. S., & Claiborne, L. T. (2007). Fundamental limitations on reading range of passive IC-based RFID and SAW-based RFID. In *IEEE international conference on RFID* (pp. 41–48).
- Hashimoto, K.-Y. (2009). *RF Bulk Acoustic Wave Filters for Communications*. Artech House Microwave Library.
- Heng, A., Zhang, S., Tan, A. C. C., & Mathew, J. (2009). Rotating machinery prognostics: State of the art, challenges and opportunities. *Mechanical Systems and Signal Processing*, 23(3), 724–739.
- Hu, C., Youn, B. D., Wang, P., & Yoon, J. T. (2012). Ensemble of data-driven prognostic algorithms for robust prediction of remaining useful life. *Reliability Engineering and System Safety*, 103, 120–135.
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- Levis, P., Patel, N., Culler, D., & Shenker, S. (2004). Trickle: A self-regulating algorithm for code propagation and maintenance in wireless sensor networks. In *Proceedings of the 1st conference on symposium on networked systems design and implementation*.
- Lanter, M. (2011). Collection tree protocol. http://www.vs.inf.ethz.ch/edu/FS2011/DS/slides_talks/2011-03-22_marin-lanter_collection.pdf.
- Medjaher, K., Tobon-Mejia, D., & Zerhouni, N. (2012). Remaining useful life estimation of critical components with application to bearings. *IEEE Transactions on Reliability*, 61(2), 292–302.
- Morgan, D. (2007). *Surface acoustic wave filters with applications to electronic communications and signal processing*. Amsterdam, Boston: Academic Press.
- Plessky, V. P., & Reindl, L. M. (2010). Review on SAW RFID tags. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 57(3), 654–668.
- Pohl, A., Seifert, F., Reindl, L., Scholl, G., Ostertag, T., & Pietsch, W. (1994). Radio signals for SAW ID tags and sensors in strong electromagnetic interference. *Proceedings of IEEE Ultrasonics Symposium*, 1, 195–198.
- Pohl, A., Steindl, R., & Reindl, L. (1999). The 'intelligent tire' utilizing passive SAW sensors measurement of tire friction. *IEEE Transactions on Instrumentation and Measurement*, 48(6), 1041–1046.
- Preradovic, S., & Karmakar, N. C. (2012). *Multiresonator-based chipless RFID. Barcode of the future*. New York: Springer.
- Reindl, L., Scholl, G., Ostertag, T., Ruppel, C. C. W., Bulst, W. E., & Seifert, F. (1996). SAW devices as wireless passive sensors. *Proceedings of IEEE Ultrasonics Symposium*, 1, 363–367.
- Scherr, H., Scholl, G., Seifert, F., & Weigel, R. (1996). Quartz pressure sensor based on SAW reflective delay line. *Proceedings of IEEE Ultrasonics Symposium*, 1, 347–350.
- Skolnik, M. (1990). *Radar handbook* (2nd ed.). New York: McGraw-Hill.
- Soualhi, A., Medjaher, K., & Zerhouni, N. (2015). Bearing health monitoring based on Hilbert–Huang transform, support vector machine, and regression. *IEEE Transactions on Instrumentation and Measurement*, 64(1), 52–62.