Multipurpose use of radiofrequency sources for probing passive wireless sensors and routing digital messages in a wireless sensor network

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***Abstract*—As the interest for sensor networks is growing, the demand for integrating both measurement algorithm and data transmission pushes to develop adapted electronic platforms to address this challenge. The use of radiofrequency (RF) passive surface acoustic wave sensors probed by radiomodem interfaces commonly found on wireless sensor node platforms is therefore investigated in this work. This approach allows for providing sensors with virtually infinite life expectancy since no local power source is needed on the sensing site. Rather than harvesting energy from the environment, the passive sensor is loaded by an incoming RF source provided by the same RF interface than the one used for digital communication of the gathered data. Implementing such a scheme in an ad-hoc wireless sensor network configuration is demonstrated using a novel platform based on the XE1203F radiomodem which provides the specific interfaces mandatory to such an application. Furthermore, a measurement demonstration locating the sensing element in an oven heated to 550 ^{o}C emphasizes environmental conditions in which no energy storage or battery would withstand such harsh conditions, while the wireless interrogation between the interrogation unit (reader) and the sensor removes the need for high temperature-compatible connector and electrical cable. Implementing the sensor probing algorithm as well as the radiomodem control interface in the TinyOS executive environment then provides access to all the functionalities of this portable development tool, including multi-hop data routing and dynamic ad-hoc network construction, while complying with a clear software hierarchy ranging from low level drivers accessing the hardware to user applications implemented as tasks.**

***Index Terms*—wireless, surface acoustic wave, sensor, temperature, radiomodem**

I. Introduction

Energy harvesting for powering wireless sensor nodes aim at addressing the requirement of providing virtually infinite life expectancy of the measurement setup for hard to reach environments [1], [2], or when the sensor node is no longer reachable once installed in its final location, as is the case for sensors buried in ice [3] or concrete [4]. A hybrid scheme is discussed in which the sensor node requires significant amount of power to activate a radiofrequency (RF) source, but this RF link will not only be used for routing digital data to a sink in the classical wireless network scheme, but also for probing the physical quantity observed by a fully passive sensor, thus meeting the requirement of the infinite life expectancy of the sensing element.

Thus, the general strategy adopted in this document is to use a single radiomodem component for multiple purposes, on the one hand characterizing the frequency dependent of a resonance acoustic sensor operating in the RF 434 MHz European ISM band, and on the other hand routing digital data to a sink connected to a personal computer for displaying and storing the recorded data. Because these multiple tasks become algorithmically complex, time sharing is needed between the various steps (scheduling), and packet routing over an ad-hoc wireless network is already implemented in various embedded operating systems, we have selected to port our low level sensor probing algorithms to the TinyOS executive environment.

In order to fully exploit the functionality provided by an executive environment, most significantly portability, task handling and networking, TinyOS has been ported to the microprocessor selected for this application – ST Microelectronics STM32 – and the functionality of probing a passive acoustic sensor under such an environment has been implemented as well. Furthermore, low level input-output functionalities for communicating with the selected RF interface – Semtech XE1203F radiomodem operating in the 434 MHz European ISM band – in order to take advantage of the ad-hoc [5] wireless network routing capability of TinyOS. Thus, the purpose of porting the developed low level software to the TinyOS executive environment is, more globally, to take advantage of high-level functionalities provided by the TinyOS community on other platforms. Such envisioned functionalities include data storage on non-volatile medium such as Secure Digital (SD) cards.

II. Multiple uses of RF sources

In the context of Software Defined Radio (SDR), an increasing fraction of RF communication functionality is removed from the hardware and taken care of by software. Thus, reconfigurability becomes intrinsic to the design: the RF frontend converts a low-frequency bitstream to a RF signal through modulation, mixing and power amplification for the emission side, while on the reception side a low noise amplifier followed by mixers generates a low-frequency In-Phase and Quadrature (I and Q) streams which are then processed by software to recover the transmitted signal. Although communication bandwidth following such a scheme is still limited by digital signal processing power (dependent on available electrical power), it reveals most suitable to the classically low communication bandwidth requirement of wireless sensor networks.

In our case, the RF frontend under consideration is the Semtech (formerly Xemics) XE1203F radiomodem, configured (hardware design) to operate in the 434 MHz European ISM range. Although this component includes all the necessary hardware for digital communication which will be discussed later (section IV), it most significantly provides raw analog I and Q outputs suitable for digitization and processing. We have previously shown [6] that these two analog outputs, when sampled simultaneously by a dual channel analog-to-digital microcontroller, provide a signal relevant for identifying the resonance frequency of an acoustic Surface Acoustic Wave (SAW) resonator acting as a passive sensor. While this discussion focuses on the XE1203F, any radiomodem providing the raw I and Q outputs, either in analog or digital format, will be suitable to the application envisioned in this document.

III. Passive wireless sensors interrogated through a RF link

The raw I and Q outputs provide demodulated signals representative of the RF power recovered close to the local oscillator (LO) preset frequency. In the present case, the XE1203F is considered as an integrated system providing both the emitter and receiver stages of a frequency sweep, monostatic, pulsed RADAR, as opposed to the classical approach of processing the returned RF signal emitted by a remote generator. During a sensor loading phase, a continuous RF at a given emission frequency transfers energy from the radiomodem to the sensor. Once the sensor is loaded, emission is switched off and the returned power is processed through I and Q outputs.

Switching time between emission and reception lasts at least 200 ns (Hittite HMC349MS8G switch between emission and reception pins of the XE1203F chip) and the low pass filter after the mixers in the XE1203F are tuned to either 200 or 600 kHz bandwidth: thus, the time constant of the returned power must be about 1.5 μs for this scheme to be usable (Fig. 1). High quality factor acoustic transducers manufactured on single crystal piezoelectric substrate appear as suitable candidates for this task [7].

As opposed to silicon based RF identification devices (RFID) whose antenna exhibits low quality factor and thus must be loaded while the antenna impedance modulation provides the means for communication (backscattering [8]), the high quality factor exhibited by acoustic devices yield unloading energy decay time constants of a few microseconds. Indeed, a surface acoustic wave (SAW) resonator operating in the f =434 MHz range and exhibiting a $Q = 10000$ quality factor unloads energy with a time constant of $(Q/\pi f)$ =7 μs.

Similarly, acoustic delay lines are hardly compatible with such a strategy: exhibiting echos 50 to 100 ns long returned every 500 ns for a total duration of less than 5 μs, a recording bandwidth of at least 50 MHz is needed to recover each symbol and the phase representative of the acoustic velocity and thus the physical quantity under investigation. Such a bandwidth is far beyond the capability of radiomodems operating in the 434 or 868 MHz bands, although this option might be considered with suitable interfaces available for the 2.45 GHz-centered international ISM band (80 MHz-wide band) [9].

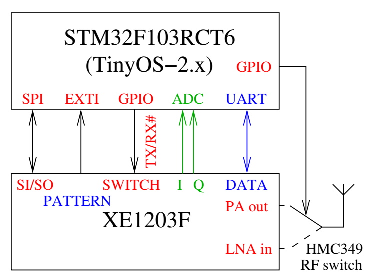

Fig. 1. Schematic of each node geometry: the XE1203F provides, in addition with the usual digital communication signals (blue), the raw I and Q analog outputs needed to probe wireless acoustic sensor responses (green). Such acoustic transducers are here used as passive sensors.

Recording the signal characteristic of an acoustic sensor using the I and Q outputs of a XE1203F radiomodem has already been described previously [10], and the reader operating sequence will only be reminded briefly:

1) first, frequency is swept from the beginning to the end of the frequency band in which the sensor resonances are located by design. Complying with ISM regulation, this band spreads from 433.05 to 434.79 MHz,
2) for each frequency step, the sensor is loaded with energy by emitting an RF pulse lasting for 5 time constants, typically 40 μs in the present case,
3) the emission is switched off, and after a known delay aimed at allowing clutter to fade out and all RF components on board to discharge, the returned signal is sampled on the I and Q outputs,
4) having repeated the last two steps for all frequencies of interest – typically 128 steps in the 1.7-wide ISM band, a cross correlation algorithm is applied between the first half of the dataset and the second half. Since the exploited SAW sensors are designed as dual resonators for differential measurements, with one resonance lying in the first half of the ISM band and the second resonance lying in the second half of the ISM band, the cross correlation acts as a matched filtering improving signal to noise ratio and providing an accurate estimate of the frequency difference between both resonances through the cross correlation maximum position. Because both resonators are designed to exhibit different frequency with temperature dependence, the relationship between temperature (the physical quantity under investigation here) and frequency difference is bijective. Thus, an accurate estimate of the frequency difference provides and accurate estimate of the temperature: with a 2500 Hz/K sensitivity, the targeted resolution of 0.1 K requires a 250 Hz frequency difference resolution effectively achieved along the above-described interrogation scheme.

The general scheme is described in Fig. 2: a root sensor node (also known as data sink) collects all information gathered by the nodes distributed as a Wireless Sensor Network (WSN). Each node is associated with a single passive sensor, in the present case a SAW-resonator based sensor. Indeed, since such devices do not benefit from identification capability other than frequency multiplexing, only a limited number of passive sensors is associated with a single node reader. For benefitting at best from ISM regulations, a single passive sensor exploits the full 1.7 MHz wide ISM band to operate. In case of multiple passive sensors associated with a single node, frequency multiplexing is required, sacrifying ISM compliance: the XE1203F can sweep a 434±8 MHz range and is thus compatible with the interrogation of up to 8 passive sensors, assuming each sensor might be located into a 1 MHz band as the physical parameter under investigation varies.

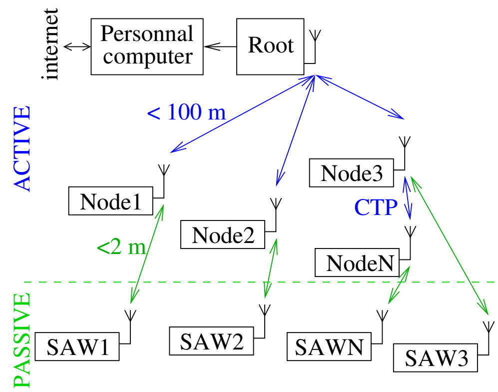

Fig. 2. General setup of the WSN combining active data routing nodes (blue) and passive acoustic sensors (green) interrogated by the nodes.

Considering the basic strategy for probing a passive sensor using a general purpose radiomodem providing raw I and Q outputs, the remaining issue is the porting to a programming environment providing higher level facilities such as message routing, while keeping some of the hard real time requirements of probing the sensor response (*i.e* making sure the duration between switching from emission to reception and recording the I and Q values is constant with sub-200 ns resolution).

IV. Multi-hop digital data routing in a wireless sensor network

The purpose of porting a low-level language application to the TinyOS executive environment is to take advantage of some its portable facilities, including routing and Media Access Control (MAC) layer [11] implementations above the radiomodem layer, thus providing true wireless network functionality once the passive sensor characteristics has been recorded.

The clear layering of the TinyOS architecture only requires some of the low level functionalities of the XE1203F radiomodem to be implemented (e.g. accessing the radiomodem registers, digitally tunable attenuator programming and switching from emission to reception) by using the interfaces provided by TinyOS-2.x. Higher level functionalities – e.g. routing using the CTP protocol [12] and access to MAC – require the implementation of the `ActiveMessage` interface to the XE1203F radiomodem driver. This `ActiveMessage` is the common interface for all packet communication within TinyOS-2.x: implementing this interface provides access to all the other functionality already available in the executive environment.

Specifically, the module hierarchy from low level hardware access towards high level functionalities such as routing of digital data over the wireless medium on the one hand, and interpreting the returned power from a sensor probed by the same radiomodem hardware on the other hand, and up to the user application level, yields the following module architecture selection:

1) the lowest level using the SPI interface (as implemented in the TinyOS port to a specific processor) configures the radiomodem (emitted frequency, emitted power, lack of modulation when probing the sensor or activating the modulation when communicating digital data) and uses General Purpose Input Output (GPIO) ports for programming a digitally controlled RF attenuator in order to optimize the received signal to noise ratio. Selecting whether the radiomodem is in reception mode (its default condition) or emission also requires switching a duplexer in our monostatic antenna configuration, also under control of a GPIO bit controlled by this low level driver. This piece of software complies with the higher level requirements by implemented a dedicated communication interface as defined by the TinyOS architecture and described in Fig. 3, since none of the generic TinyOS interfaces provided the needed flexibility. These low level functions are thus never explicitly called, but services are requested from high level (more abstract) pieces of software as tasks end up requesting access to the hardware.
2) probing the sensor response requires calling some of the core driver functionalities since the modem must be specifically configured for such a task (no modulation, tune the attenuator power which is otherwise at maximum output power for digital communication, switch the duplexer to emission mode and then back to reception with stringent delay requirements since any variable lag in this process will affect the quality of the recovered transfer function). This sensor probing function also accesses the microcontroller analog-to-digital through one of the TinyOS generic interfaces connected to the dedicated interface described above. Since in a SDR approach, the frequency of each probe pulse is independent of the previous measurement step (as opposed to an analog continuously sweeping Voltage Controlled Oscillator), two measurement schemes have been implemented as two interfaces: either a frequency range is provided and multiple measurements are performed to gather the complex (I and Q) transfer function of the sensor over this range, or a single measurement at one user-defined frequency is performed, and in this case a single complex measurement is returned. The latter approach is needed when implementing more efficient measurement strategy than the basic frequency sweep, as described in [13], [14].
3) digital data communication is located in a dedicated driver, if only for improving the attractivity of the software to a wider audience who might not be interested in probing acoustic sensors while still using the high level routing schemes of TinyOS for ad-hoc network communication. Here again, the first driver level is used for configuring the carrier frequency and communication direction. The values to be transferred are communicated through an asynchronous (RS232 compatible) port, using the generic TinyOS implementation for such an interface. Thus, communicating digital data can be at the byte level with no additional routing protocol as will be described below, as would be done in a wired connection between two microcontrollers.
4) finally, the most abstract driver provides the glue between the `ActiveMessage` interface and the last driver we just described: all more abstract functionalities of TinyOS are then accessed through `ActiveMessage`.
5) this hierarchy scheme is probably portable to any other radiomodem providing similar functionalities and interfaces as the XE1203F – and specifically configuration through one of the busses supported by TinyOS as well as raw analog I and Q output.

One independent driver implements the mathematical processing algorithm for identifying the resonance frequency difference of the dual-resonator differential SAW sensors. The Fast Fourier Transform (FFT) needed for the cross correlation computation performed to achieve this task is best debugged independently of the whole acquisition process and is thus well suited for a separate task acting on any array of data and might be useful for applications other than acquiring data from the I and Q outputs of a radiomodem.

Thus, the hardware level aims at porting in `Xe1203` 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

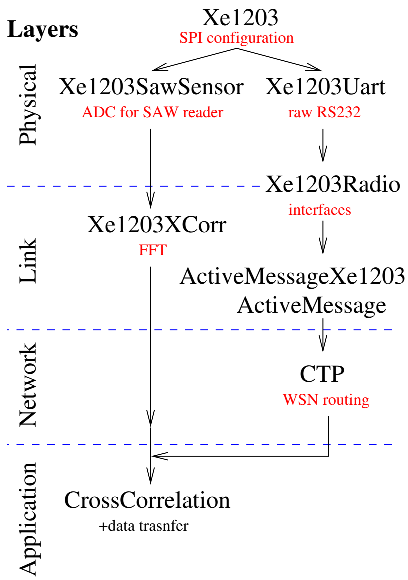

Fig. 3. Layering of the software developed in TinyOS-2.x for using the XE1203F: in this particular case, TinyOS-2.x was ported on a STM32 microcontroller with the unusual functionality of a dual, synchronous ADC for probing the I and Q outputs of the radiomodem.

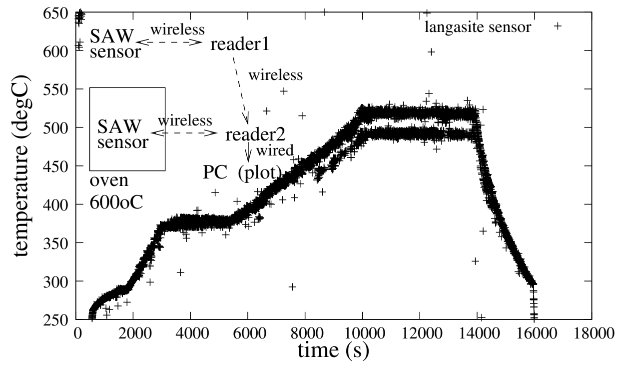

Fig. 4. Scheme of the experiment (upper left) in which two sensors were probed by two interrogation units (wireless link for recovering I and Q of a SAW sensor) which communicated measurements results through the wireless digital link using the same RF interface. Measurement results of the sensor located in the high temperature oven – set to 550^{o}C – for a full day during an exhibition are exhibited with no filtering nor sliding average.

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 functionality 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. All this software is portable to architectures other than the STM32 willing to take advantage of the XE1203F radiomodem.

In parallel to all this digital communication activity, the `XE1203SawSensor` implements the low level functionalities needed to probe a SAW sensor S_{11} transfer function through a wireless link. Either a single frequency response is recorded, or the whole transfer function over a frequency range. The only non-portable aspect of this software is the need for a synchronous dual ADC used for simultaneously recording I and Q outputs of the radiomodem.

An application takes advantage of these two drivers by first recording the transfer function of a passive SAW sensor, and extracting the frequency difference between two resonances using a Fast Fourier algorithm implemented in `Xe1203Corr` through a cross-correlation algorithm. Secondly, these data are transferred through the digital wireless link while providing support to the CTP communication protocol by keeping the radiomodem in listen mode until the routing tree has been built. Once all transactions are completed (after a given delay), both microcontroller and radiomodem are set to a low power mode to be awaken by a periodic timer. Furthermore, the implementation of the `ActiveMessage` interface provides access to all other application examples using such a communication protocol as classically available in TinyOS-2.x (Fig. 4. In the such an experimental scheme as demonstrated in Fig. 4, the interrogation unit *reader2* collects, through a wireless digital link, the measurements from the isolated *reader1* (interrogation range of several tens of meters since in a one way radiofrequency link, the power decreases as the inverse second power of distance, as opposed to the inverse fourth power in the RADAR equation which limits the interrogation range to 1.5 m) and transfers the measurements through an asynchronous (RS232) interface to a personal computer. The computer is used to convert the frequency difference to a temperature by applying calibration coefficients defined as a preliminary step to the measurement, and display the result as a graphical plot of the temperature evolution. The flexibility of the radiomodem based interrogation unit is emphasized in this high temperature measurement using a langasite sensor [15] whose resonance frequency extends from 439 to 446 MHz, out of the ISM band regulation but accessible to a XE1203F radiomodem fitted with a 39.5 MHz (third overtone) core clock oscillator rather than the expected 39 MHz oscillator source.

Were the number of remote readers multiplied, a more complex wake up scheme would be implemented beyond the simple periodic wake up which, after some time, will necessarily end up with some collision of data transferred at the unique frequency carrier on which the receiver (root) radiomodem is set: S-MAC provides one such time domain multiplexing scheme [16]. Indeed, the current communication scheme only uses time-multiplexing for avoiding collision between the messages communicated by all the sensor nodes, all operating on the same carrier frequency since the default low-power reception mode of the radiomodem requires setting such a frequency to be aware of communication requests from remote nodes. Adding a hardware-based MAC by monitoring the radiofrequency power as the magnitude of I and Q components would improve the stability of the collision avoidance.

V. Conclusion

In this paper, the dual use of a hardware RF interface has been demonstrated for, on the one hand, probing passive acoustic RF resonators based on single crystal piezoelectric substrates acting as sensors, and on the other hand communicating the resulting digital records through an ad-hoc multi-hop wireless sensor to a centralizing root node. Practical demonstration is performed on a two-node architecture in which one of the nodes is located near a high-temperature oven, in which the sensor measures temperatures up to 550 ^{o}C, incompatible with any battery powered sensor, and the other node recovers the measured data, measures room temperature and communicates with a personal computer for data display and storage.

Among the remaining issues, collision between interrogation of sensors and data communication in the same frequency bands seems to prevent multiple nodes from waking up at the same time and disseminate data to the root node. Adding MAC functionality is aimed at solving this issue.

All source codes of the port of TinyOS to the STM32 platform and the XE1203F radiomodem used either for probing the analog signal from sensors and digital communication are available at http://sourceforge.net/projects/tinyosonstm32/.

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