Radiofrequency transceiver for probing SAW sensors and communicating through a wireless sensor network

C. Droit, J.-M.Friedt
SENSeOR SAS
Besançon FRANCE
{*christophe.droit,jmfriedt@femto-st.fr*}

G. Goavec-Mérou, G. Martin, S. Ballandras,
K. Breschi-Jimenez-Ramirez, J. Bernard, H. Guyennet
Time & frequency (TF)
Computer science & complex systems (DISC)
FEMTO-ST institute UMR 6174
Besançon FRANCE

***Abstract*—A radiofrequency transceiver is used for the dual purpose of probing surface acoustic wave resonator sensors and communicating the resulting measurements through a digital wireless link. Thus, the radiofrequency hardware exhibits a complementary use of short range probing of piezoelectric sensors subject to harsh environmental conditions, and long range digital communication through a wireless sensor network. The demonstration is performed in the 434 MHz European Industrial, Scientific and Medical band, yielding half-duplex communication ranges well beyond 100 m.**

***Keywords*-Transceiver, radio communication, 434 MHz ISM band, SAW resonator, temperature sensor**

I. INTRODUCTION

Piezoelectric surface acoustic wave (SAW) transducers [1] have been widely used as passive (no local energy source) wireless sensors [2], [3], [4], [5], [6]. Despite apparent similarities with silicon based RadioFrequency IDentification tags (RFID), SAW devices underlying physical principles differ vastly, requiring only linear processes in the electromagnetic to mechanical sensing wave conversion and thus improved interrogation ranges [7]. 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) [8] and the delay lines (wideband devices, characterized by a propagation delay dependent on a physical quantity under investigation) [9], [10], [11]. While the latter strategy often requires fast electronics and large data storage memories (typical time constants are in the hundreds of MHz bandwidth, with typical 40-ns long pulses), probing resonator can be as simple as an embedded frequency sweep network analyzer probing the reflection coefficient of the transducer. Because of the wireless link, a pulsed mode RADAR provides improved isolation (and hence interrogation range): the typical solution is a pulsed-mode frequency-sweep RADAR. Multiple references in the literature discuss the implementation of dedicated hardware for probing such devices [12], [13], [14], [15], either as Fourier-transform based [16] by emitting a wideband pulse and identifying the frequency of the signal returned by the sensor, or sweeping a narrowband pulse [17] for identifying the frequency at which the sensor returns most power (meeting the resonance frequency condition, hence allowing for the resonator to store energy which is then released during the listening step).

On the other hand, 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. All operations will be restricted to the European 434 MHz Industrial, Scientific and Medical (ISM) band: the same hardware is first configured to probe locally (range 0.1-2 m) a SAW sensor, and then reconfigured for sharing the acquired data through a digital wireless link with a sink in charge of storing the data and sharing them through the Internet.

II. HARDWARE SELECTION

Because we aim at processing the analog signal returned by the sensor, access to the raw I and Q outputs of the receiver stage of the transceiver is mandatory. Due to increased requirement of compacity and low pin count, most radiofrequency transceivers only provide digital interfaces to the user. We have identified 3 suppliers of radiofrequency transceivers potentially compatible with our need: Semtech XE1203F, Maxim MAX7203 and Melexis TH7122. Because the latter is already used in a commercial product [18] in a dual chip (separate emitter and receiver) configuration which is hardly satisfactory, we have focused on the former reference which provides a tunable frequency source with 500 Hz frequency step, I/Q analog outputs, and most significantly a fast (pin triggered) switching from emitter to receiver mode capability. This last point is significant: since the time constant of a resonator operating at frequency f_0 is $Q/(\pi f_0)$ with Q the quality factor of the device, the power loss is 8.7 dB/time constant during the exponential decaying response of the sensor. Typical values at $f_0 = 434$ MHz are $Q \in [8000 - 1000]$ so that typical time constants for sampling the returned signal are in the 6-7 μs.

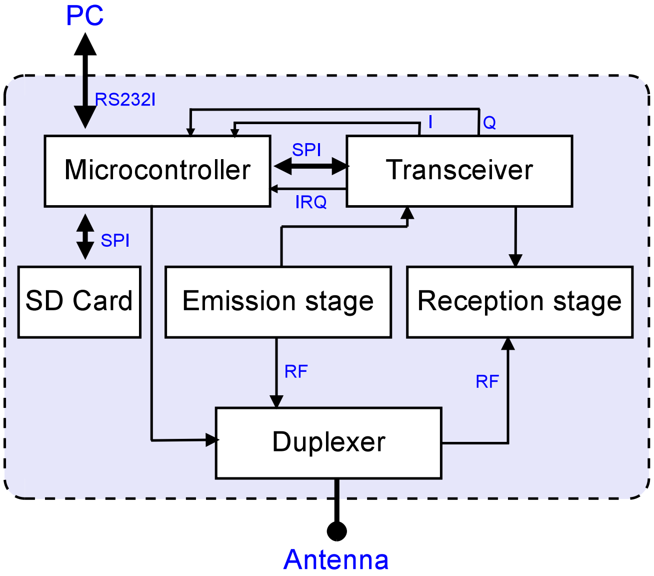

Figure 1. Synoptic description of the card. The microcontroller configures components depending on the actions chosen. The two modes available are communication mode (fixed 434 MHz carrier, 4800 bit/s) and a SAW probing mode. In the latter operating mode, the radiomodem scans the ISM frequency band step by step so as to detect the resonant frequencies of resonators. The resonance frequency difference is returned as the quantity representative of the temperature measurement. This measurement result is also stored on a SD card. The external radiofrequency duplexer is mandatory for improved isolation between the emission and reception stage and thus an interrogation range of the SAW sensor reaching 1 m.

Using an integrated transceiver for probing SAW devices, although attractive in terms of integration, footprint and power consumption, is challenging since the signal processing performed at the output of the mixer of the reception stage are hardly documented. Nevertheless, the frequency-dependent response of SAW sensors is characterized using such a hardware, and the frequency at which the returned power is maximum is identified by sampling simultaneously the I and Q output using a dual analog-to-digital converter embedded in a ST Microelectronics STM32 microcontroller (Fig. 1). Using this approach, the total number of integrated circuits needed to design a SAW resonator reader is restricted to 4 : a XE1203 transceiver, a microcontroller providing fast (>1 Msamples/s A/D conversion), a fast radiofrequency duplexer for switching from emission to reception stages in a monostatic antenna configuration, a digitally programmable radiofrequency attenuator for improved measurement range dynamics and possibly a RS232 to USB (FTDI FT232RL) converter (Fig.1). Reducing the number of active circuits aims at reducing the total power consumption: the STM32 based on an ARM Cortex M3 architecture exhibits reduced deep-sleep mode power consumption of less than 4 μA. All dedicated radiofrequency chips are powered by General Purpose Input Output (GPIO) pins of the microcontroller while the radio frequency transceiver provides deep sleep mode capabilities. Measured power consumptions are summarized in table I.

Operation mode	Consumption (mA)
RF digital communication	140
Probing SAW resonators	80
Standby mode microcontroller and transceiver in reception mode	22.3
Standby all components	1.2

Table I
Power consumption of the SAW interrogation unit based on a XE1203F radiomodem and STM32 microcontroller, depending on the operating modes. The supply voltage is 3.3 V.

Although the time constant of the resonator discharge is 6 to 7 μs, Fig. 2 exhibits a significant returned signal for more than 25 μs after switching the duplexer from emission to reception positions. This signal is interpreted as the impulse response of the low pass filters located on the I and Q channels output, after the internal radiomodem mixers (here set to a cutoff frequency of 200 kHz). The oscillations observed on the I and Q outputs are the result of mixing a fixed frequency returned by the sensor (resonance frequency) with the emitted tunable frequency source. Following this time dependent characterization of the output of the I and Q channels, the practical use of these information only requires a single measurement by the analog to digital (A/D) converters of the STM32, selected at a time 20 μs after switching the duplexer position.

Once the relevant data from the SAW sensors are recorded, the radiofrequency transceiver is reconfigured to operate in its original purposes, namely wireless digital data communication. While the current demonstration focuses on a point to point communication towards a sink configured as a sink (constantly listening for incoming messages), dynamic signal routing is under investigation using the MAC layer provided by the TinyOS executive environment under the Collection Tree Protocol (CTP) routing protocol [19]. Because failure of the sink (either due to operating system crash or overload, malicious attacks when connected to the Internet, or power failure) is considered as the weakest link in the dissemination of the measurement data, the embedded SAW reader has been fitted with a Secure Digital (SD) mass storage medium for keeping a local record of all emitted sentences (Fig. 4). Because most users request

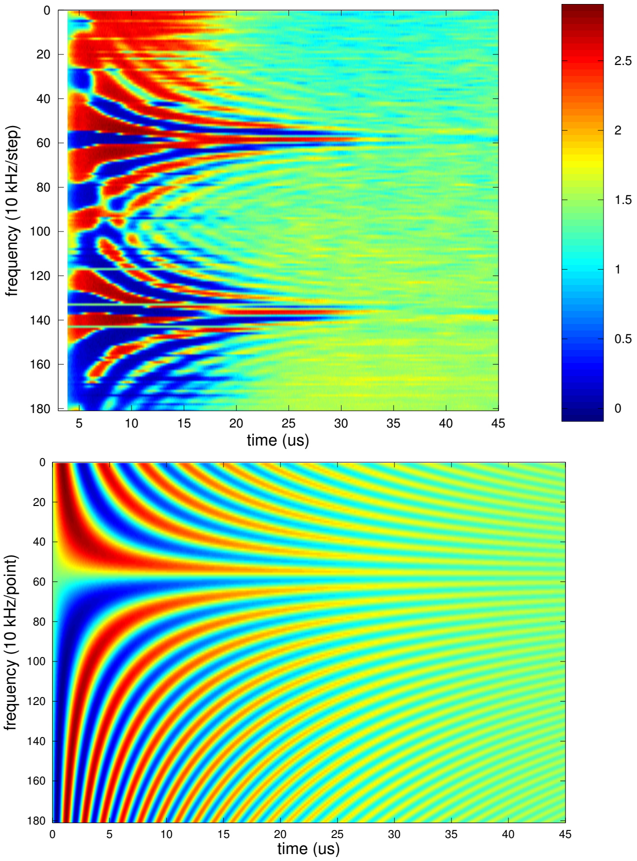

Figure 2. Top: experimental measurement of the time-dependent output of the I output of the XE1203F transceiver when a dual resonator SAW sensor is connected to the antenna output. Bottom: simulation of the returned signal as $\sin(2\pi(f-f_0)t)$ with f_0 the fixed resonance frequency of the sensor and f the frequency emitted by the transceiver (ordinate), hence demonstrating the the signal returned by the sensor is at the natural frequency of the resonator. The optimum signal to noise ratio was identified with a unique sampling by the microcontroller A/D converter 20 μs after the duplexer was switched from emission to reception positions.

the ability to recover the stored data on widely available Personal Computers, a FAT-based data storage was selected as a tradeoff between a filesystem compatible with low power microcontroller, while still widely available on most commonly used operating systems. Thus, the EFSL library was ported to the STM32 platform for this purpose.

All measurements are differential: the sensor is made of two resonators in parallel, one exhibiting a strong frequency dependence with temperature and the other one a turnover temperature within the operating range. Using this approach, each measurement requires a sampling duration of 33ms, including programming the transceiver, recording the two values (I and Q) from the analog to digital converter for each sampled frequency (128 samples in the 1.7 MHz wide ISM band), applying a cross-correlation algorithm through a fast Fourier transform to measure the frequency difference between both resonances, and transmitting the data through the wireless link as well as storing a copy on SD card. Digital data communication is performed at the bandwidth of 4800 bits/s for improved immunity to noise and extended communication range. SAW resonators hardly provide enough information to allow for both measuring a physical quantity and identification: since a resonator is characterized by only two parameters (resonance frequency and quality factor), the only available means for identifying multiple sensors located within interrogation range of a transceiver is by using frequency multiplexing. Despite not being compliant with ISM radiofrequency emission regulations, the transceiver can synthesize frequencies in the 434 ±8 MHz range, far beyond the ISM band, compatible with reading up to 32 resonances.

Although the (SAW) sensor does not require local power, the interrogation unit is battery powered. In order to extend the operating duration of the sensor network, deep sleep mode is active most of the time with only intermittent wakeup sequences to probe the sensor and transmit data to the sink. Each SAW reader is identified by a unique, user defined, 32-bit address used as pattern during the data transmission (hardware feature of the XE1203F chip).

III. OPERATING MODES

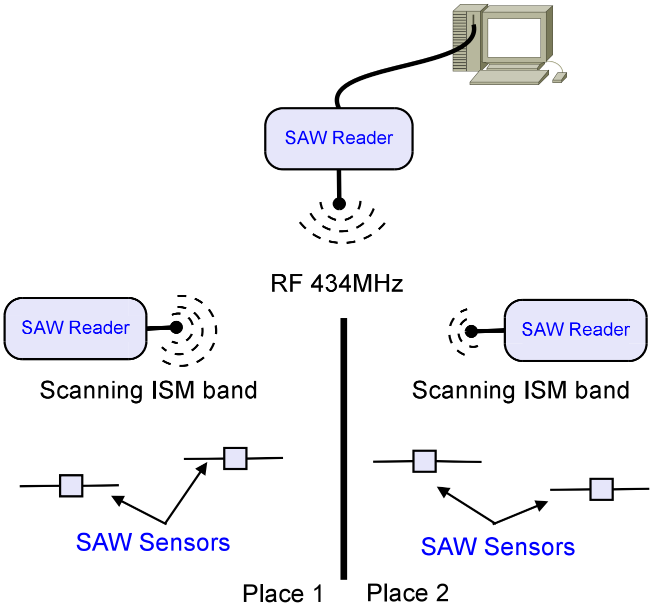

Figure 3. Three SAW readers are used in this model of the wireless sensor network considered here: one reader acts as the sink and triggers the data transfer (master) from the other readers used for probing SAW sensor responses (slaves). Each slave reader is associated with nearby SAW sensors: after receiving the command for performing a measurement, the SAW reader probes the nearby resonator resonance frequencies and transmits the result through a wireless digital link.

Two operating modes have been implemented:

- one reader is configured as the sink, constantly listening for incoming data, and connected to a Personal Computer for data storage and transfer. In this case, the radiomodem transceiver is used in its default operating mode, namely digital data transmission. The other readers, spread on the field within a digital communication range of about 100 m, are configured in standby mode and periodically wake up to probe the nearby SAW sensor (interrogation range of $\simeq$1 m). Once the SAW sensor properties (resonance frequency and signal power) are recorded on the remote system, data are transmitted to the sink (Fig.3). One challenge in scalability of this simple approach is that readers are assumed *not* to wake up simultaneously in order to avoid interferences on the radiofrequency link. Furthermore, the digital link is half duplex, leading to potentially significant limitations in the extension of this approach to a fully distributed, multi-hop wireless network protocol. This issue is under investigation by porting the current low level (C-language based) implementation of the communication algorithms to the TinyOS executive environment, targeted at providing the MAC layer and associated communication protocols. Although the periodic wake up of each node hardly qualifies this implementation as a deployed Wireless Sensor Network (WSN), power consumption is optimized since the readers deployed in the field spend most of their life in deep sleep mode, yielding significant power consumption reduction.

- The second approach is based on a master/slave communication protocol, in which the sink (master) requests measurements from the readers deployed on the field (slaves). Again the multi hop protocol is not implemented, but here all nodes are constantly in receive mode, potentially acting as routers of the incoming messages to nodes located further away from the sink. The drawback is that although the microcontroller is in sleep mode (wake up by a hardware interrupt generated by the radiomodem), the radiofrequency transceiver exhibits significant power consumption even in receive mode, reducing the life expectancy in a battery powered application.

IV. EXPERIMENTAL RESULTS

One example of harsh environment [20] where battery powered sensors exhibit a limitation is buried sensors: once the sensor is installed in concrete or buried in soil, access for maintenance or battery replacement is no longer an option. Thus, our experimental demonstration is performed on a SAW sensor buried 30 cm deep in soil (fig.4). Such a device has been installed for more than 4 years with no dedicated packaging other than a standard micro-electronics 5 mm× mm ceramic packaging, with neither drift nor signal loss despite direct contact of the soldered dipole antenna (enameled wires) and the sensor with soil [21]. Alternative technologies include distribued measurements along a buried optical fiber exhibiting Brillouin backscatter [22], or if infinite life expectancy is not mandatory, battery powered systems with extended life expectancies have been used [23], [24].

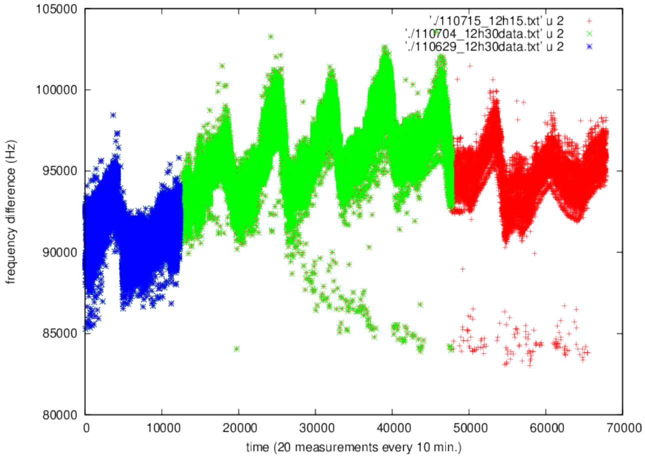

Figure 4. 10-day temperature record of a SAW sensor buried 30 cm deep in soil: 20 measurements are stored on a FAT formatted SD card every 10 minutes and transmitted through a digital radiofrequency link. The various colors indicate successive manual recoveries of the data stored on the SD card.

The measurement standard deviation is 2 kHz: considering that the dual resonator sensor difference frequency dependence with temperature is 2500 Hz/^{o}C, the observed temperature variations between day and night is about 4 ^{o}C. The temperature measurement resolution is 1 ^{o}C.

V. CONCLUSION

While the use of SAW as passive sensors interrogated through a wireless link has demonstrated unique operating conditions in harsh environments, the widespread deployment as part of a wireless sensor network is here investigated by reconfiguring the same digital data transmission transceiver for probing SAW resonator properties and hence the associated physical quantity under investigation. A practical demonstration of temperature measurement with local data storage on a non-volatile medium and real time data transmission to a remote sink connected to a personal computer is performed. Thus, the complementarity of the approach is emphasized: a short (0.1 to 1 m interrogation range) interrogation distance of the passive sensor located in a harsh environment, coupled with long range wireless digital data transmission.

REFERENCES

[1] R. White and F. Voltmer, “Direct piezoelectric coupling to surface acoustic waves,” *Applied Physics Letters*, vol. 7, no. 12, pp. 314–316, december 1965.

[2] W. Buff, F. Plath, . Schmeckebier, M. Rusko, T. Vandahl, H. Luck, F. Möller, and D. Malocha, “Remote sensor system using passive SAW sensors,” in *IEEE Ultrasonics Symposium*, 1994, pp. 585–588.

[3] A.Pohl, F.Seifert, L.Reindl, G.Scholl, T. Ostertag, and W.Pietsch, “Radio signals for SAW ID tags and sensors in strong electromagnetic interference,” in *IEEE Ultrasonics Symposium*, Cannes, France, 1994, pp. 195–198.

[4] H. Scherr, G. Scholl, F. Seifert, and R. Weigel, “Quartz pressure sensor based on SAW reflective delay line,” in *IEEE Ultrasonics Symposium*, San Antonio, TX, USA, 1996, pp. 347–350.

[5] L. Reindl, G. Scholl, T. Ostertag, C. Ruppel, W.-E. Bulst, and F. Seifert, “SAW devices as wireless passive sensors,” in *IEEE Ultrasonics Symposium*, 1996, pp. 363–367.

[6] P. Hartmann, “A passive SAW based RFID system for use on ordnance,” in *IEEE International Conference on RFID*, 2009, pp. 291–297.

[7] C. Hartmann and L. Claiborne, “Fundamental limitations on reading range of passive IC-based RFID and SAW-based RFID,” in *IEEE International Conference on RFID*, Gaylord Texan Resort, Grapevine, TX, USA, March 2007.

[8] J. Beckley, V. Kalinin, M. Lee, and K. Voliansky, “Non-contact torque senseor based on SAW resonators,” in *IEEE Int. Freq. Control Symposium and PDA Exhibition*, New Orleans, LA, USA, 2002, pp. 202–213.

[9] A. Pohl, R. Steindl, and L. Reindl, “The “intelligent tire” utilizing passive SAW sensors – mesurement of tire friction,” *IEEE Transactions on Instrumentation and Measurement*, vol. 48, no. 6, pp. 1041–1046, december 1999.

[10] W. Bulst, G. Fischerauer, and L. Reindl, “State of the art in wireless sensing with surface acoustic waves,” *IEEE Transactions on Industrial Electronics*, vol. 48, no. 2, pp. 265–271, April 2001.

[11] J. H. Kuypers, M. Esashi, D. A. Eisele, and L. M. Reindl, “2.45 GHz passive wireless temperature monitoring system featuring parallel sensor interrogation and resolution evaluation,” in *IEEE Ultrasonics Symposium*, 2006, pp. 1453–1458.

[12] X. Q. Bao, W. B. an V.V. Varadan, and V. Varadan, “SAW temperature sensor and remote reading system,” in *IEEE Ultrasonics Symposium*, Denver, CO, USA, 1987, pp. 583–585.

[13] A. Pohl, G. Ostermayer, and F. Seifert, “Wireless sensing using oscillator circuits locked to remote High-Q SAW resonators,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 45, no. 5, pp. 1061–1168, september 1998.

[14] A. Stelzer, S. Schuster, and S. Scheiblhofer, “Readout unit for wireless SAW sensors and ID-tags,” in *International Workshop on SiP/SoC Integration of MEMS and Passive Components with RF-ICs*, 2004.

[15] G. Bruckner, A. Stelzer, L. Maurer, J. Biniasch, L. Reindl, R. Teichmann, and R. Hauser, “A high-temperature stable SAW identification tag for a pressure sensor and a low-cost interrogation unit,” in *11th International Sensor Congress (SENSOR)*, Nuremberg, Germany, 2003, pp. 467–472.

[16] M. Hamsch, R. Hoffmann, W. Buff, M. Binhack, and S. Klett, “An interrogation unit for passive wireless SAW sensors based on Fourier transform,” *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 51, no. 11, pp. 1449–1456, november 2004.

[17] J.-M. Friedt, C. Droit, G. Martin, and S. Ballandras, “A wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement,” *Rev. Sci. Instrum.*, vol. 81, p. 014701, 2010.

[18] D. Beier and W. Meierfrankenfeld, “Method for temperature measurement in a household appliance,” U.S. Patent 7 358 464, Apr. 15, 2008.

[19] R. Fonseca, O. Gnawali, K. Jamieson, S. Kim, P. Levis, and A. Woo, “The collection tree protocol (CTP),” 2007. [Online]. Available: www.tinyos.net/tinyos-2.x/doc/html/tep123.html

[20] R. Fachberger, G. Bruckner, R. Hauser, and L. Reindl, “Wireless SAW based high-temperature measurement systems,” 2006.

[21] J.-M. Friedt, T. Rétornaz, S. Alzuaga, T. Baron, G. Martin, T. Laroche, S. Ballandras, M. Griselin, and J.-P. Simonnet, “Surface acoustic wave devices as passive buried sensors,” *Journal of Applied Physics*, vol. 109, no. 3, p. 034905, 2011.

[22] T. Parker, “A fully distributed simultaneous strain and temperature sensor using spontaneous Brillouin backscatter,” *IEEE Photonics Technology Letters*, vol. 9, no. 7, pp. 979–981, 1997.

[23] J. Hart, K. Rose, K. Martinez, and R. Ong, “Subglacial clast behaviour and its implication for till fabric development: new results derived from wireless subglacial probe experiments,” *Quaternary Science Reviews*, vol. 28, pp. 597–607, 2009.

[24] J. Hart and K. Martinez, “Environmental sensor networks: a revolution in the earth system science ?” *Earth Science Reviews*, vol. 78, pp. 177–191, 2006.