Network Demonstration of Low-cost and Ultra-low-power Environmental Sensing with Analog Backscatter

Eleftherios Kampianakis, Stylianos D. Assimonis and Aggelos Bletsas

ECE Dept., Technical University of Crete, Chania, Greece 73100
ekabianakis@isc.tuc.gr, {assimonis, aggelos}@telecom.tuc.gr

***Abstract*— Recent advances in antennas used as sensors have clearly demonstrated sensing capabilities. However, such approaches typically require manufacturing precision or high-sensitivity, expensive receivers. Furthermore, sensors that utilize communication by means of reflection have been proposed. However, such sensors typically suffer from small communication range. In sharp contrast to prior art, this work adopts analog bistatic backscatter radio principles and demonstrates a network of *simultaneously* operating sensors. Communication range on the order of 60m was achieved with commodity, low-cost receiver. Environmental humidity was measured with accuracy 1.9%RH RMS error, 0.5milliWatt power consumption and cost approximately 5€ per tag. Interesting tradeoff between measurement accuracy and number of sensors is briefly described.**

I. Introduction

Wireless sensor networks (WSN) with conventional, Marconi-type radio is the present solution for dense environmental monitoring across broad geographical regions. However, such design principles impose critical power, cost and complexity constraints [1].

Communication by means of reflection has recently attracted attention for low-power, wireless sensing, as a low-cost alternative to conventional Marconi-type radios. An example, is work in [2], where humidity sensing was implemented by modulating the reflection of a carrier. However, communication range was limited to a few centimeters. The idea of using an *antenna as an environmental humidity sensor* has has also appeared in the literature. Examples include humidity sensors as in [3], [4], where polyimide coatings or silicon nanowires, respectively, changed the antenna permitivity as a response to environmental relative humidity (%RH). However, such approaches require either increased manufacturing cost (e.g. due to safety requirements) or have been tested with high sensitivity, expensive receivers, such as network analyzers.

This work takes advantage of recent discoveries in monostatic [5] or bi-static [6] backscatter radio, that allow ultra low-power and low-cost communication with extended ranges and single transistor RF front-ends. A network is demonstrated, consisting of simultaneously operating low-cost and ultra-low power environmental humidity sensors that exploit the backscatter radio principle. In sharp contrast to prior art, extended communication ranges have been achieved with low-cost, commodity, software defined

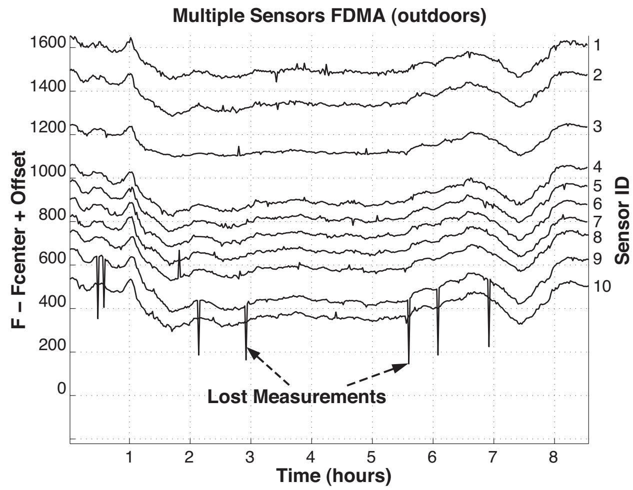

Fig. 1. Simultaneous sensing from various tags, as a function of time. Each sensor corresponds to a unique subcarrier (i.e switching) frequency, even though all sensors share a common carrier frequency transmitted by a remote emitter.

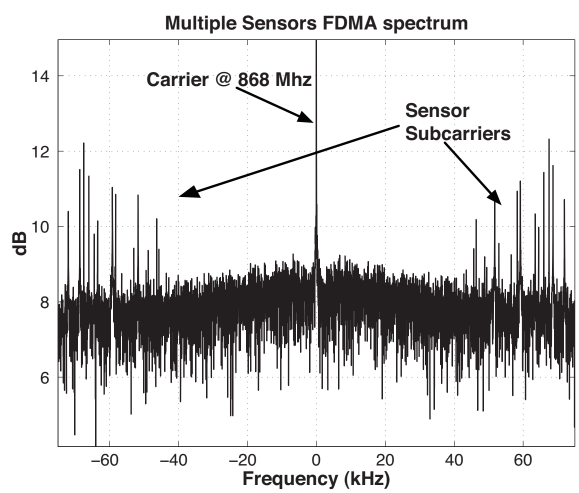

Fig. 2. Received spectrum of a the implemented network consisting of 14 tags. The subcarrier (i.e switching) frequencies from multiple tags occupy different frequency bands, thus achieving frequency division multiple access (FDMA).

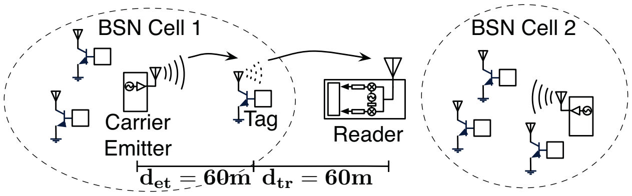

Fig. 3. Bistatic dislocated architecture sensor network with reader detached from the carrier emitter. d_{et} and d_{tr} denote the emitter - tag and the tag-reader distance, respectively. A maximum range of 60m for both values was achieved (total 120m) with a RMS error of 2%RH.

radio (SDR) equipment, exploiting analog radio principles.

II. Implementation

The system was developed for maximum scalability, and minimum cost, complexity and power. This section briefly describes: a) the backscatter radio-enabled humidity tag, b) the multiple access control (MAC) networking scheme, and c) the low-cost backscatter radio receiver.

a) Backscatter radio-enabled humidity tag: This device is an oscillator that produces square voltage pulses with varying frequency, based on passive components and a capacitive humidity sensor [7]. The output frequency is given in (1), where R and C is the corresponding passive resistor and capacitor, and C_s is capacitance that varies with environmental quantity (e.g. humidity):

$$F = \frac{1}{\ln(2)\ R\ (C + C_s)}. \tag{1}$$

The voltage pulses produced are routed to the RF switching transistor connected to the tag antenna and enables backscatter operation. The subcarrier (i.e switching) frequency signal with the value of (1) modulates with frequency modulation (FM) the humidity measurement on the carrier produced by a dislocated, remote emitter. The FM modulated carrier is scattered back towards the receiver.

b) MAC networking: Frequency division multiple access (FDMA), is adopted since tags can operate in distinct frequency regions, even though, a single carrier is utilized. Let F_{iL} and F_{iH} denote the subcarrier frequency output of th i-th tag for 100% and 0%RH, respectively. Then the occupied spectrum band is given by:

$$\begin{aligned} B_i &= F_{iH} - F_{iL} \\ &\stackrel{(1)}{=} \frac{C_H - C_L}{\ln(2)\ B_i\ R_i\ (C_L + C_i)(C_H + C_i)}, \end{aligned} \tag{2}$$

where R_i and C_i are unique for the i-th tag, and, C_L and C_H are the humidity sensor's capacitance value for 0% and 100%RH, respectively. By solving the equation system for fixed F_{iL} and B_i, the values for C_i and R_i are calculated

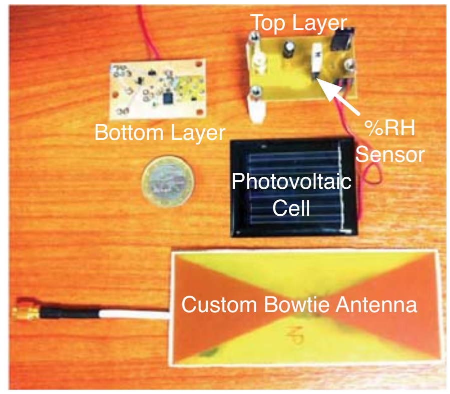

Fig. 4. The fabricated backscatter radio-enabled tag with photovoltaic cell and humidity sensor attached. The whole tag/sensor is fully operational with the depicted, limited size and cost photovoltaic cell and consumes *only* 0.5mW. A custom bowtie antenna is also depicted.

accordingly:

$$C_i = \frac{B_i\ C_L + F_{iL}\ (C_H - C_L)}{B_i}, \tag{3}$$

$$R_i = \frac{B_i}{\ln(2)\ F_{iL}\ (C_H - C_L)\ (F_{iL} + B_i)}. \tag{4}$$

The network's total required spectrum is lower-limited by the RF clutter around the carrier frequency [8] and upper-limited by maximum operational frequency of the capacitive sensor, as well as the harmonics of the signal that drives the single transistor front-end. Smaller bandwidth per tag B_i results to larger number of sensors operating simultaneously. On the other hand, larger B_i offers better frequency resolution and thus, better resistance to noise and other non-idealities which in turn results to better accuracy. Therefore, there is an interesting tradeoff between network size and sensing accuracy.

c) Backscatter radio receiver: The receiver utilizes a commodity SDR platform based on homodyne architecture. A periodogram-based, subcarrier frequency $\hat{F}_i$ estimator was implemented for each i-tag:

$$\hat{F}_i = \underset{F \in [F_{iL}, F_{iH}]}{\arg\max}\ |X(F)|^2, \tag{5}$$

where, $X(F)$ is the Fourier transform of the baseband downconverted and carrier frequency offset (CFO)-compensated signal. CFO estimation and compensation was based on time and frequency domain techniques [9]. Sampling duration time for each measurement is dependent on sensor's response time. In this work, the response time was on the order of 1 second for the specific humidity capacitive sensor. Such increased sampling time duration offered robust estimation of subcarrier frequencies and thus, extended communication ranges for the proposed network; therefore, low-cost, efficient reception was implemented with analog radio principles.

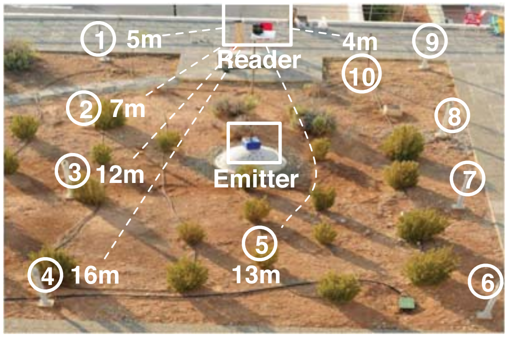

Fig. 5. Outdoor deployment of 10 tags placed around the carrier emitter and up to a 16m radius from the reader (covering approx. $155m^2$).

III. Results

A demonstration network of 10 tags was deployed outdoors (Fig. 5), using a bistatic backscatter radio architecture (Fig. 3): the carrier emitter is at the center of the backscatter sensor network (BSN) "cell" and tags were located around it. Each tag occupies a frequency band of 2kHz, which, together with the guard frequency bands, amounted to a total spectrum occupation of 50kHz. The deployment covered an area of approx. $155m^2$ and demonstrated the potential for broad area environmental sensing. The subcarrier frequencies of *simultaneously* operating tags, as a function of time and subcarrier frequency are depicted in Fig. 1 and Fig. 2.

Maximum communication range of 60m emitter-to-tag and 60m tag-to-reader was achieved, with RMS error of 2%RH. Range measurements were conducted with the prototype bow-tie antenna depicted in Fig. 4. The antenna was fabricated in-house for reduced cost. The overall cost for each sensor/tag was on the order of 5€ (including the photovoltaic cell as well as the fabrication cost). The bow-tie antenna design was chosen as an enhanced variation of a dipole, due to its wide-band characteristics, small fabrication complexity and robustness to manufacturing tolerances [10].

Each tag consumes 0.5mW and is powered by a low-cost photovoltaic cell. RMS error of 1.9%RH was measured, in comparison to a reference calibrated sensor (Fig. 6). Finally, the tag can be easily extended to other sensing parameters by replacing the capacitive or resistive components of the oscillating circuit. Therefore, the proposed network offers highly *flexible* sensing capabilities.

IV. Conclusion

A sensor network of simultaneously operating tags utilizing the analog, backscatter radio has been demonstrated. Communication range on the order of 60m was achieved with commodity, low-cost receiver. Environmental humidity was measured with accuracy 1.9%RH RMS error, 0.5mW power consumption and cost approximately 5€ per tag. Future work will extend the network to other sensing applications.

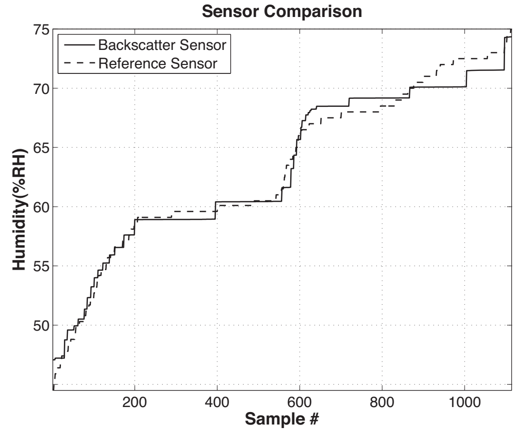

Fig. 6. 1200 %RH samples of a calibrated tag, and a reference precision sensor are depicted. RMS error of 1.9%RH was measured.

Acknowledgment

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