Spectrally Efficient 4-PAM Ambient FM Backscattering for Wireless Sensing and RFID Applications

Spyridon N. Daskalakis[1], Ricardo Correia[2], George Goussetis[1],
Manos M. Tentzeris[3], Nuno Borges Carvalho[2], Apostolos Georgiadis[1]

[1]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, Scotland, UK
sd70@hw.ac.uk, g.goussetis@hw.ac.uk, a.georgiadis@hw.ac.uk

[2]Instituto de Telecomunicações, Universidade de Aveiro, 3810-193 Aveiro, Portugal
srjoao@ua.pt, nbcarvalho@ua.pt

[3]School of Electrical and Computer, Engineering, Georgia Institute of Technology, Atlanta, GA 30308, USA
etentze@ece.gatech.edu

***Abstract*—This work presents a novel wireless tag operating solely with ambient backscatter signals while featuring high-order modulation capabilities. Specifically, the proposed tag communicates with a low-cost software defined radio reader using backscatter radio principles on ambient commercial FM station signals, while sensing information from sensors can be modulated on the analog signals using 4-pulse amplitude modulation (4-PAM). The tag transceiver implementation is based on an ultra-low-power microcontroller for data processing and an RF front-end for wireless communication. A proof-of-concept prototype was demonstrated indoors over a 2 m tag-reader distance for a low bit rate of 328 bps with a power consumption under 20 μA.**

***Index Terms*—Ambient backscattering, backscatter communication, high order modulation, Internet of Things (IoT), radio frequency (RF) identification (RFID) sensors.**

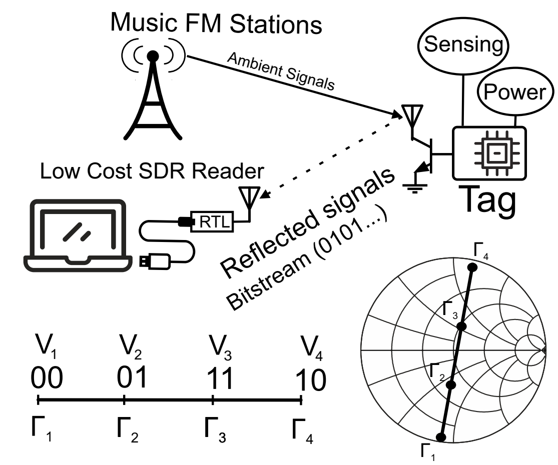

Fig. 1. Top: Backscatter communication scheme using ambient signals from FM stations. Bottom Left: 4-PAM high-order modulation symbols. Bottom Right: Smith Chart with required 4-PAM antenna S_{11} parameters.

I. Introduction

The ultra-low-cost and ultra-low-power potential of backscattering approach in Internet-of-Things (IoT) applications makes it a very attractive technology for short range communications, such as typical radio frequency (RF) identification (RFID)-enabled wireless sensors. Typical RFID systems require a carrier wave (CW) emitter, the sensor node/tag and a reader. The reader provides the CW for both power supply and communication purposes. Recently, the ambient RF signals have been proposed for backscatter communication instead of a CW signal. In [1], commercially broadcast frequency modulated (FM) signals have been used for power and communication. Ambient backscattering could be an optimal approach for on-body sensors [2] due to the inherent low energy and low cost budgets of tags. In [3], a front-end consisting of an RF switch and a dipole antenna was used to implement binary On-Off keying (OOK) modulation on ambient FM station signals. The power consumption was 1.3 mW for a data rate of 500 bps and 5 m communication range.

Recent works [4], [5] have shown that backscatter communication can be extended to include higher order modulation schemes, such as four-state quadrature amplitude modulation (4-QAM), 16-QAM, and four-pulse amplitude modulation (4-PAM). In [4], authors used a 16-to-1 Mux with SP4T RF switches to modulate the antenna impedance between 16 impedance states. In [5] a novel circuit including a Wilkinson power divider and two transistors was presented. Schemes of M-QAM or M-PAM can be effectively implemented as each transistor can be switched with different voltage levels to achieve different reflection coefficient values. In [1], 4-frequency-shift keying (4-FSK) was used to transmit data over the ambient FM signals.

In this work we introduce a novel tag that uses for the first time 4-PAM high-order modulation for backscattering over ambient FM signals (Fig. 1, Top). This scheme was selected mainly due to its hardware simplicity and low power consumption, as it can be implemented only with one transistor and an antenna. The main part of the tag consists of a microcontroller (MCU) for processing and control of the transistor. This work is a different approach from [4] and [5] due to the fact that

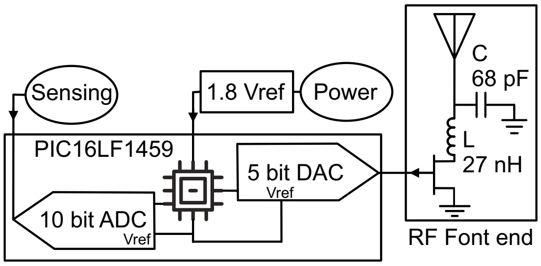

Fig. 2. The proof-of-concept tag consists of an MCU and an RF front-end (transistor and antenna). An ADC collects data from integrated sensors, and a DAC generates the appropriate gate voltages of the 4-PAM modulation.

ambient analog FM signals are used as the carrier instead of a pure transmitted CW signal. The reader architecture is simplified to a low cost software defined radio (SDR) receiver and a communication range over 2 m demonstrated for a power consumption 28.8 μW and bit rate 328 bps.

II. Backscatter 4-PAM scheme

The 4-PAM scheme is based on a four distinct antenna-load values with reflection coefficients: $\Gamma_\text{i} = (Z_\text{i} - Z_\text{a}^*)/(Z_\text{i} + Z_\text{a})$, [4], [5] with $\text{i} = 1, 2, 3, 4$ and Z_a being the antenna impedance 50 Ohm. An RF transistor is used to change the antenna termination load value. Each switch state can create a specific impedance for each transmitted symbol effectively introducing modulation through the change of each Γ_i over time. The performance of 4-PAM is maximized when Γ_i lie on the same line in Smith Chart with equal distances between different states (Fig. 1, Bottom Right). In time domain, four distinct pulse amplitudes ("symbols") with period T_symbol are used to convey the information. The amplitude voltage levels are represented by two bits each: `00`, `01`, `11`, and `10` as depicted in Fig. 1 (Bottom Left). The pairs are "Gray coded" thus two adjacent values differ in only one bit. The data rate is doubled and 4-PAM is twice bandwidth-efficient as conventional binary OOK modulation. This scheme requires a high signal-to-noise ratio (SNR) because the extra two amplitude levels reduce the level spacing by a factor of 3, therefore making the modulation more susceptible to noise than the binary modulation.

III. Sesnor Node/Tag Design

Our proof-of-concept sensor node/tag consists of a MCU and an RF front-end as depicted in the block diagram of Fig. 2. In this work the 8-bit PIC16LF1459 MCU from Microchip was selected with a power consumption of only 25 μA/MHz at 1.8 V. The 31 KHz low-power internal oscillator was utilized as a clock source with an ultra-low-power consumption. The tag can collect data from sensors using the embedded 10-bit Analog-to-Digital Converter (ADC) and it can drive the RF front-end through a 5-bit Digital-to-Analog Converter (DAC). The external voltage regulator XC6504 was used to supply the tag with a stable reference voltage (V_ref) 1.8 V. The DAC switches the gate of the RF front-end transistor with $V_\text{ref}/2^5$ distinct voltage levels in order to change the antenna load impedance according to the chosen modulation.

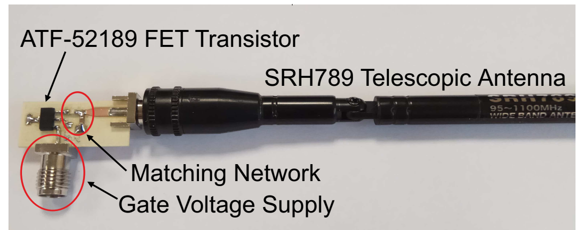

Fig. 3. Fabricated RF front-end prototype board.

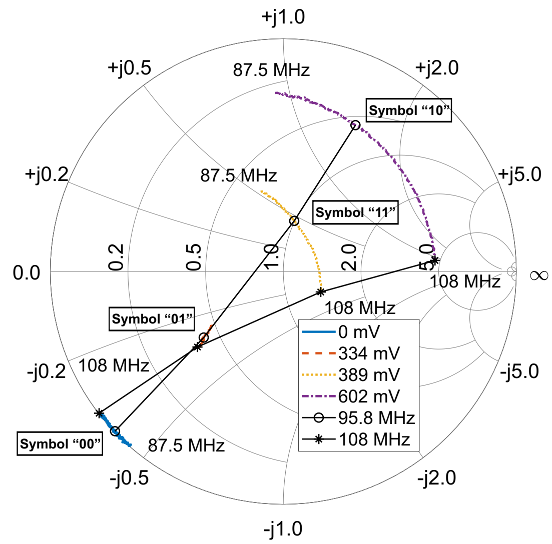

Fig. 4. Smith Chart with measured S_{11} values for 4 different voltage levels at the gate of transistor for $P_\text{in} = -20$ dBm at $87.5 - 108$ MHz.

The RF front-end consists of an RF transistor ATF52189 and a monopole antenna SRH788 for FM signal reception (Fig. 3). This part is responsible for the modulation over the backscattered FM signals with the main challenge being the appropriate change of the drain impedance by varying the voltage at the gate only between 0 to 0.6 V. The RF front-end circuit was optimized using the Advanced Design System (ADS) from Keysight to perform four different discrete Γ_i values at 95.8 MHz. The matching network between the transistor and the antenna was composed by a capacitor and an inductor as depicted in Fig. 2. The Large-Signal S-Parameter simulation was used to perform the backscatter modulation and the components were optimized at 68 pF and 27 nH in order to maximize the distance between the consecutive Γ_i values. The RF front-end prototype was fabricated on Astra $MT77$ substrate with thickness 0.762 mm, $\epsilon_r = 3.0$ and $tan\delta = 0.0017$. The fabricated board was measured using a vector network analyser (VNA) with $P_\text{in} = -20$ dBm over FM frequencies $87.5 - 108$ MHz (full FM band). The CW signal of VNA was used for the measurements and the Γ_i that correspond to the four voltage levels for 4-PAM are presented in Fig. 4. The frequency sweep demonstrates the fact that each state becomes an "arc" on the Smith Chart and a set of the four states (line) rotates clockwise as the frequency increases. By generating four voltages at the DAC (0, 334, 389 and 602 mV,

TABLE I
TAG CURRENT CONSUMPTION

Tag Operation Mode @V_{DD} = 1.8 V	μA	Bit rate (bps)
Sleep: (no DAC, no ADC)	0.6	0
Active: OOK (no DAC, no ADC)	3.6	147
Active: OOK (no DAC, ADC)	220	147
Active: 4PAM (DAC, no ADC)	16	328
Active: 4PAM (DAC, ADC)	232	328

respectively) the Γ_i symbols for the fixed frequency 95.8 MHz and 108 MHz are depicted in Fig. 4.

For comparison and validation purposes, OOK with FM0 encoding was implemented on the proof-of-concept tag; thus, this modulation requires only a digital output pin from MCU [3]. The minimum T_{symbol} achieved was 3.4 ms for a bit rate of 147 bps. Current consumption results for OOK and 4-PAM are presented in Table. I. In OOK modulation the dissipated current was measured 3.6 μA when the ADC was off and 220 μA when the ADC was activated. In this work the transistor switches between four states and the minimum T_{symbol} achieved was 6.1 ms. Every symbol contains 2 bits, thus leading to a calculated maximum bit rate of 328 bps ($2/T_{symbol}$). The current consumption on 4-PAM was measured at 16 μA with ADC disabled and 232 μA with ADC enabled. Table I shows that there is a clear tradeoff between the bit rate and the power power consumption between the two modulation schemes. In this work the power of the tag was supplied from a battery and in the sleep mode operation the measured current consumption was 0.6 μA. This work doesn't focus on sensing or power aspects but only on the novel telecommunication aspect of the system. An efficient solar and RF harvester can be used to charge a super capacitor instead of a battery, in future work.

IV. READER & COMMUNICATION RESULTS

In this work, the low cost RTL-SDR reader was used [3]. The SDR is responsible for receiving the backscatter signal (I/Q samples) of the most powerful FM station. In our case the 95.8 MHz FM station was selected and MATLAB software was utilized for further processing. In the receiver algorithm, the envelope detector of the signal (absolute squared value) was taken and a low-pass filtering was utilized to remove the high frequency interferences. The low-pass filter is a matched filter (square pulse) with the duration T_{symbol}, that was used to display the received symbols in time domain.

The proposed system was tested in the lab using the setup shown in Fig. 5. The proof-of-consent tag prototype was installed on a breadboard and was programmed to send a fixed packet bit-stream (`1010101111-01-01-0011010001`) to the reader. The symbol representation of bit-sequence is depicted in Fig. 6 with the oscilloscope measurement showing the four voltage levels of the transmitted symbols that are used to drive the transistor. Due to the non-linear relationship between the transistor gate voltage and the Γ_i, the small variation between the gate voltages corresponding to the states

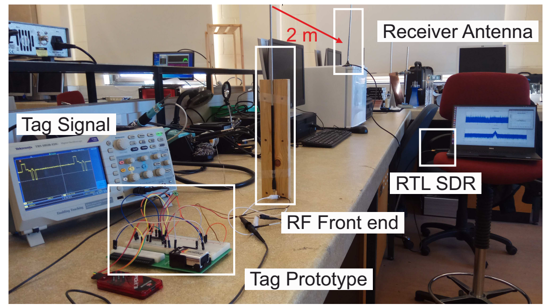

Fig. 5. Indoor lab measurement setup. The tag antenna was placed 2 m away from the receiver antenna. The SDR reader was tuned at a 95.8 MHz FM station located 34 Km away for the lab.

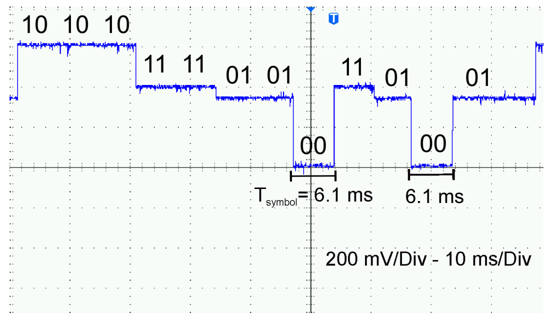

Fig. 6. Oscilloscope measurement of the time-domain backscatter packet at the gate of the transistor. Voltage levels correspond to the 4-PAM symbols.

`01` and `11` (Fig. 6) leads to the maximum distance between the respective Γ_i (Fig. 4). To test the performance of the backscatter communication link, the RF front-end antenna was placed 2 meter away from the receiver antenna while the FM station antenna was 34 Km way from the experimentation setup. The power level of the FM signal received by the tag's antenna, was measured on a spectrum analyser at -54.4 dBm.

The received packet waveform, in time domain, after the low-pass filtering is shown in Fig. 7. The envelope of the FM signal is computed by combining the magnitudes of the I and Q channels, while the low-pass filtering maximizes the symbol detection probability while high-frequency components (fast fading) be effectively removed. The maximization of received packet energy could be used in the future to find the start of the transmitted packet and synchronize it at the correct sampling instants. After that, a soft decision method is required to detect the transmitted symbols of Fig 6. The signal could be quantized to the nearest element of the 4-PAM alphabet using the nearest neighbour method. Using three amplitude thresholds, as depicted in Fig. 7 the specific symbol region corresponding to a received sample for a given T_{symbol} can be easily determined. Finally, the transmitted bits could be easily extracted through the detected symbols.

V. CONCLUSION

In this paper, we introduce an ultra-low-power sensor node with ambient FM backscatter and high-order modulation capabilities. The information of the integrated sensors is modulated

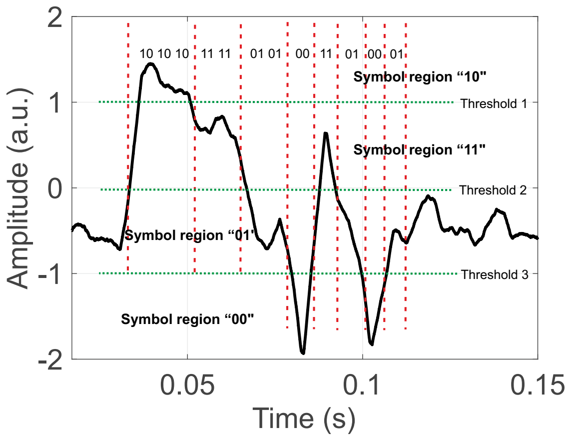

Fig. 7. Received packet after matched filtering. A good agreement with Fig. 6 is observed and the respective symbols can be detected using nearest neighbour method.

on an ambient FM signal using a 4-PAM scheme. The reflected signals are sent back to a computer through a low cost RTL-SDR reader. This approach is the first demonstration of backscatter 4-PAM modulation on ambient FM signals and paves the way toward enabling practical deployment for short-range, ultra-low-power RFID sensors such as wearable body-area-network ID-enabled sensors.

Acknowledgment

The work of S. Daskalakis was supported by Lloyds Register Foundation (LRF) and the International Consortium in Nanotechnology (ICON). S. Daskalakis, G. Goussetis, M. M. Tentzeris and A. Georgiadis would like to thank LRF and ICON. This work of R. Correia and N. B. Carvalho was supported by the European Regional Development Fund (FEDER), through the Competitiveness and Internationalization Operational Programme (COMPETE 2020) of the Portugal 2020 framework, Project, MOBIWISE, POCI-01-0145-FEDER-016426 and is funded by FCT/MEC through national funds and when applicable co-funded by FEDER – PT2020 partnership agreement under the project UID/EEA/50008/2013.

References

[1] A. Wang, V. Iyer, V. Talla, J. R. Smith, and S. Gollakota, “FM Backscatter: Enabling Connected Cities and Smart Fabrics,” in *Proc. USENIX Symp. on Networked Sys. Design and Impl. (NSDI)*, Boston, MA, Mar. 2017, pp. 243–258.

[2] P. Zhang, M. Rostami, P. Hu, and D. Ganesan, “Enabling practical backscatter communication for on-body sensors,” in *Proc. ACM Spec. Interest Group Data Commun. Conf. (SIGCOMM)*, Florianopolis, Brazil, Aug. 2016, pp. 370–383.

[3] S. N. Daskalakis, J. Kimionis, A. Collado, G. Goussetis, M. M. Tentzeris, and A. Georgiadis, “Ambient backscatterers using fm broadcasting for low cost and low power wireless applications,” *IEEE Trans. Microw. Theory Techn.*, vol. PP, no. 99, pp. 1–12, Nov. 2017.

[4] S. J. Thomas and M. S. Reynolds, “A 96 Mbit/sec, 15.5 pJ/bit 16-QAM modulator for UHF backscatter communication,” in *Proc. IEEE Int. Conf. on RFID*, Orlando, FL, USA, Apr. 2012, pp. 185–190.

[5] R. Correia, A. Boaventura, and N. B. Carvalho, “Quadrature Amplitude Backscatter Modulator for Passive Wireless sensors in IoT Applications,” *IEEE Trans. Microw. Theory Techn.*, vol. 65, no. 4, pp. 1103–1110, Feb. 2017.