Intelligent Noncoherent Sequence equals Coherent Detection: Experimental Proof in Industrial RFID

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***Abstract*—This work presents the industrial RFID interrogation protocol and describes coherent (with estimated channel using short preambles) and state-of-the-art, noncoherent sequence detection algorithms. Performance is compared, utilizing both simulation and experimental results, from a software-defined testbed. This work puts forth, for the first time in the literature, experimental demonstration of intelligent, noncoherent, generalized likelihood ratio test-optimal sequence detection in an industrial setup. It is shown that performance of noncoherent, as well as coherent detection of the 128-bit tag message sequence coincide. Thus, removal of preamble/pilot bits and adoption of the noncoherent algorithm could improve reading speed of RFID tags at the reader, adding commercial value, without sacrificing bandwidth, reliability or computation power.**

***Index Terms*—FM0 coding, RFID, sequence detection, noncoherent/blind detection, batteryless tags, Internet-of-Things.**

I. INTRODUCTION

Radio frequency identification (RFID) technology has gained increased popularity over the past decade. As a result, there is growing need for better detection algorithms, performance and robustness. The contemporary industrial RFID protocol has a built-in *preamble* sequence that the tags use as a header, every time they backscatter [1]. Prior art has exploited this 6-bit preamble for channel estimation and subsequently for coherent detection at the reader [2]. The immediate question arising is how accurate such channel estimation is, based on the small number of bits in the preamble, and if there is anything better that can be done.

It turns out, that using an intelligent noncoherent sequence detection algorithm, exploiting the tag-transmitted message (and not the limited preamble), as well as properties of the RFID tag modulated signal, one can achieve the same results, if not slightly better, than its coherent counterpart (the latter with estimated channel). The above statement is backed by simulation, as well as experimental results, using commercial RFID tag interrogation.

Section II offers the system model, in terms of signal, line (tag) coding and network setup, section III offers coherent detection, section IV summarizes noncoherent detection, section V compares the two methods with both simulation and experimental results, and finally work is concluded in section VI.

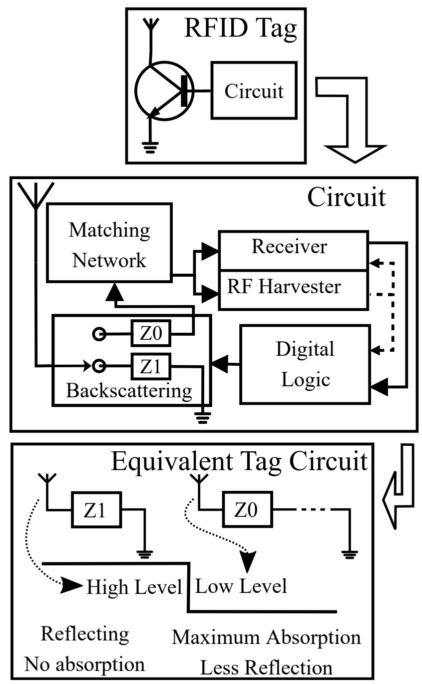

Fig. 1. Top figure: the RFID tag. Middle figure: RFID tag's circuitry. Bottom figure: RFID tag switching between 2 loads and corresponding (on-off keying) backscattered signal.

II. SYSTEM MODEL

A. Signal Model

The complex baseband equivalent of the received signal at the RFID reader is given by [2]:

$$y(t) = [m_{\rm dc} + m_{\rm mod}\ x(t)]e^{+j2\pi\Delta f t} + n(t), \qquad (1)$$

where $m_{\rm dc} \in \mathcal{C}$ is due to the illuminating carrier wave (CW) from the emitter chain of the reader and an unmodulated component scattered back from the tag, $m_{\rm mod} \in \mathcal{C}$ includes the channel coefficients between emitter-tag and tag-receiver, as well as reflection coefficients and reflection efficiency at the tag and (reader) transmission power; $x(t) \in \mathcal{R}$ is the binary waveform scattered from the tag, Δf is the carrier frequency offset (CFO) between transmitter and receiver chain oscillators at the reader and $n(t) \in \mathcal{C}$ is thermal Gaussian noise at the reader. An example of Eq. (1) is shown in Fig. 3, as given from our experimental software-defined reader.

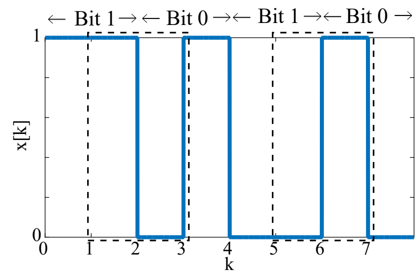

Fig. 2. FM0-coded bits $1, 0, 1, 0$. The dashed areas correspond to two orthogonal, s-shaped waveforms that can simplify notation and detection.

Typically, RFID readers utilize a single oscillator for transmission and reception and thus, there is no CFO term ($\Delta f = 0$); the resulting received samples after matched filtering, DC offset removal and synchronization are expressed as follows:

$$y[k] = hx[k] + w[k], \; k = 0, 1, \ldots, 2N + 1, \tag{2}$$

where $h \in \mathcal{C}$, $x[k] \in \{0, 1\}$ and $w[k] \sim \mathcal{CN}(0, \sigma_{\rm w}^2)$, assuming that channel coefficient h doesn't change during tag scattering of $N+1$ bits.[1] The above equation describes $2N+2$ half bits, in order to better explain below FM0 line coding, utilized in industrial RFID.

B. FM0 Line Coding as Orthogonal Signaling

The basic rule of FM0 line coding is to have a line transition at the beginning of each bit, independently of whether bit '0' or bit '1' is transmitted. In addition, a line transition occurs at the middle of bit '0', as opposed to bit '1', where line is kept constant during transmission. Under such coding, each RFID tag terminates its antenna between loads Z_0 and Z_1 with a 50% duty cycle, as shown in Fig. 1. As a result, the batteryless (passive) tag is powered by the illuminating signal from the reader, regardless the tag-backscattered bit sequence. In addition, line coding and induced memory protects from erroneous interpretation of noise as data (*"ghost" detection*).

Thus, there are four possible symbols (two for each bit). Observing each bit by an additional half bit period before and after, results into two possible, s-shaped orthogonal signals of duration T (where T is the bit duration), depicted in Fig. 2 (with dashed lined). Based on Eq. (2), a sequence of N FM0-coded symbols can be expressed as follows:

$$\mathbf{y}_i = \begin{bmatrix} y[2i+1] \\ y[2i+2] \end{bmatrix} = h\mathbf{x}_i + \mathbf{w}_i, \; i = 0, 1, \ldots, N-1, \tag{3}$$

where $\mathbf{x}_i \in \left\{ \mathbf{e}_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \mathbf{e}_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\}$ and $\mathbf{w}_i \sim \mathcal{CN}(0, \sigma_{\rm w}^2 \mathbf{I}_2)$.

C. Network Model/Brief Gen2 [1] Description

The Gen2 reader communicates with many RFID tags using a Framed Slotted Aloha (FSA) protocol. Each transaction starts with the reader transmitting a Query command that sets tag parameters, such as data rate, line coding (FM0 or Miller 2/4/8), number of slots for the FSA frame, additional pilot tone preceding the preamble etc. The tag receives the query command and responds back with a 16-bit random number (RN16), at a randomly-selected slot. Then the reader must reply with an acknowledge (ACK) message using the received RN16. The tag sends its ID data (EPC) only if the received ACK matches the original RN16 it sent (Fig. 3). Experimental results in this work utilized data rate at 40KHz, FM0 line coding, one slot for the FSA and no additional pilot tone. The handshake between RFID tag and reader is shown at Fig. 3, which depicts the norm of the received samples in Eq. (1) from the experimental, software-defined radio (SDR)-based reader of this work.

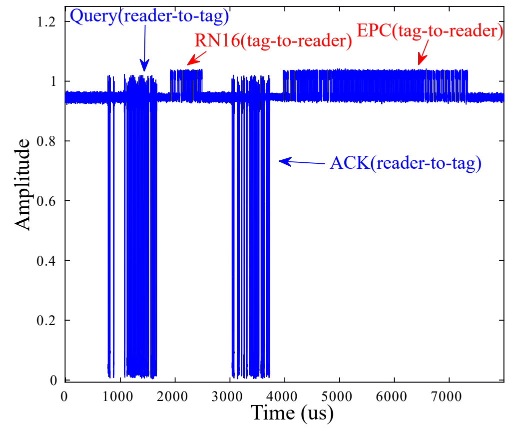

Fig. 3. The absolute value of the captured signal, from a successful communication between the Reader and the tag, plotted versus Time.

III. Coherent Detection in Gen2/FM0

A. Channel Estimation from Existing Gen2 Preamble

Each time a tag backscatters, it precedes its message with a known sequence, the Preamble. Being known, the preamble can be used to estimate the channel h of (2), using the least squares method. Thus:

$$\hat{h} = \frac{\sum_{k=0}^{N_{\rm p}-1} y[k] x_{\rm p}[k]}{\|x_{\rm p}\|^2}, \tag{4}$$

where according to the Gen2/FM0 specifications $N_p = 12$, $x_{\rm p} = [1\ 1\ 0\ 1\ 0\ 0\ 1\ 0\ 0\ 0\ 1\ 1]^T$ and $\| \cdot \|$ denotes the Euclidean norm. Note that only the six '1's of the preamble half-bits are actually used in the estimation.[2]

B. Maximum Likelihood Coherent Detection

The maximum likelihood (ML), symbol-by-symbol detection rule for (3) is given by [2]:

$$f(\mathbf{y}_i | \hat{h}, \mathbf{e}_0) \underset{d(i)=0}{\overset{d(i)=1}{\lessgtr}} f(\mathbf{y}_i | \hat{h}, \mathbf{e}_1)$$

[1] The tag appends a dummy bit '1' to the message of N data bits it backscatters.

[2] It is also noted that the preamble half-bits violate FM0 line coding, due to the repetition of 3 zero half-bits.

$$\|\mathbf{y}_i - \hat{h}\mathbf{e}_0\|^2 \underset{d(i)=1}{\overset{d(i)=0}{\lessgtr}} \|\mathbf{y}_i - \hat{h}\mathbf{e}_1\|^2$$
$$\Re\left(\hat{h}^* y[2i+2]\right) \underset{d(i)=1}{\overset{d(i)=0}{\lessgtr}} \Re\left(\hat{h}^* y[2i+1]\right)$$
$$\Re\left(\hat{h}^*\left(y[2i+2]-y[2i+1]\right)\right) \underset{d(i)=1}{\overset{d(i)=0}{\lessgtr}} 0, \quad (5)$$

where $\Re(z)$ is the real part of $z \in \mathcal{C}$ and $f(\cdot|\cdot,\cdot)$ is the pdf of $\mathbf{y}_i$ given the estimated channel $\hat{h}$ and the transmitted symbol $\mathbf{e}_j, j \in \{0,1\}$.

Taking into account the memory induced by FM0, the ML sequence detection rule is simply given by observing $2T$-signal duration for each bit of duration T [3]:

$$b(i) = d(i-1) \oplus d(i),\ i = 0, 1, \ldots, N-1, \quad (6)$$

where $d(-1) = 1$ and $\oplus$ is the 'exclusive-or' operator. Interestingly, the observation and processing of $2T$-signal duration suffices for optimal ML sequence detection and thus, there is no need to run the Viterbi algorithm, as pointed out in [3].

IV. Noncoherent Detection in Gen2/FM0

As already discussed, FM0-line coded signal can be expressed as an orthogonally-modulated signal, and more specifically, as a binary frequency shift keying (BFSK) signal, shown in Eq. (3). When channel coefficient h in Eq. (3) is constant but unknown at the receiver, noncoherent, generalized likelihood ratio test (GLRT) sequence detection of N symbols results to the following problem [4]:

$$\max_{\mathbf{x}\in\{1,2\}^N} |\mathbf{y}_0[x_0] + \mathbf{y}_1[x_1] + \ldots + \mathbf{y}_{N-1}[x_{N-1}]|, \quad (7)$$

where $\mathbf{y}_i,\ i \in \{0, \ldots, N-1\}$ is the received 2×1 vector of Eq. (3), $x_i \in \{1,2\}$ points to the first or second element of vector $\mathbf{y}_i$ and corresponds to BFSK symbol $\mathbf{e}_0$ or $\mathbf{e}_1$, respectively; $\mathbf{x}$ is the sequence $x_0\ x_1 \ldots x_{N-1}$ to be detected. It is also noted that in case of Rayleigh fading, GLRT sequence detection is equivalent to ML noncoherent detection. For a sequence of N BFSK symbols, exhaustive search among 2^N possible sequences in Eq. (7) is prohibitive in real-time RFID readers, even for moderately small N. A radically different approach is needed [4], summarized below.

A. GLRT-Optimal Noncoherent Sequence Detection in Time $\mathcal{O}(N \log N)$

For every $z \in \mathcal{C}$, there exists a $\phi \in [0, 2\pi)$ that adheres to the following [5]:

$$|z| = \max_{\phi\in[0,2\pi)} \Re\{e^{-j\phi} z\}. \quad (8)$$

Using Eq. (8), Eq. (7) can be rewritten as follows:

$$\max_{\mathbf{x}\in\{1,2\}^N} \max_{\phi\in[0,2\pi)} \Re\left\{e^{-j\phi}\left(\mathbf{y}_0[x_0] + \ldots + \mathbf{y}_{N-1}[x_{N-1}]\right)\right\} =$$
$$\max_{\phi\in[0,2\pi)} \max_{\mathbf{x}\in\{1,2\}^N} \left\{\Re\{e^{-j\phi}\mathbf{y}_0[x_0]\} + \ldots \right.$$
$$\left. \ldots + \Re\{e^{-j\phi}\mathbf{y}_{N-1}[x_{N-1}]\}\right\}, \quad (9)$$

and thus, the inner maximization can be calculated independently for each $x_n,\ n = 0, 1, \ldots, N-1$. Consequently,

$$\hat{x}_n = \underset{x_n\in\{1,2\}}{\operatorname{argmax}} \Re\left\{e^{-j\phi}\mathbf{y}_n[x_n]\right\}$$
$$\Leftrightarrow\ \Re\left\{e^{-j\phi}\mathbf{y}_n[1]\right\} \underset{\hat{x}_n=1}{\overset{\hat{x}_n=2}{\lessgtr}} \Re\left\{e^{-j\phi}\mathbf{y}_n[2]\right\}$$
$$\Leftrightarrow\ \cos\left(\phi - \underline{/\mathbf{y}_n[1] - \mathbf{y}_n[2]}\right) \underset{\hat{x}_n=1}{\overset{\hat{x}_n=2}{\lessgtr}} 0, \quad (10)$$

where $\hat{x}_n$ is the decision of x_n on the nth BFSK symbol and $\underline{/z} \in [0, 2\pi)$ is the angle of complex number z. Eq. (10) shows that as ϕ goes through $[0, 2\pi)$, the decision $\hat{x}_n$ changes only when:

$$\cos\left(\phi - \underline{/\mathbf{y}_n[1] - \mathbf{y}_n[2]}\right) = 0$$
$$\Leftrightarrow\ \phi = \pm\frac{\pi}{2} + \underline{/\mathbf{y}_n[1] - \mathbf{y}_n[2]} \pmod{2\pi}. \quad (11)$$

Thus, these $2N$ angles are calculated and sorted, resulting in $2N$ distinct intervals in which the decisions $\{\hat{x}_n\}$ remain constant. As a result, only $2N$ sequences in principle need to be tested in (7), i.e., those that correspond to the above intervals. The complexity of the above algorithm is dominated by the computational cost of sorting, which is $\mathcal{O}(2N \log(2N)) = \mathcal{O}(N \log N)$. Further improvements can simplify the algorithm, as discussed in [4].

The performance gap of this algorithm compared to the coherent tends to zero, as the sequence length N tends to infinity. It will be shown in Fig. 4 that $N = 16$ bit length sequence suffices, i.e., it can reach almost the same performance (within 0.05 dB).

V. Numerical Results

A. Simulation

The bit error rate (BER) versus signal-to-noise ratio (SNR) is shown in Fig. 4, using block flat fading $h \sim \mathcal{CN}(0,1)$ and mean SNR defined as $\text{SNR} = 1/(2\sigma_{\text{w}}^2)$. The following detection methods are compared: coherent detection with perfect channel state information (CSI) to assess optimal BER, coherent detection with estimated CSI using only 3 non-zero bits of the Gen2/FM0 protocol preamble sequence (no pilot sequence), noncoherent detection on 128 bit sequences (EPC), noncoherent detection on 16 bit sequences (RN16) and finally, symbol-by-symbol noncoherent detection (1 bit).

Surprisingly, coherent detection with estimated CSI (using only the 3 non-zero preamble bits) performs worse than both noncoherent 128- and 16-bit sequence detection. The two latter methods get close to the BER of coherent with perfect CSI, i.e., noncoherent 16-bit sequence detection achieves the BER of coherent with perfect CSI, within 0.05dB. Finally, 1-bit noncoherent performs worse than all the other methods.

B. Experimental Testbed

The experimental setup is shown in Fig. 5. A USRP N200 alongside with the RFX900 daughterboard, two circularly-polarized antennas, a passive Gen2 RFID tag and a laptop were used. The software stack of [2] was augmented with the

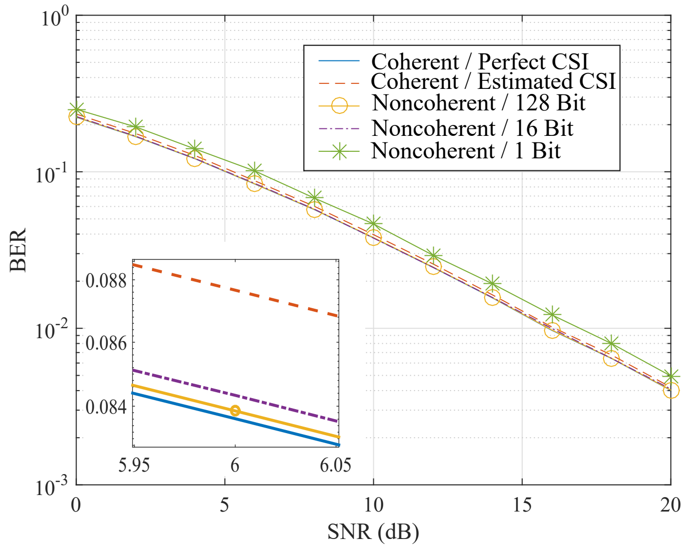

Fig. 4. BER vs SNR. Single-bit noncoherent method has been omitted in the zoomed-in legend.

noncoherent log-linear sequence detection method, described above. Due to the small transmission power of the reader, tag-to-reader distances were limited to up to 1 meter, otherwise the batteryless tag was not harvesting enough RF power from the illuminating reader.

A successful transaction is defined as follows: the reader detects correctly the *preamble bits* of the authentication message from the tag (RN16) and also detects correctly the *preamble bits* of the data message part from the tag (EPC). It is emphasized that the RN16 bit sequence transmitted from the Gen2 tag is always unknown at the reader and must be correctly detected and acknowledged, before tag starts transmitting its EPC; 5000 transactions were conducted, for each detection method of the 16-bit RN16 sequence, i.e., coherent and noncoherent, as a function of tag-reader distance. Results are depicted in Fig. 6-left vertical axis, showing that performance of noncoherent, as well as coherent detection of the RN16 bit sequence coincide.

The BER was calculated by summing the total number of erroneous bits in the EPC tag message, which is known at the reader, in each *successful* transaction and dividing by the total number of data bits received from the successful transactions (Fig. 6-right vertical axis). This method ensures that BER is calculated when tag has harvested enough RF energy and reflects; again, it is shown that performance of noncoherent, as well as coherent detection of the 128-bit sequence (96 ID bits and additional CRC and control bits) coincide.

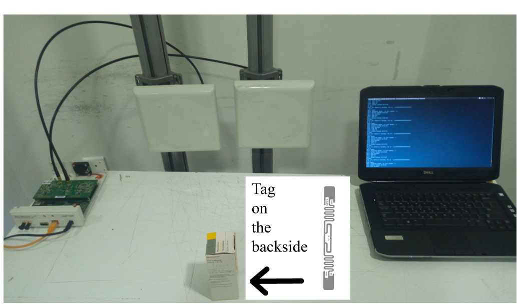

Fig. 5. The setup that was used to capture samples from communication between the reader and the RFID tag.

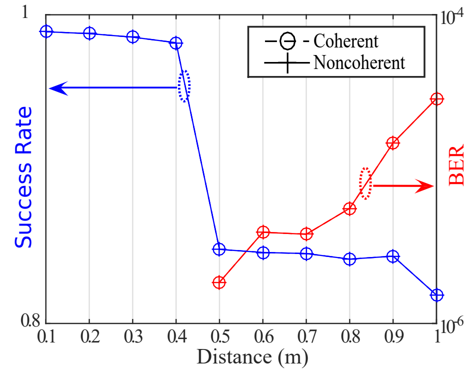

Fig. 6. Results extracted after processing the captured samples.

Such perhaps surprising result stems from the fact that noncoherent detection is performed in an intelligent way, as well as the fact that passive tags operate at short ranges, due to limited RF harvesting sensitivity, currently several orders of magnitude worse than readers' communication sensitivity. The latter offers relatively high received SNR at the reader.

VI. Conclusion

Apart from preamble bits, Gen2 also provisions optional tag *pilot* bits, enabled from reader query commands. Future versions of Gen2 could exploit results of this work, perhaps omitting pilot/preamble bits; the latter are typically used for synchronization and could be replaced by energy-based techniques. In that way, reading speed of RFID tags at the reader could be amplified, adding commercial value, without sacrificing bandwidth, reliability or computation power. This work puts forth, for the first time in the literature, experimental demonstration of intelligent, GLRT-optimal sequence detection in industrial setups.

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