Increasing Performance of Ambient Backscatter-based Communication by Using Method of Moments and C/A codes

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***Abstract*—A communication system that enables two battery-free devices to communicate using ambient RF as the only source of power has been proposed [1]. In this system, the transmitter modulate information and send it to the receiver by changing the amount of reflection. In the proposed method in [1], authors neglected the effect of noise and used average power at the receiver to extract the signal. In this report we intend to use some novel methods to decrease the bit error rate (BER) and hence increase the data rate of the ambient backscatter system. First, we propose method of moments to estimate and extract the transmitted data from the sender at the receiver with the existence of noise. We consider two cases: 1) no delay between the original TV in the line of sight of the receiver and the backscattered signal from the transmitter, and 2) there is a fractional delay between the original TV signal and its backscattered signal. For both of these cases we formulate the detection criteria. We also discuss how we can estimate the variance of TV signal and noise by using method of moments. Then, we introduce using C/A codes to repeat our data at the transmitter based on a predefined pattern which is known at the receiver. Finally, we propose a hybrid method based on the method of moments and pre-coding by using C/A codes to achieve higher performance. We find that using method of moments and specially using it with C/A codes (or coding in general) results in performance enhancement from a BER point of view. We examine our method through numerous simulations and validate our arguments.**

***Index Terms*—Ambient backscatter; Autocorrelation function; C/A codes; Method of moment.**

I. Introduction

The idea of communication using ambient RF has been proposed in [1]. The proposed method leverages existing TV and cellular transmissions to eliminate the need for wires and batteries, thus enabling ubiquitous communication where devices can communicate among themselves at unprecedented scales and in locations that were previously inaccessible. Communication through ambient backscatter has some advantages: 1) it avoids the expensive process of generating radio waves, 2) it is more power-efficient than traditional radio communication, and 3) it leverages the ambient RF signals that are already around us, it doesn't require a dedicated power infrastructure as in traditional backscatter communication. However, one challenging problem in ambient backscatter is that ambient backscatter uses uncontrollable RF signals that already have information encoded in them. Hence it requires a different mechanism to extract the backscattered information. The authors in [1] used a simple averaging criteria at the receiver to extract the transmitted information from the transmitter. They also assumed a noiseless scenario which may not be an accurate assumption in practice.

In this project we intend to use some methods to mitigate this drawback. We assume that noise exists and it can be powerful compared with the TV signal (the term ″noise″ here may include some multipath signals which are seen at the receiver but not at the transmitter). Firstly, we consider our problem as a statistical problem and propose the method of moments to extract the information (as an unknown parameter in the distribution of received signal) at the receiver. We will find that by using method of moments we can also estimate some unknown parameters like variance of noise, variance of signal as well. Since we see our problem from a statistical piont of view and we need variance of TV signal and noise signal, we propose a criteria to estimate variance of noise and the signal. By using method of moments we find that we can increase the reliability of our system by decreasing bit error rate (BER). Since there can be a fractional delay between the non-backscattered (original) TV signal and backscattered signal, we formulate the detection criteria in this case. We will estimate the sample autocorrelation function to use it in the detection. Second, we will discuss a pre-coding method to encode our information and repeat it in a more consistent way. We use C/A codes as a set of golden codes to encode our information at the transmitter. C/A codes are codes with 1023-length codes which can help us to encode our information in a more secure way against noise and interference. Furthermore, these codes can help us to increase the data rate as well. For example, by using 32 C/A codes we will be able to encode 5 bits information. Then, we can reach to the lower BER and the higher data rate at the same time. Finally, we combine method of moments and pre-coding with C/A code to achieve better performance in our system. We validate our arguments through a number of simulations.

The rest of this report is organized as follows. In section II, we will review the concept of ambient backscatter and the previously proposed solution to extract information at the receiver. In section III, we review the concept of method of

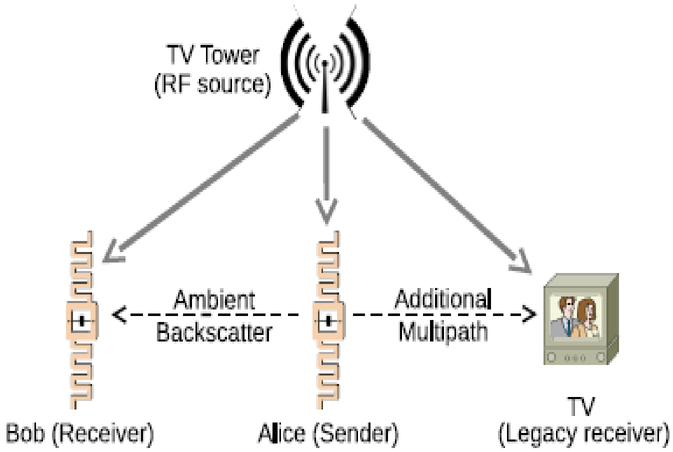

Fig. 1. Ambient backscatter [1]

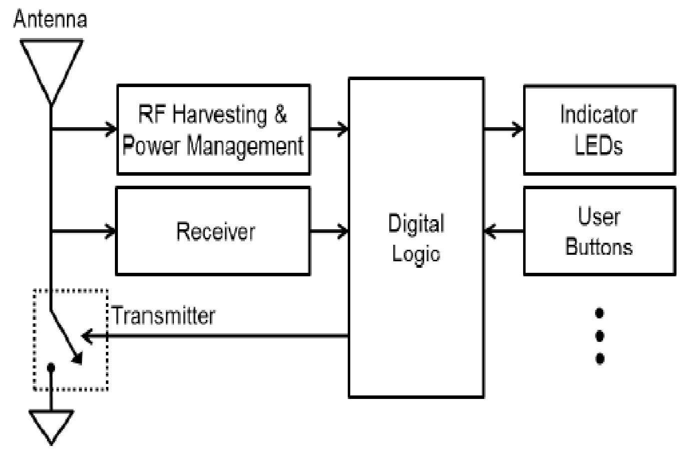

Fig. 2. Block diagram of an ambient backscatter [1]

moments to estimate unknown parameters and C/A codes to encode information. In section IV, we will propose method of moments to extract information at the receiver in two different scenarios, delayed and non-delayed scenarios. We also propose methods to estimate the variance of noise, variance of TV signal, and sample autocorrelation function. Hybrid method, including method of moments and C/A codes, is proposed in this section as well. In section V, we will have a number of simulations to validate our argument. In section VI, we conclude our report.

II. Ambient backscatter

Fig.1 illustrates communications between two battery-free devices in ambient backscatter system [1]. One such a device, Alice, can backscatter ambient signals that can be decoded by another ambient backscatter device, Bob.

Fig.2 illustrates the block diagram of an ambient backscattering device. The transmitter, receiver, and the harvester are all connected to a single antenna and use the same RF signals. The transmitter and receiver communicate by backscattering the ambient signals. The harvester collects energy from the ambient signals and uses it to provide the small amount of power required for communication and to operate the sensors and the digital logic unit.

To describe how an ambient backscatter works we consider two separate sections: 1) ambient backscattering transmitter, and 2) ambient backscattering receiver.

A. Ambient backscattering transmitter

The aim of ambient backscattering is to use ambient signals, embed data in them, and send them to the receiver. Backscattering at the transmitter is achieved by changing the impedance of an antenna in the presence of an incident signal. Indeed, when a wave reaches to a boundary between two media, some part of it will be reflected because of impedance mismatch between two media. The amount of reflection is dependent on the difference between the impedance of two media. Then, an ambient backscatter modulates the electrical impedance at the port of antenna and it modulates the amount of incident RF energy that is scattered. In this way, an ambient backscatter can embed bits 0 or 1 by changing the amount of reflection and transmits information to the receiver. An ambient backscattering includes a transistor-based switch to modulate the impedance of antenna. For bit 0 the transistor is OFF, the impedances are matched and a little of the incident signal is reflected. For bit 1 the transistor in ON and the boundary is shorted and the majority of the incident signal will be reflected. Therefore, by using the technique of impedance modulation based on bits 0 or 1, a backscattering transmitter is able to send information.

B. Ambient backscattering Receiver

The aim of an ambient backscattering receiver is to extract information (bits 0 and 1) from the received signal (including the original ambient TV signal and its backscattered version). In this section we describe how an ambient backscatter can extract the information. Fig.3a and fig.3b illustrate the original TV signal (before backscattering) and the received signal (original TV plus backscatter signal) at the receiver. As it can be seen, the backscattered signal changes the ambient TV signal.

To be able to extract the received signal it is assumed that the transmitter backscatters information at a lower rate than the ambient signal, then it is possible to separate the two signals (original TV signal and backscattered signal) by leveraging the difference in communication rates. In [1], an averaging criteria has been proposed to separate these two signals at the receiver and extract information. Suppose that our receiver is a digital receiver and it can sample the received signal at the Nyquist-information rate of the TV signal. The received samples including the original TV signal and the backscattered signal is given by

$$y[n] = x[n] + \alpha B[n]x[n] + w[n] \tag{1}$$

where $x[n]$ are the samples corresponding to the TV signals, $w[n]$ is the noise, α is attenuation of the backscattered signal relative to the TV signal, and $B[n]$ are bits transmitted by the backscattering transmitter. Since, the receiver samples the

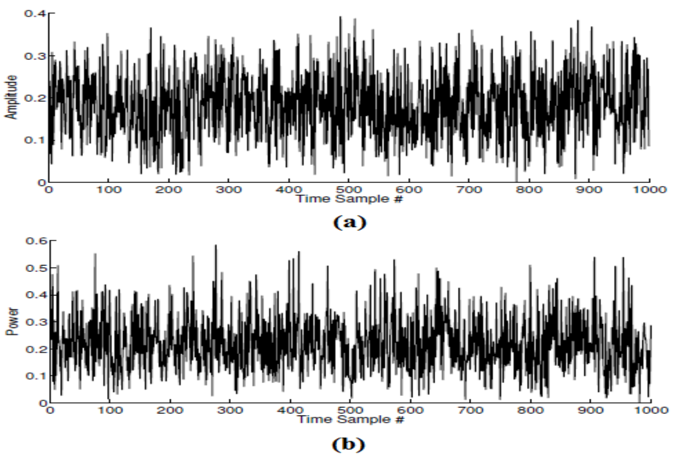

Fig. 3. (a) Original TV signal, (b) Original TV signal plus backscattered signal [1].

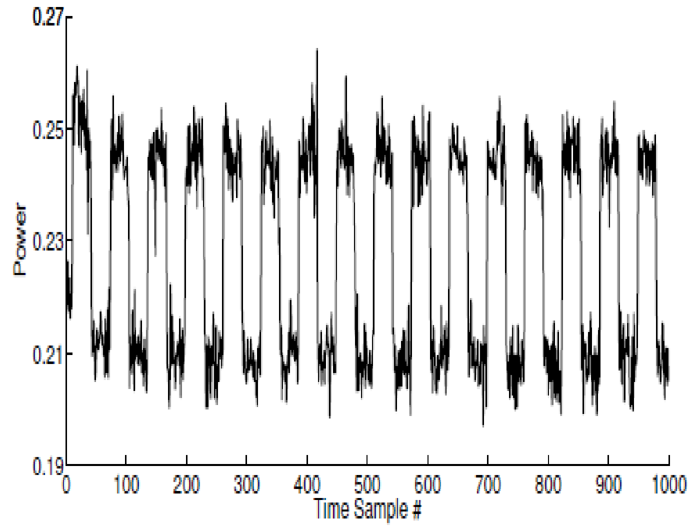

Fig. 4. Averaged power at the receiver [1].

received signal at the TV Nyquist rate, the adjacent samples are uncorrelated. If we assume that the backscatter conveys information at a fraction of the data rate, say $\frac{1}{N}$, then $B[Ni+j]$s are all equal for $j = 1$ to N.

By averaging the instantaneous power in the N receiver samples corresponding to a single backscattered bit and by knowing that $x[n]$ and $w[n]$ are uncorrelated, we have

$$\frac{1}{N}\sum_{n=1}^{N} \mid y[n] \mid^2 = \frac{1}{N}\sum_{n=1}^{N} \mid x[n] + \alpha B x[n] + w[n] \mid^2$$
$$= \frac{\mid 1+\alpha B \mid^2}{N}\sum_{n=1}^{N} \mid x[n] \mid^2 + \frac{1}{N}\sum_{n=1}^{N} \mid w[n] \mid^2 \quad (2)$$

By defining $P = \frac{1}{N}\sum_{i=1}^{N} \mid x[n] \mid^2$ as the average power in the received TV signal and ignoring the effect of the noise, the average power at the receiver is $\mid 1 + \alpha B \mid^2$ P and P for reflecting (bit 1) and non-reflecting (bit 0) states, respectively. Then the receiver can distinguish between two states and extract the transmitted information. Fig. 4 illustrates the averaged power at the destination. As it can be seen by choosing an appropriate threshold we can extract the transmitted bits.

III. Review on method of moments and C/A codes

In the previous section we had a review on the transmission and reception strategy proposed in [1]. In this section we will have a brief review of detection by using method of moments and encoding by using C/A codes.

A. Review on method of moments [2]

In statistics, the method of moments is a method of estimation of population parameters such as mean, variance, median, etc. (which need not be moments), by equating sample moments with unobservable population moments and then solving those equations for the quantities to be estimated [2].

Suppose that the problem is to estimate p unknown parameters $\theta_1, \theta_2, , \theta_p$ characterizing a distribution $f_W(\omega, \theta)$. Suppose p of the moments of the true distribution can be expressed as functions of the θs:

$$\mu_1 \equiv E\{W^1\} = g_1(\theta_1, \theta_2, , \theta_p)$$
$$\mu_2 \equiv E\{W^2\} = g_2(\theta_1, \theta_2, , \theta_p)$$
$$.$$
$$\mu_p \equiv E\{W^p\} = g_p(\theta_1, \theta_2, , \theta_p) \quad (3)$$

Let $\hat{\mu}_j = \frac{\sum_{i=1}^{n} \omega_i^j}{n}$ be the jth sample moment corresponding to the population moment μ_j. The method of moments estimator for $\theta_1, \theta_2, , \theta_p$ denoted by $\hat{\theta}_1, \hat{\theta}_2, , \hat{\theta}_p$ is defined by the solution (if there is one) to the equations:

$$\hat{\mu}_1 = g_1(\hat{\theta}_1, \hat{\theta}_2, , \hat{\theta}_p)$$
$$\hat{\mu}_2 = g_2(\hat{\theta}_1, \hat{\theta}_2, , \hat{\theta}_p)$$
$$.$$
$$\hat{\mu}_p = g_p(\hat{\theta}_1, \hat{\theta}_2, , \hat{\theta}_p) \quad (4)$$

Then method of moments provides a good solution to estimate the unknown parameters. We will use this method in section IV to estimate parameters in ambient backscatter and extract information at the receiver.

B. Review on C/A codes [3]

The main application of C/A (coarse acquisition) codes is in GPS (Global Positioning System) [3]. The C/A codes are 1,023 bit deterministic sequence called pseudorandom noise (also pseudorandom binary sequence) (PN or PRN code) which, when transmitted at 1.023 megabits per second(Mbit/s), repeats every millisecond. These sequences only match up, or strongly correlate, when they are exactly aligned. Each satellite transmits a unique PRN code, which does not correlate well with any other satellite's PRN code. In other words, the PRN codes are highly orthogonal to one another. This is a form of code division multiple access (CDMA), which allows the receiver to recognize multiple satellites on the same frequency. Then, C/A codes which are used in GPS can discriminate the different satellites. Some examples of C/A codes are

$$\begin{aligned}(C/A)_1 =&[1100 \quad \cdots \quad 0000]\\ (C/A)_2 =&[1110 \quad \cdots \quad 1000]\\ &.\\ (C/A)_{32} =&[1111 \quad \cdots \quad 0010]\end{aligned} \tag{5}$$

If we map bits 1 to 1 and bits 0 to -1 in C/A codes to obtain new codes $C_1, C_2, \cdots C_{32}$, they have the following property

$$C_i \cdot C_j = -1 + 1024\delta(i-j) \tag{6}$$

From the above equation it can be seen that these codes can be discriminated very well. There are 37 C/A codes with 1023 bits length which are used now. In section IV we will use C/A codes to have a predefined pattern (as a redundancy) to send information instead of the simple repetition which has been used in [1].

IV. Proposed method to increase the performance of ambient backscatter communication

In section II we reviewed the detection method based on the power averaging which has been proposed in [1]. In the previous section, we briefly described using the method of moments to estimate the unknown parameters and using C/A codes to repeat information (bits) in a predefined pattern. In this section we propose using method of moments to estimate information in two different scenarios, non-delayed and delayed ambient backscatter. We also describe how we can estimate variance of noise, variance of signal, and sample autocorrelation function (needed for delayed case). After that we propose a method based on encoding information by using C/A codes. Finally, we will combine the two proposed methods to enhance the performance of the system as much as possible.

A. Using method of moments to extract information at the receiver

In this subsection we will propose a strategy based on method of moments to to extract our information and to estimate some unknown parameters such as variance of noise. We discuss this method mathematically and we will see how this method can work in our system. We divide the estimation by using the method of moments to two parts: 1) no fraction delay between the TV signal and the backscattered signal, and 2) fractional delay between these two signals.

1) No fractional delay between the TV signal and the backscattered signal: In this part we considered the estimation of information without considering any delay between the TV signal and its backscattered signal from the transmitter.

Assume that the noise signal and TV signal are uncorrelated random variables with Gaussian distributions are given by

$$x[n] \sim N(0,\sigma_x^2), \;\; w[n] \sim N(0,\sigma_w^2) \tag{7}$$

Gaussian distribution for the noise signal is an acceptable assumption, about the TV signal because the number of their samples (e.g. N) in the process of information detection is large. Based on the central limit theorem we can approximate its distribution as a Gaussian distribution as defined in (7). In this section we assume that we know the variance of noise and the variance of TV signal and the only unknown parameter is our information, B. By writing the moments for the received signal y, we have

$$\begin{aligned}\hat{\mu}_1 = E\{y[n]\} = \mu_y &= \frac{1}{N}\sum\nolimits_{n=1}^{N} y[n]\\ &= E\{x[n] + \alpha B x[n] + w[n]\}\\ &= (1+\alpha B)E\{x[n]\} + E\{w[n]\}\\ &= 0\end{aligned} \tag{8}$$

Then, by having zero mean assumption for random variables $x[n]$ and $w[n]$, the first moment doesn't help the receiver to estimate any parameters. If we have a non-zero mean for random variable $x[n]$, then (8) will help us to estimate the parameter B (or $E\{x[n]\}$ if it is unknown). The second moment of the received signal is given by

$$\begin{aligned}\hat{\mu}_2 = E\{y^2[n]\} = \sigma_y^2 &= \frac{1}{N}\sum\nolimits_{n=1}^{N} y^2[n]\\ &= E\{|x[n] + \alpha B x[n] + w[n]|^2\}\\ &= (1+\alpha B)^2 E\{x^2[n]\} + E\{w^2[n]\}\\ &\quad + 2(1+\alpha B)E\{x[n]\}E\{w[n]\}\\ &= (1+\alpha B)^2\sigma_x^2 + \sigma_w^2\end{aligned} \tag{9}$$

From (9) it can be seen that there are three unknown parameters: B, σ_x^2, and σ_w^2. If we assume that the variances of the noise and the TV signal are known (or they can be estimated from (23) as it is discussed in $Appendix A$), there is only one unknown parameter B to be estimated. By this assumption, the information bit (B) is given by

$$\tilde{B} = \frac{\frac{\sqrt{\frac{\sum_{n=1}^{N} y^2[n]}{N} - \sigma_w^2}}{\sigma_x} - 1}{\alpha} \tag{10}$$

From (10) we can see that by estimation the variance of output and by knowing the variance of TV signal and noise we can estimate the transmitted information at the receiver. This method is much better than the method proposed in (2) which is an estimation without noise consideration. Fig.1 illustrates the schematic of data extraction based on the second-order moment of the received signal.

We can continue to find the higher order moments. By using Binomial theorem

$$(a+b)^k = \sum\nolimits_{l=1}^{k} \binom{k}{l} a^l b^{k-l} \tag{11}$$

The pth order moment is given by

$$\begin{aligned}\hat{\mu}_p = E\{y^p[n]\} &= \frac{1}{N}\sum\nolimits_{n=1}^{N} y^p[n]\\ &= E\{|x[n] + \alpha B x[n] + w[n]|^p\}\\ &= \sum\nolimits_{l=1}^{p} \binom{p}{l} (1+\alpha B)^l E\{x^l[n]\}E\{w^{k-l}[n]\}\end{aligned} \tag{12}$$

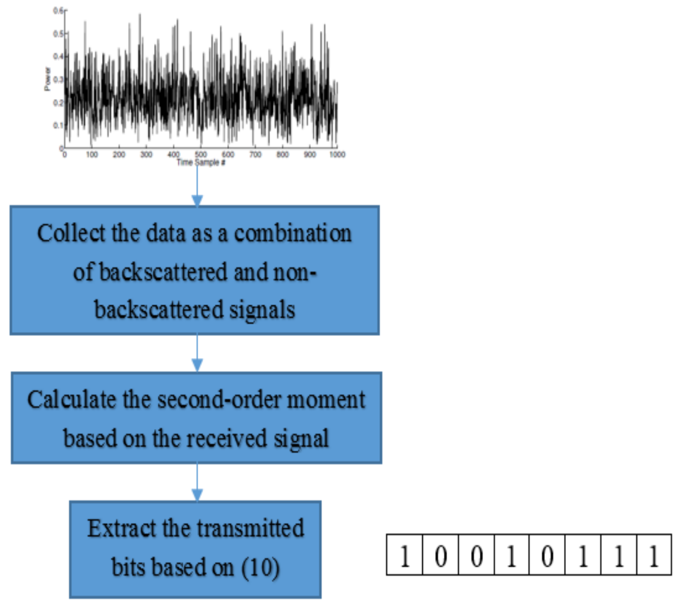

Fig. 5. Schematic of data extraction based on the second-order moment.

Then, we can have more equations to estimate the unknown parameters. By having more equations, we can use least square method to estimate the unknown parameters. Method of moments is a simple way to estimate the unknown parameters and its complexity is lower than other methods such as maximum likelihood. By the way, if a more exact method is needed to estimate the parameters, maximum likelihood is a good method. In this report we only consider method of moments because of its simple structure which is compatible with the battery-free receiver. We will assume that we know the variance of the noise and the TV signal (or they can be estimated) and hence (10) will be used to estimate bit B. Fig.5 illustrates data extraction at the receiver by using the second-order moment.

2) Fractional delay between the TV signal and the backscattered signal: We have already discussed the detection criteria in the absence of any delay between the TV signal and its backscattered signal. Now it is assumed that there is a fractional delay τ $(0 < \tau < 1)$ between the TV signal and its backscattered signal. In this case the received signal is given by

$$y[n] = x[n] + \alpha B x[n-\tau] + w[n] \tag{13}$$

By using (13), the first and the second moments are given by

$$\begin{aligned}\hat{\mu}_1 &= E\{y[n]\} = \mu_y = \frac{1}{N}\sum\nolimits_{n=1}^{N} y[n] \\ &= E\{x[n] + \alpha B x[n-\tau] + w[n]\} \\ &= E\{x[n]\} + \alpha B E\{x[n-\tau]\} + E\{w[n]\} \\ &= 0 \end{aligned} \tag{14}$$

$$\begin{aligned}\hat{\mu}_2 &= E\{y^2[n]\} = \sigma_y^2 = \frac{1}{N}\sum\nolimits_{n=1}^{N} y^2[n] \\ &= E\{|x[n] + \alpha B x[n-\tau] + w[n]|^2\} \\ &= E\{x^2[n]\} + (\alpha B)^2 E\{x^2[n-\tau]\} + E\{w^2[n]\} \\ &+ 2\alpha B E\{x[n-\tau] E\{x[n]\} + E\{x[n]\} E\{w[n]\} \\ &+ \alpha B E\{x[n-\tau]\} E\{w[n]\} \\ &= (1 + (\alpha B)^2)\sigma_x^2 + 2\alpha B R_x(\tau) + \sigma_w^2 \end{aligned} \tag{15}$$

where $R_x(\tau)$ is the autocorrelation function of signal x for the fractional delay τ. Estimation of autocorelation function is provided in $Appendix B$. It should be noted that if the delay is a factor of sampling interval, $R_x(\tau)$ is given by

$$R_x(\tau) = \sigma_x^2 \delta(\tau) \tag{16}$$

Now, if it is assumed that the variance of the TV signal and the noise are known (or can be estimated by (23) in $Appendix A$), the transmitted bit can be estimated by

$$\tilde{B} = \frac{1}{\alpha}\left(-\frac{A_2}{2} + \sqrt{\frac{A_2^2}{4} + A_1}\right) \tag{17}$$

where

$$\begin{aligned} A_1 &= \frac{\frac{1}{N}\sum_{n=1}^{N} y^2[n] - \sigma_x^2 - \sigma_w^2}{\sigma_x^2} \\ A_2 &= \frac{2R_x(\tau)}{\sigma_x^2} \end{aligned} \tag{18}$$

As it can be seen from (17) and (18), the estimation is changed when there is a delay between the TV signal and its backscattered signal.

In section V, we will simulate our proposed methods for delayed and non-delayed scenarios and compare them from a BER point of view.

B. Using C/A codes as pre-coding to enhance the throughput of the system

In the previous subsection we proposed a strategy to extract the transmitted data from the mixed noisy signal at the receiver. In this subsection we investigate the possibility of using pre-coding by using C/A codes to enhance the performance of the system.

One strategy which can help the receiver to extract the transmitted data with higher probability is to code the transmitted data with codes within a predefined codebook known at the receiver (source coding). These codes should be distinct enough that the receiver can extract the signal with highest possible probability. In this way, the receiver can combat the noise and the interference better at the receiver. As we discussed in section III in (6), C/A codes are such distinct codes and can be used to code information at the transmitter.

Using C/A codes has another advantage. Assume that we have 32 C/A codes which can be used to transmit the data in our system. 32 distinct codes can represent 32 distinct states and hence represent 5 bits. Then, we can send 5 bits by sending each of 32 codes and the data rate will be increased. It is also possible to repeat each bit in C/A codes to detect the data more exactly. To put in a nut shell, using C/A codes has two main benefits for our system: 1) it helps the system to combat

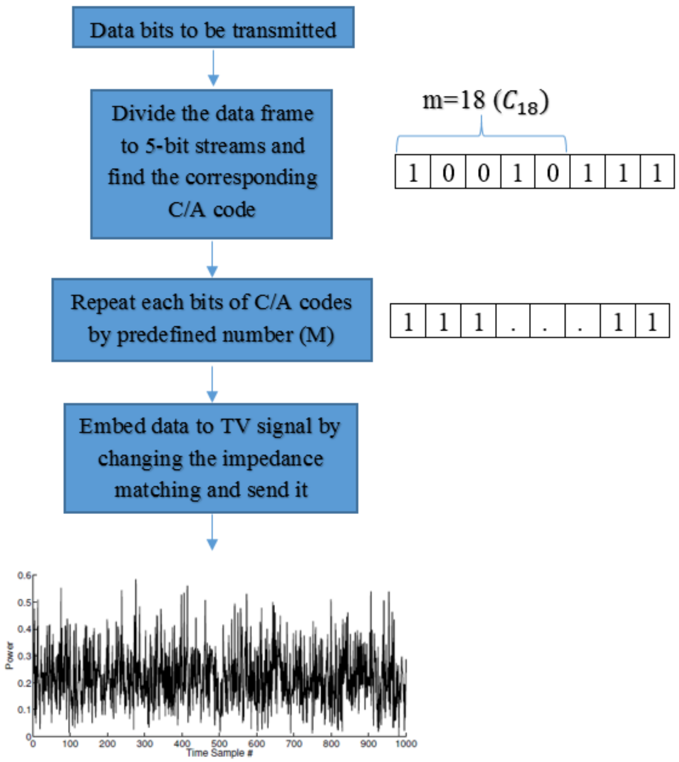

Fig. 6. Schematic of using C/A codes at the transmitter.

against the noise and the interference 2) it increases the data rate. Fig.6 illustrates the schematic of using C/A codes for pre-coding at the transmitter and extracting the data at the receiver.

C. Final proposed method as a combination of moment-based estimation and pre-coding

Until now, we have proposed the estimation based on method of moments to use the repetitions more efficiently and extract the transmitted data from the transmitter. We have also proposed pre-coding by using C/A codes to enhance the performance of the system. In this subsection, we combine these two methods (method of moments and pre-coding by using C/A codes) together to achieve the best result. For doing this work, we will repeat each bit in C/A codes in a predefined number M and send them. At the receiver we first use method of moments to extract each 1023 bits in C/A codes by using successive M-bit blocks:

$$\tilde{C}_e^m = \frac{\frac{\sqrt{\frac{\sum_{(m-1)\times M+1}^{m\times M} y^2[n]}{N} - \sigma_w^2}}{\sigma_x} - 1}{\alpha}, \quad m = 1, 2, ..., 1023 \quad (19)$$

where $\tilde{C}_e^m$ is mth bits in the estimated code at the receiver. By extracting of all C/A bits ($m = 1, 2, ..., 1023$) and estimation of C/A code, we look for a C/A code in a codebook (including 32 distinct codes) which closely matches to the estimated C/A code:

$$I_C = \arg\max_{i=1,2,...,32} \{\tilde{C}_e^m \cdot C_i\} \quad (20)$$

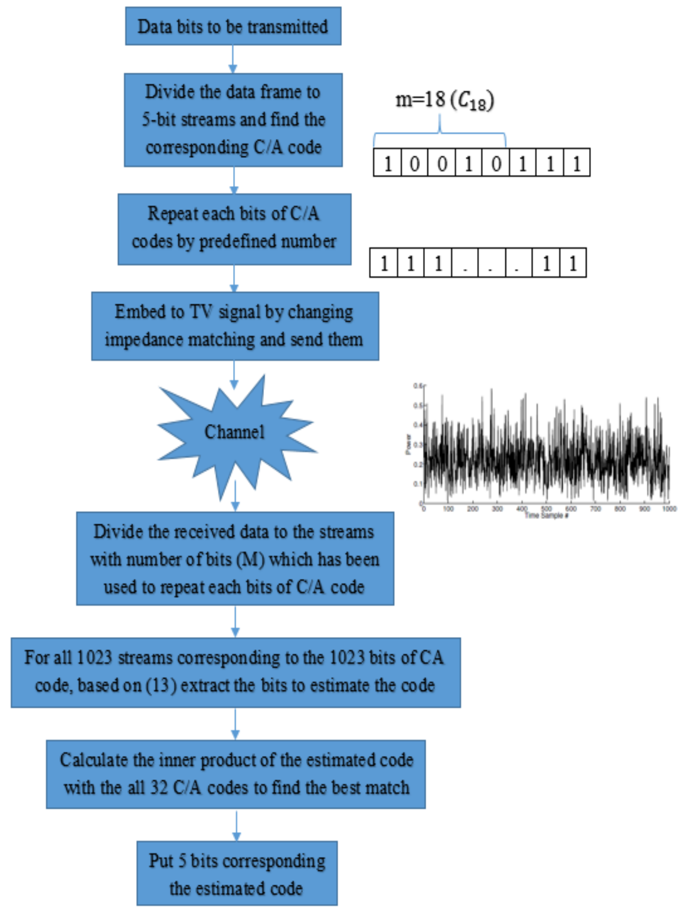

Fig. 7. Schematic of the proposed combined method.

where I_C is the index of the closest C/A code with the estimated code $\tilde{C}_e^m \cdot C_i$ and C_i is the ith C/A code.

Finally, by finding the closest match among 32 C/A codes, we are able to extract the corresponding 5 bits information which has been transmitted. Then, we will have 5 bits information (instead of 1 bit) at the receiver. Fig.7 illustrates the schematic representation of the proposed combined method. In this section we have proposed method of moments for non-delayed and delayed scenarios and also a combined method to enhance the performance of the system. In the next section we will validate our arguments in this report through a number of simulations.

V. Simulations

In this section we compare the proposed methods with the existing method [1] through a number of simulations. It should be noted that 32 C/A codes can represent 5 bits and sending a C/A code is equivalent to sending 5 bits. Then, for a correct comparison and having the same data rate to compare differents methods, we assume that the methods without pre-coding uses 200 repetitions and the method including the pre-coding which has data rate five time than others uses 1023 repetitions corresponding to its length. Fig.8 compares the proposed estimation methods in this method with the method which has been proposed in [1] when the number of repetitions for non-coded methods is $N = 200$. As it can be seen, our

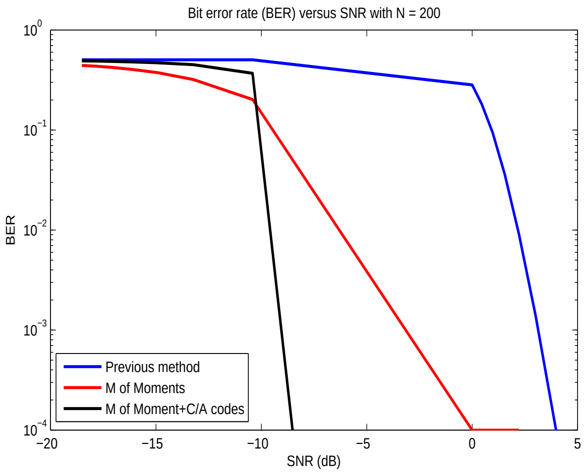

Fig. 8. Comparison among the method in [1], proposed method in this report with $N = 200$ for methods without using C/A codes.

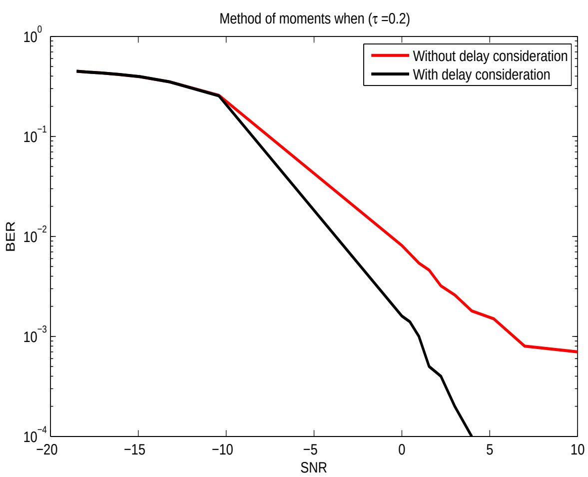

Fig. 9. Method of moments with and without delay consideration when there is a fractional delay $\tau = 0.2$ with $N = 200$.

proposed combined method has a lower BER than the method in [1] and a lower BER compared with method of moments only, especially when SNR is bigger that -10 dB. To emphasize the effects of fractional delay we did some simulations. Fig. 9 and Fig. 10 show the BER when $N = 200$ repetitions is considered for fractional delay $\tau = 0.2$ and $\tau = 0.5$. As it can be seen, if there is a fractional delay between the original TV signal and its backscattered signal from the transmitter, ignoring effect of delay results in performance degradation. The amount of the degradation is dependent of the value of delay: more delay, more degradation. Fig. 11 shows the sample autocorrelation function against the delay when our signal is a Gaussian random variable with zero mean. As can be seen from Fig. 11 and (15), by increasing the amount of fractional delay, the effect of the backscattered signal will be decreased.

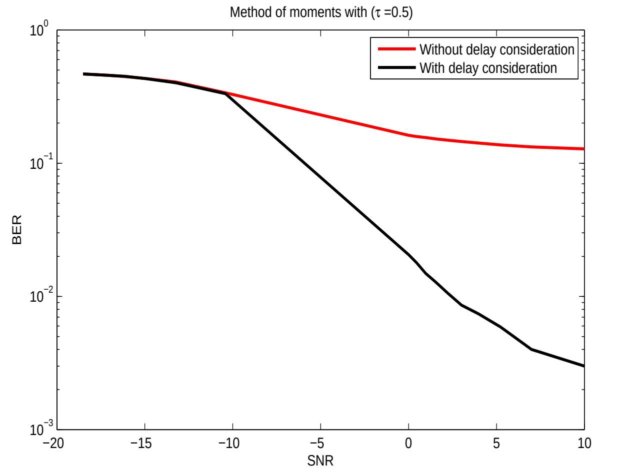

Fig. 10. Method of moments with and without delay consideration when there is a fractional delay $\tau = 0.5$ with $N = 200$.

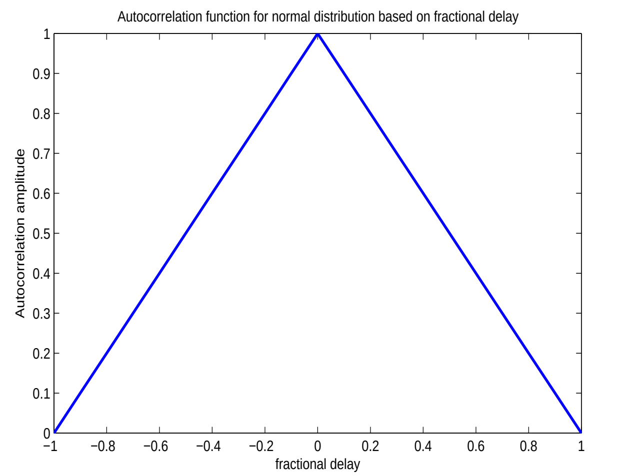

Fig. 11. Estimation of sample autocorrelation function for a zero-mean Gaussian random signal (x)

Appendix

A. Estimation of variance of TV signal and noise signal

In section IV, we assumed that we know the variance of noise but we can estimate them. To estimate these variances we need two equations with two unknown parameters. By considering (9), it can be seen that by knowing B we have only two unknown parameters σ_x^2 and σ_w^2. If the transmitter sends bit 0 ($B = 0$) through backscattering, based on (9), the variance of the received signal is given by

$$\sigma_{y0}^2 = \sigma_x^2 + \sigma_w^2 \tag{21}$$

And if the transmitter sends bit 1 ($B = 1$) through backscattering, the variance of the received signal is given by

$$\sigma_{y1}^2 = (1+\alpha)^2\sigma_x^2 + \sigma_w^2 \tag{22}$$

Now, by using (15) and (16), the variance of TV signal and noise are given by

$$\sigma_x^2 = \frac{\sigma_{y1}^2 - \sigma_{y0}^2}{\alpha^2 + 2\alpha}$$
$$\sigma_w^2 = \frac{(1+\alpha)^2\sigma_{y0}^2 - \sigma_{y1}^2}{\alpha^2 + 2\alpha} \tag{23}$$

B. Estimation of sample autocorrelation function

As it has been discussed in section IV-A-2, to estimate the transmitted information with a fractional delay between the TV signal and its backscattered signal we need the autocorrelation function ($R_x(\tau)$). We can estimate the autocorrelation function by using the delayed samples of the TV signal which is given by linear interpolation between two successive samples. By having the delayed samples, the sample autocorrelation function is given by

$$R_x(\tau) = limit_{N\to\infty}(\frac{1}{N}\sum_{n=0}^{N-1} x[n]x^*[n-\tau]) \tag{24}$$

Conclusion

In this report we considered communication by using ambient backscatter technique. First, we proposed estimation based on method of moments to extract information with more accuracy. We considered two different scenarios: 1) no delay between the original ambient TV signal and its backscattered signal from the transmitter 2) fractional delay between these two signals. After that, we consider C/A codes to encode information at the transmitter to repeat information based on a known pattern which is known at the receiver. We discuussed that using C/A codes can decrease the error and increase the data rate simultaneously. Finally, we propose a combined method including encoding information by C/A codes and extraction by using method of moments. This combination can result in the lower probability of error. Our arguments were validated through a number of simulations.

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References

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