Energy Efficient Source Coding and Modulation for Wireless Applications

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Abstract— **A simple and energy efficient source coded On/Off Keying modulation and near optimal error detection scheme for wireless applications is presented in this paper. Many low-power battery operated radio systems, especially for microsensor applications, has a need for saving power both at the system level and circuit level implementation. Our main objective in this paper is to come up with energy efficient coded modulation scheme that consumes comparatively less power both at system and circuit level. A simple On/Off keying (OOK) digital modulation scheme is used for this purpose. The basic idea of Minimum Energy coding (ME-coding) for source with known statistics (probabilities of occurrence of symbols) is obtained from [3]. In ME-coding scheme, source bits are mapped to constant length codes (ME-Codes) which has less number of high-bits in it. Since the OOK transmitter consumes energy only when transmitting a high-bit, mapping to ME-Codes reduces the total energy consumed in RF transmitter. In this paper, we have come up with ME-Coding scheme for sources with unknown statistics and we further propose a new method of code-by-code detection that can detect and correct certain errors in the codeword received. The inferior performance of OOK when compared to other simple modulation schemes is overcome by ME-Coding. A total of about 6 dB improvement in signal-to-noise ratio (SNR) per bit is observed when a 3-bit message symbol is mapped to a 7-bit ME-Code. It also performs 3 dB better than a Hamming(7,4)-coded BPSK.**

I. Introduction

Current advancement in the semiconductor industry has made it possible to have wireless microsensor applications [1][2], especially related to the civil and military operations. These sensors are mainly used for sensing, data gathering or surveillance use. They involve very low data rate of the order of few kilo bits per second (Kbps) and of transmission range of the order of few meters, unlike other wireless applications. Deploying the sensors and frequent replacement of the battery is a major issue. For some specific bio-sensor applications, over heating due to excess of power consumption leads to the damage of tissues [1]. Thus the wireless communication system for such sensitive applications have to be designed with a different perspective altogether. It demands energy efficient design of the radio systems in order to minimize the battery power consumption of the device. This energy efficiency must be brought about at every stage of the design. Power efficiency at system level must be brought about by keeping in mind the circuit complexities and the circuit power consumption. Every design comes with a trade-off, hence, we have to compromise either with power, bandwidth or error. Sensor applications with very low data rates of the order of few KBPS operating in the ISM Band (unlicensed) can afford to compromise on bandwidth requirements of the system but definitely not on the power consumption. This is the main reason for us to think in terms of developing a most energy efficient wireless communication system at the expense of bandwidth that performs considerably good with least circuit complexities.

Many new coding and modulation schemes like Turbo codes can be employed to bring about power efficiency at system level. The system can be made to operate with less SNR for a given error performance, but these are complex codes and circuit power consumption of the algorithms are more.

There has been many recent works in the field of wireless microsensors to bring about energy efficiency at both system level and circuit level. Wang et al. [5] have discussed the issues of many low power wireless microsensor applications. They have proposed energy efficient modulations and MAC protocols for asymmetric RF microsensor systems. Comparison of various modulation techniques with respect to transmit power and bandwidth efficiency is discussed. Methods to over come the transmitter complexities and also the MAC protocols are described for microsensor applications. They compare the transmit power of M-PSK, M-QAM and M-FSK and their bandwidth efficiencies for different values of M in a fading channel. It is found that as M (no. of symbols) increases, M-PSK/M-QAM sacrifices transmit power to achieve higher bandwidth efficiency and M-FSK on the other hand sacrifices bandwidth efficiency to achieve less transmit power. Thus, FSK can be used for power constrained applications. However, it is noted that M-FSK consumes less transmit power compared to M-PSK/M-QAM only for $M>8$. M-FSK is less energy efficient for $M<8$ as it requires 6 dB more RF power to achieve the same error performance [5]. For applications involving RF wireless microsensors where either the bandwidth required is

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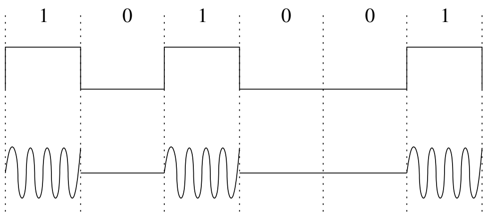

Fig. 1. **Typical OOK Modulation Scheme**

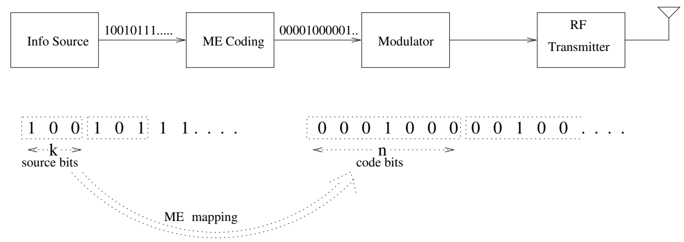

Fig. 2. **Block Diagram of ME Mapping Scheme**

low or when there are limited number of users, B-PSK which consumes less power looks like a reasonable choice. Simple digital modulation technique like OOK is totally ignored due to its bad error-performance. Typically uncoded OOK requires double the power (3 dB more SNR) to perform as much as BPSK/BPAM.

Erin and Asada [4], have discussed many approaches towards optimizing the energy consumption problem and have proposed efficient source coding scheme for information transmission in wireless environment. We propose to use the basic idea of minimum energy source coding scheme proposed by them [3].

In the course of this paper we discuss the basic idea of Minimum Energy Coding in section II. Followed by our approach towards minimum energy coding in section III. Section IV describes our approach in improving the error-performance of ME-coding. A brief overview of the sensor application is mentioned in sectionV. SectionVI concludes on our efforts in coming up with energy efficient source coding scheme and modulation.

II. Minimum Energy Coding (ME-coding)

For low data-rate wireless applications, simplest form of digital modulation technique like On/Off keying (OOK) can also be considered. In OOK, the base band signal modulates a carrier wave at a higher frequency f_c and transmits it as RF waves. That is, a carrier signal is transmitted when a bit-1 is to be sent and no signal is transmitted when a bit-0 is to be sent. Figure 1 shows OOK transmitted signals for a sequence of bits. Hence transmitter expends energy only when transmitting a signal for bit-1. Thus, for a system that uses OOK modulation technique, the obvious way to reduce the energy consumed would be to reduce the number of bit-1's transmitted compared to the bit-0's. Since we have no control over the information source, the only way to reduce the high bits (bit-1s) would be to map a set of information bit sequence to a constant length codeword (ME-Code) which has less number of bit-1's in it. This is originally based on the idea proposed by Erin and Asada [3]. They have formulated the power optimization problem for wireless communication applications with message source of known statistics. They bring about the reduction in energy consumption in two steps. Firstly, use a set of codes that have less number of high bits in it. Secondly, assign these set of codes to the messages in such a way that, codes with lesser number of ones are assigned to messages of higher probabilities. They have also taken one step towards improving the performance of these codes by simple concatenation process. Their approach of ME-Coding cannot be applied to sources with unknown statistics. We keep the basic idea of ME-Coding (source-bits mapped to code-bits) for source with unknown statistics (unknown probabilities of occurrence of symbols) and use a very simple near optimal detection process to improve the performance of ME-coding, thus proposing a new approach towards ME-coding.

III. Our Approach Towards ME-coding

The basic transmitter-side block diagram is as shown in Figure 2. Information source produces information bits 1's and 0's. The info-bits are fed to the source encoding block or the ME-Coding block. The ME encoder gives out a sequence of bits that has a reduced number of bit-1s in it. These source encoded bits are now OOK modulated in the modulator block and then transmitted by a RF transmitter bit-by-bit.

A. *Codes considered*

Consider k binary bits (1's and 0's, with $k > 1$) from the source. ME-encoder groups these k bits together and maps it to a ME-Code word of length n, where $n > k$. Thus, there can be a total of $M = 2^k$ possible incoming symbols mapped on to M codewords that are predetermined. As already mentioned these codewords have less number of high bits compared to the original information sequence but with more number of bits in it. Our main idea is to apply the ME-coding to sources with unknown statistics. That is, say, a source symbol 1011000 or 1101011 can be mapped only to a code with not more than two ones or four ones in it respectively. Otherwise, the whole idea of reducing the number of ones in the transmitted bit sequence is lost. Figure 2 also shows the mapping of k source bits on to a codeword of n bits.

We consider the extreme form of coding where we use a maximum of one high bit in the entire codeword sequence. The reason being, firstly, we satisfy the criteria of having less number of ones in the transmitted codeword bit sequence compared to source bit sequence. Secondly, this codeword can safely be assigned to any of the M source symbols occurring at any probability. Finally, this results in the maximum reduction of total number of ones in the transmitted codeword bit sequence.

Table I shows the source symbol and their corresponding mapped codewords for M = 4 and 8. For mapping of $M = 2^k$

TABLE I

Minimum-Energy Code table for $k = 2$ and 3

$Sourcebits$ $ME(3,2)$	$Codeword$ $ME(3,2)$	$Sourcebits$ $ME(7,3)$	$Codeword$ $ME(7,3)$
00	000	000	0000000
01	001	001	0000001
10	010	010	0000010
10	100	011	0000100
		100	0001000
		101	0010000
		110	0100000
		111	1000000

source symbols, we need a codeword of length $n = M-1$. This is because the all-zero source symbol is mapped to an all-zero codeword sequence and the remaining $M - 1$ source symbols can be mapped to codeword with $M - 1$ bits in it, with each codeword having one of its bit high. In general, for grouping k bits we need a code length of $2^k - 1$. The code rate for this form of source coding is $k/n = k/(2^k - 1)$. We use the standard form of representation of the codes by ME(n, k), where n represents the codeword length assigned to message symbol of k bits. The minimum euclidean distance between any two ME-code is $d_{min} = 1$. Thus, these codes have no capability of correction or detection of errors. However, the basic characteristic of the code (maximum of one high bit in the codeword) makes it possible to detect errors when the receiving codeword has more than one high bit in it. ie. if a bit-by-bit hard decision with 0.5 threshold is made on the demodulated signal, and if any codeword is detected with more than one high bit, then it can be considered as code in error and hence, all the final k message bits corresponding to that codeword at the receiver is considered to be in error. Figure 3 shows an example of the process of error detection for a ME(3,2) code.

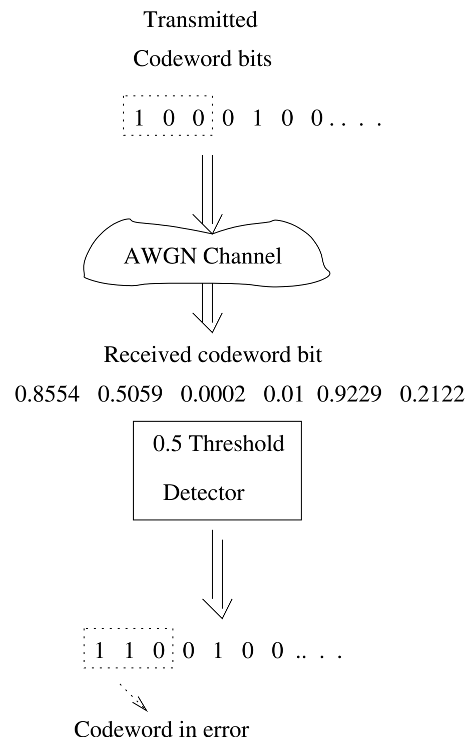

Fig. 3. **Flow of bit-by-bit detection process**

B. *Performance of ME-code with bit-by-bit hard decision decoding*

For simulation purpose, we consider a source generating binary bit sequence (1's and 0's) and additive white gaussian noise (AWGN) channel. Matlab 6 was used for simulation purpose. When ME(3,2) code from the table I is applied to the source symbols, and a bit-by-bit hard decision with 0.5 threshold is made without any error correction at the receiver, there is an improvement of 2 dB in the SNR per bit for a probability of error of 10^{-4}. An improvement of 5 dB and 7 dB is seen with a ME(7,3) and ME(15,4) codes respectively. Figure 4 depicts the same. The code rates of these code sets are $2/3$, $3/7$ and $4/15$ respectively. With the increase in value of k, there is a remarkable increase in the bandwidth requirements of the system. The performance of ME(7,3)-coded OOK and ME(15,4)-coded OOK are 2 dB and 4 dB better than the uncoded BPSK/BPAM.

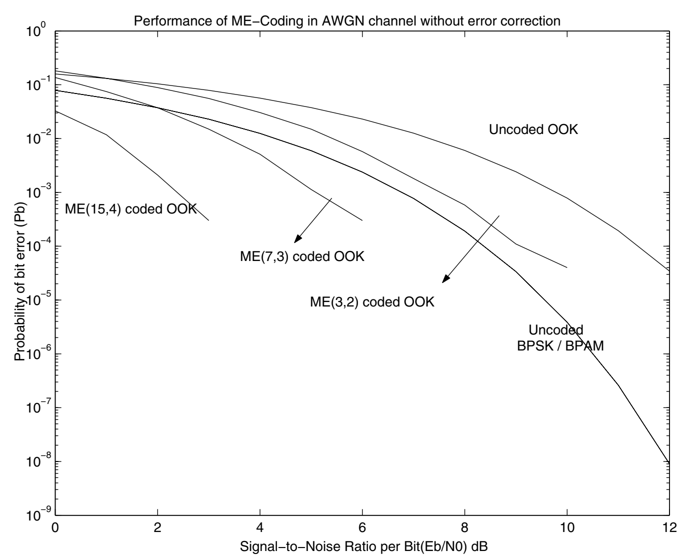

Fig. 4. **Performance Comparison and Evaluation of ME-Coding**

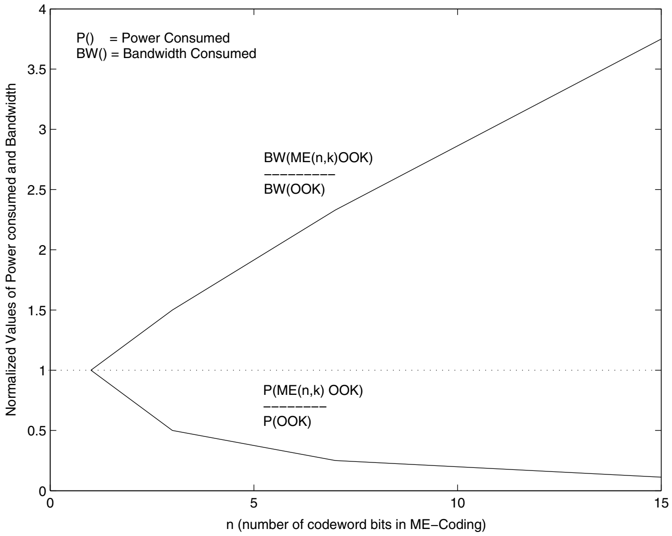

Fig. 5. **Normalized Bandwidth and Power Consumption**

C. *Power and Bandwidth Requirement of ME-Coding*

This simple ME-Coded OOK modulation scheme now performs better (in terms of power consumption) than scheme like BPSK. Figure 5 shows the amount of decrease in the normalized power and an increase in the bandwidth requirement of the system for increasing values of n. However, a trade-off must be done between power and bandwidth consumption of the system. For applications operating in the unlicensed ISM band, there is a scope for using higher bandwidth to achieve power efficiency. ME-coding being a simple mapping technique, can be implemented with less power requirement. Further, we present a scheme to improve the performance of this non-optimal bit-by-bit detection by using a simple code-by-code detection process.

IV. Error correction in ME-coding

The sensor applications have transceiver with limited computing capabilities, memory resources and reduced processor speed. Another important factor to be considered is the delay in the receiver processor. There are many efficient codes with higher code gains like turbo codes to achieve energy efficiency at a system level [6][8]. It is complicated to generate and detect these codes. Complex algorithms take up more power in computing. Computation time also increases with complexities. Moreover, our sole idea of having less number of bit-1's in the transmitted code bit sequence must be maintained. The main objective here is to bring about a considerable conservation in the energy at a system level with algorithms of least complexities, demanding less resources and consuming lower power in the circuit level implementation.

Error correction schemes like Convolution codes and Block codes can be adopted to have an improvement in the error performance of the ME-coding scheme. Convolution codes are tough to be combined with ME-codes as they are generated in a finite-state machine and they do not allow a direct concatenation with ME-codes [3]. Block codes like Hamming code are used for error performance improvement in ME-coding [3]. For example, Systematic binary Hamming block code scheme, say a standard (7,4) Hamming code can be combined with the ME-codes using the parity check equation $C_m H' = 0$ (C_m is the codeword and H' is the transpose of parity check matrix). This effort of improving the error performance of ME-code by combining it with Hamming Code proves unsuccessful as the basic approach of ME-coding to have a reduced number of ones in the transmitted codeword bit sequence is lost. The coding gain provided by Hamming codes for smaller values of n is small and also has a higher circuit complexities for syndrome detection at the receiver [8]. It also increases the length of the ME-codeword.

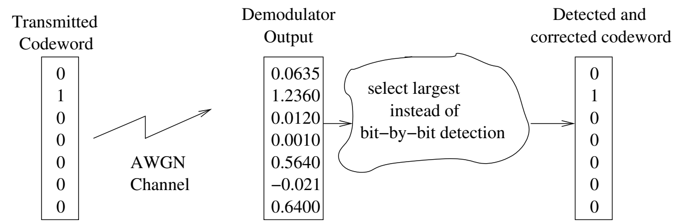

Fig. 6. **Error Correction with Code-by-Code Detection**

A. *Error Correction in ME-Codes with Code-by-Code Detection*

The performance of the bit-by-bit detection explained in the earlier section can be further increased by code-by-code detection. The problem of uncorrected ME-code bits faced by the bit-by-bit detection process was explained in the previous section. We have also discussed the limitations of using ME-codes along with other simple error correcting codes like Hamming codes. Hence, we need to look at other energy efficient approach in improving the performance of the ME-coding scheme.

The signal strengths of the demodulated bits vary due to the presence of noise in the channel, the bits may not be the same as it was sent from the transmitter. We consider AWGN with zero mean and unit variance. After a bit-by-bit 0.5 threshold detection is made, a codeword bit sequence say, 0 1 0 0 0 0 0 might be sent and may be detected as 0 1 0 0 1 0 1. As already discussed, the basic property of the codeword has made it possible to detect an error in the codeword. Instead of declaring this codeword as one to be in error, we follow a different approach for codeword detection.

Before a bit-by-bit hard detection is made, we observe the energy levels of all the incoming n bits of the codeword. Then we make the bit with highest strength as a high-bit and the rest as low-bit. Figure 6 shows the process of our code-by-code detection for a codeword. It shows a transmitted codeword 0 1 0 0 0 0 0. This is demodulated as 0.0635, 1.236, 0.012, 0.001, 0.564, -0.02, 0.64. In our earlier approach of bit-by-bit detection with 0.5 threshold, it would have been detected as 0 1 0 0 1 0 1. Now, by our approach we look at the bit with highest strength in the entire codeword. The original high-bit of energy 1.236 is set as bit-1 and the rest is made as bit-0's. Thus, it is detected as 0 1 0 0 0 0 0. Since the noise is AWGN, the probability of energy of genuine bit-1 being greater than the energy of the error bit-1 is more. ie. if energy of genuine bit-1 is e_i and that of the error bit-1 is e_j, then, $P(e_i > e_j)$ is more than $P(e_j > e_i)$. This fact is clear from a Gaussian distribution curve.

By code-by-code detection process we accomplish two things. Firstly, we eliminate the occurrence of an invalid codeword at the receiver and improve the error performance of ME-Coding. Secondly, this method performs exactly like an optimal detector.

In an optimal decoding scheme, the demodulator output produces the receiver codeword of length n as $\mathbf{r} = [r_1, r_2, ...r_n]$. An optimal detector maximizes the probability of detecting a correct codeword $C_m = [c_{1m}, c_{2m}, ...c_{nm}]$ from the codeset $\mathbf{C}$, given, received code $\mathbf{r}$. ie. $argmax_{m=1,2,...8} P_r(\mathbf{C}_m/\mathbf{r})$ [8]. It maximizes the correlation metrics $C(\mathbf{r}, \mathbf{C}_m)$. The correlation metrics $C(\mathbf{r}, \mathbf{C}_m)_{m=1,2,3...8} = r.C_m = (r_1C_{1m} + r_2C_{2m} + r_3C_{3m}..... + r_nC_{nm})$. Since our codeword has only one high bit in it, $MAX[C(\mathbf{r}, \mathbf{C}_m)_{m=1,2,3...8}]$ is nothing but considering the highest energy bit. This method of code-by-code detection proves to be simpler than the optimum detection.

B. Performance of ME-Coding with Code-by-Code Detection

It is noted that ME-coded OOK modulation scheme when detected with code-by-code detection, performs better than the bit-by-bit detection. Figure 7 shows the relative improvement in the error performance. In the Figure 7, ERCN represents the code-by-code detection which has error correction capability. For an error probability of 10^{-4}, a total of about 3 dB, 6 dB and 9 dB improvement in SNR per bit was seen with ME(3,2), ME(7,3) and ME(15,4) respectively compared to uncoded OOK. ie. ME-Coded OOK can now perform a given probability of error with lesser SNR per bit value. ME(7,3)-coded OOK is about 2 dB better than Hamming(7,4)-coded BPSK/BPAM. The main reason for such a comparison is to emphasize the fact that ME-coded OOK is more energy efficient than other simple schemes like block-coded BPSK/BPAM and also to propose a new and simple approach of improving the inferior error performance of the OOK scheme.

Although this scheme is based on On-Off Keying modulation technique, the characteristic of the code makes it look like an orthogonal signaling scheme [8], except for the presence of an all-zero code. As a matter of fact, it is quite different compared to orthogonal signals in terms of transmission / reception techniques and also performance. In orthogonal signal scheme, each symbol (group of k bits) is transmitted as one of 2^k orthogonal signals and received as one of 2^k orthogonal signal vector. However, in ME-coding scheme used here, a code representing a group of k bits is transmitted bit-by-bit and received bit-by-bit.

The theoretical performance of orthogonal signals has already been dealt in detail [8]. Say, for probability of bit error

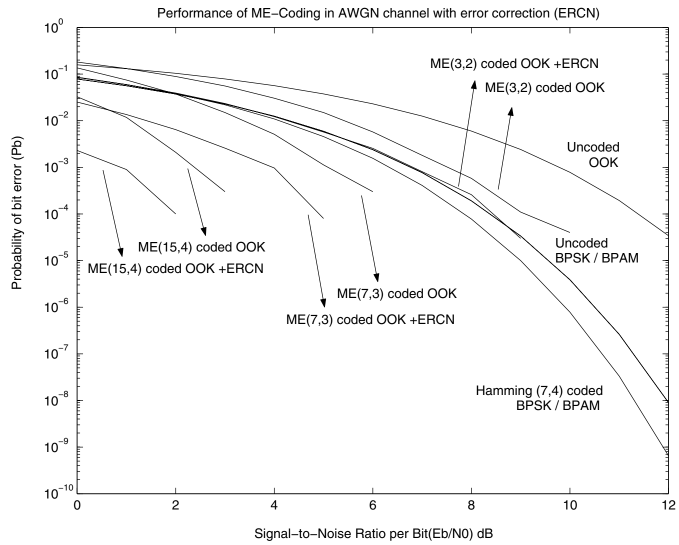

Fig. 7. **Performance of Me-Coding with Error Correction**

10^{-4}, SNR per bit required is about 7.5 dB, 6.5 dB and 6 dB for $M = 2^k = 8, 16, 32$ respectively. Simulations show that in the case of ME-coding, the same probability of bit error performance can be achieved at a lesser average SNR per bit value.

V. Sensor Application

Many researchers have been working on development of a wireless system that gives sight to people suffering from age-related macular degeneration or retinitis pigmentosa [1]. In this application, few of the diseased rods and cone cells of retina in the eye is artificially stimulated by current from electrodes present on the implanted chip inside the eye. We are working on development of such a system which is constrained mostly by power consumption and complexity of operation. A simple and reliable communication system is to be designed to establish a wireless link between a camera/processor outside the eye to a minute chip implanted inside the eye-ball on the retina. The system has to transmit the camera captured/processed video data via a wireless medium. The receiver inside the eye generates signals for stimulation based on the video information received. This has been the main motive for us to develop such a modulation and coding scheme that operates at very low power, consuming less energy, simple and less complex to implement. We have also developed a channel model for wireless communication inside human body [10]. It behaves like an AWGN channel, but with large amount of attenuation due to the presence of water in the tissue. This is the reason for us to use an AWGN channel for simulation and performance evaluation of our scheme.

VI. Conclusion

A simple and energy efficient source coded On/Off Keying modulation and near-optimal error detection scheme for wireless applications is proposed. This coding and modulation schemes can be made use in wireless applications with unknown source statistics. ME-Coding and the code-by-code detection proves to be simple and energy efficient. It also improves the error-performance of uncoded OOK considerably. ME-Coded OOK can be made to perform much better than Hamming-coded BPSK/BPAM.

VII. Acknowledgment

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