Adaptive threshold setting for OOK modulation with a prefix code in THz band

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Abstract: In this paper, we investigate a signal detection technique for wireless nanosensor communications in THz band. Due to a limitation of battery size in nanosensor terminal, the wireless nanosensor communication is highly energy-constrained. Therefore, on-off-keying (OOK) modulation with an energy efficient prefix code is a promising approach for achieving energy efficient communications. Energy detector (ED) is employed for symbol detection since it is a simple technique. We propose an Enhancing ED (EED) with adaptive threshold setting that is suitable for THz usage. We evaluated the EED in THz channel in which an effect of molecular absorption is considered. The numerical evaluation showed the advantages of the proposed scheme.

Keywords: energy detection, prefix code, wireless nanosensor communications, OOK

Classification: Wireless communication technologies

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1 Introduction

Wireless nanosensor networks (WNSN) is an attractive technology in various fields, such as medical and agriculture fields [1]. The wireless communications based on nanosensors can be performed in THz band due to small antenna size and material [2]. Communication in WNSN should be highly energy-constrained due to a limited battery size [1, 3].

For this issue, an energy efficient prefix coding (EPC) for on-off keying (OOK) pulse modulation has been investigated in [3]. In this OOK pulse modulation, if it is logical one (high bit: HB), pulse signal is transmitted, otherwise non-signal is transmitted under logical zero (low bit: LB). The EPC is designed to reduce the average number of HB in the codewords to reduce energy consumption per bit at the expense of throughput since average length of codeword is increased.

In this paper, we propose an adaptive threshold setting in energy detector (ED) for OOK pulse modulation with the EPC. In the EPC, the probability of HB depends on the bit sequence of codeword. The adaptive threshold is set based on the probability of HB. The proposed threshold setting is numerically evaluated under THz wireless channel environment by Monte Carlo simulations. The evaluations reveal that the proposed adaptive threshold can achieve reliable and energy efficient communications.

The rest of this paper is organized as follows. In section 2 we explain our system model, while section 3 introduces the design of adaptive threshold in signal detection. In section 4 adaptive threshold is evaluated by numerical simulations. Section 5 concludes this paper.

2 System model

| Table I. Prefix code \( l = 3 \). |
|---|---|---|---|---|---|---|---|---|
| \( m \) | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 0 0 0 | | | | | | | | | | |
| 0 0 1 | | | | | | | | | | |
| 0 1 0 | | | | | | | | | | |
| 0 1 1 | | | | | | | | | | |
| 1 0 0 | | | | | | | | | | |
| 1 0 1 | | | | | | | | | | |
| 1 1 0 | | | | | | | | | | |
| 1 1 1 | | | | | | | | | | |
| \( P_1 \{\%\} \) | 50 | 50 | 50 | 13 | 14 | 17 | 20 | 25 | 33 | 50 |
From a source of information (SoI), each $l$ bits sequence is input for the EPC and there are $N = 2^l$ types of bit sequences. The length of bits $l$ indicates the modulation level in one sequence. The EPC is described by Binary Tree based on Weight Decrease (BTWD) algorithm [3]. The output of EPC also has $N$ types of bit sequences which corresponds to a codeword. The $n$th codeword $c_n$ is given by

$$c_1 = [b_{n,0}, \cdots b_{n,m} \cdots b_{n,N-1}] = \begin{bmatrix} N-1 \\ \vdots \\ N-n \end{bmatrix} 0 \cdots 0$$

$$c_n = [b_{n,0}, \cdots b_{n,m} \cdots b_{n,N-n+1}] = \begin{bmatrix} N-n \\ \vdots \\ 0 \end{bmatrix} 0 \cdots 1 \quad 1 < n \leq N,$$

where $b_{n,m}$ denotes the bit information at the $m$th bit in the $n$th codeword. A probability of HB at the $m$th bit is given by $1/(N + 1 - m)$ and this probability is denoted by $P_1(m,N)$. In Table I, an example of the codeword with $l = 3$ is shown. The number of HBs in each codeword is at most one. Therefore, the EPC can achieve less energy consumption.

Pulse based wireless communication at THz band is assumed and the radiate Gaussian pulse is given by

$$p(t) = e^{-t^2/(10^2 \pi B^2)} \cos(2 \pi f_c t),$$

where standard deviation is $\sigma_G = 10^2 \pi B$, bandwidth of the pulse is $B = 1$ THz, and the center frequency is $f_c = 7$ THz, respectively. Example of the transmitted pulse is shown in Fig. 1 (a). A line of sight propagation and time invariant channel are assumed. The channel in THz band has molecular absorption and spreading loss, and the channel can be modeled by impulse response $h(\tau)$ as shown in Fig. 1 (b) in which pressure is 1010 hPa, relative humidity is 69.6%, temperature is 298.55 K, and distance between the transmitter and the receiver is 5 cm are assumed [4]. In this case, the

![Fig. 1. (a) Transmitted pulse $p(t - T_b/2)$, (b) Impulse response $h(\tau)$, and (c) Received pulse without noise.](image)
received signal with one bit for HB and LB are given by
\[
\begin{align*}
y(t|\text{HB}) &= \int_{-\infty}^{\infty} h(\tau)p(t - (n_b + \frac{1}{2})T_b - \tau)d\tau + w(t), \\
y(t|\text{LB}) &= w(t),
\end{align*}
\tag{3}
\]
with \(T_b\) as the time duration for one pulse and \(w(t)\) is Additive White Gaussian Noise (AWGN).

Let \(y[j] := y(j/fs)\) be the \(j\)th sampled signal from \(y(t)\) with \(fs\) sampling rate. Then the observed energy \(S\) during one bit duration is
\[
S = \sum_{j=(n_b-1)J}^{n_bJ} |y[j]|^2,
\tag{4}
\]
where \(J = \lceil T_b \cdot fs \rceil\) is the number of samples in \(T_b\). In the ED with a threshold \(\gamma\), the detection rule is as follows: if \(S > \gamma\), the detection result is HB, otherwise, the detection result is LB.

### 3 Adaptive threshold setting

Probability density functions (PDFs) of \(S\) under HB and LB are as follows:
\[
p(S|\text{LB}) = \frac{S^{\frac{J}{2}-1}}{2^{\frac{J}{2}} \Gamma(\frac{J}{2})} \exp\left[-\frac{S}{2}\right],
\tag{5}
\]
\[
p(S|\text{HB}) = \frac{S^{\frac{J}{2}-1}}{2^{\frac{J}{2}} \Gamma(\frac{J}{2})} \exp\left[-\frac{1}{2}(S + \delta)\right] \sum_{k=0}^{\infty} \frac{(\delta S)^k}{k! \Gamma(\frac{J}{2} + k)}
\tag{6}
\]
with \(\delta = \frac{1}{\sigma^2} \sum_{j=1}^{J} (\mu_j)^2\) as a non-central parameter [5], \(\sigma\) is standard deviation of AWGN, and \(\mu_j\) is the mean of \(y[j]\). Let \(P(\text{LB})\) and \(P(\text{HB})\) denote probabilities for LB and HB, respectively. Then, averaged bit error rate (BER) with the threshold is given by
\[
P_e(\gamma) = P_e^{\text{LB}}(\gamma)P(\text{LB}) + P_e^{\text{HB}}(\gamma)P(\text{HB})
\tag{7}
\]
while \(P_e^{\text{LB}}\) and \(P_e^{\text{HB}}\) are BER under LB and HB, respectively, as
\[
P_e^{\text{LB}}(\gamma) = \int_{\gamma}^{\infty} p(S|\text{LB})dS,
\]
\[
P_e^{\text{HB}}(\gamma) = \int_{-\infty}^{\gamma} p(S|\text{HB})dS.
\]
Equation (7) indicates the knowledge of \(P(\text{LB})\) and \(P(\text{HB})\) can be used to find the optimum threshold which can minimize BER.

In the case of \(l = 3\) (Table. I), \(P(\text{HB}) = 1/(8 - (m - 1))\) for the \(m\)th bit. In addition, if the detection result is HB or \(m = N - 1\), this indicates the end of the codeword. In the adaptive threshold setting, we set the threshold \(\gamma_a\) according to \(P(\text{HB}) = 1/(2^l - (m - 1))\) and \(P(\text{LB}) = 1 - P(\text{HB})\) for the \(m\)th bit to minimize \(P_e(\gamma)\).

In a comparison method, the threshold \(\gamma_c\) is set based on the assumption \(P(\text{LB}) = P(\text{HB}) = 1/2\). The purpose of this comparison is to show the benefit due to considering \(P(\text{HB})\) and \(P(\text{LB})\) in the adaptive threshold setting.

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Fig. 2. (a) Average packet error rate, (b) Energy efficiency, and (c) Throughput.

4 Numerical result

We compare performance of our proposed EED that is based on the adaptive threshold $\gamma_a$ and the static threshold in the comparison method $\gamma_c$. Signal to noise ratio in the received signal is set to 0 dB.

Nanosensors are assumed to use packet based communication scheme [6]. In this section, one packet conveys 20 codewords and the number of packets is 6000 for Monte Carlo simulation. A packet error rate denoted by $P_{\text{err}}^{\text{pack}}$ is evaluated in Fig. 2 (a). If there is any detection error regarding codeword in one packet, it is a packet error. In this evaluation, the modulation level $l$ is changed from three to seven. Red line and blue line indicate the results obtained by the adaptive threshold and the comparison method, respectively. As $l$ is increased, average packet error rate is increased since the average of codeword lengths is increased. The result indicates that the adaptive
threshold is better than the comparison method.

In the wireless communication in THz, energy efficiency is also important. The energy efficiency is defined by the average number of bits received successfully per joule as

\[ \epsilon = \frac{l(1 - P_{\text{err}}^{\text{pick}})}{E_1(N - 1)/N}, \]

(8)

where the numerator indicates the average number of bits successfully received at the receiver per codeword and the denominator indicates the required energy per codeword. \( E_1 \) denotes the energy for one pulse. Fig. 2 (b) shows an evaluation of energy efficiency as a function of \( l \). The EPC inherently can achieve better energy efficiency by increasing modulation level \( l \). Specifically, there is only one HB in a codeword of EPC for any \( l \) which determines the number of bits in one codeword. This aspect of EPC can be confirmed in the result of the adaptive threshold. On the other hand, in case of the comparison method, the energy efficiency is not improved by increasing \( l \) rather than it gets worse at \( l = 7 \). This is due to high \( P_{\text{err}}^{\text{pick}} \) which can be confirmed in Fig. 2 (a).

Increasing \( l \) leads to decreasing throughput since increasing \( l \) leads to increasing \( P_{\text{err}}^{\text{pick}} \) and average of the codeword lengths. The throughput is defined as

\[ \eta = \frac{l(1 - P_{\text{err}}^{\text{pick}})}{((N^2 + N - 2)/2)T_b} \]

(9)

where the numerator indicates the average number of bits successfully received at the receiver per codeword and the denominator indicates average time duration of the codewords. The throughput performance is shown in Fig. 2 (c). In this result, the adaptive threshold also outperform the comparison method. At \( l = 7 \), the throughput of the adaptive threshold is 2.5 time of the throughput of constant threshold.

5 Conclusion

In this paper, we propose the adaptive threshold for ED in THz wireless communication. In the adaptive threshold, the threshold is adjusted according to the probabilities of HB and LB in each bit. The adaptive threshold for ED is evaluated in THz channel in which the molecular absorption is assumed. Numerical evaluation shows that our proposal provides benefits in packet error rate, energy efficiency and throughput compared to the comparison method in which threshold is set in a static manner.

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