Energy Detection Scheme in the Presence of Burst Signals

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***Abstract*—This letter proposes an energy detection scheme based on short windows to detect the presence of a burst signal that spans over a short period of time. For practical use, the proposed scheme provides a simple computational method for the threshold, with which the measured energy is compared, that satisfies a target false alarm probability and also the optimal length of the short window that minimizes miss detection probability. To evaluate the performance of the proposed scheme, miss detection probability is analyzed as a function of the threshold. Simulation results demonstrate that the proposed scheme provides a lower miss detection probability than the conventional scheme when a burst signal is present.**

***Index Terms*—Burst signal, short packet, ultra-reliable and low latency communication, energy detection.**

I. Introduction

RECENT and emerging wireless networks are designed mainly for data transmission, where the transmitted signal for a user is discrete. The characteristics of burst transmission are expected to occur in emerging communication systems such as ultra-reliable and low latency communication including smart grids, and industrial manufacturing and control. Moreover, the burst transmissions may exhibit characteristics such as sporadic small packet transmissions in a class of sensor devices and smartphone functionalities.

Energy detection is a simple and effective scheme to detect the presence of a signal, where the measured energy over a sensing duration is compared with a threshold pre-determined to satisfy target false alarm probability [1], [2]. However, the conventional energy detection scheme does not perform well in scenarios where a burst signal is present, because energy measurement is performed over the regular sensing duration, regardless of the burstiness characteristic of a signal, under the assumption that a signal is present throughout the sensing duration [3], [4]. When there is a burst signal that is much shorter than the sensing duration, however, the conventional energy detection scheme is not likely to capture the presence of the burst signal correctly since the energy of the burst signal is diluted in the averaged energy measured over the regular sensing duration.

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There are very few research outcomes for opportunistic channel access when a burst signal is present over a short period of time. To enhance low spectrum utilization by packet bursts, [5]–[7] proposed energy detection strategies that exploit the characteristics of incoming signals. To cope with the packet burst, [7] discusses channel learning and channel access schemes based on the channel usage pattern and uses a sufficiently long window to prevent the pattern from changing multiple times during the window. However, an energy detection in the presence of a burst signal that is much shorter than the energy detection duration, which occurs by sporadic data packet transmissions, has not been investigated.

Motivated by the aforementioned studies, this paper proposes a practical energy detection scheme to detect the presence of a burst signal, such as a short packet, that is occasionally present in the channel. The main contributions of this paper are summarized as follows: an energy detection scheme based on shorter windows for detecting the presence of a burst signal without prior knowledge of a burst signal is proposed. To be used in practice, the scheme provides a simple calculation of the threshold that guarantees a target false alarm probability. In addition, the scheme shows the optimal length of the short window that captures the maximum energy of the burst signal, which further minimizes the miss detection probability. Miss detection probability and energy efficiency are analyzed to evaluate the performance of the proposed energy detection scheme.

II. Proposed Energy Detection

A. Mode of Operation

Suppose a scenario where a burst signal, such as a sporadic small data packet, is occasionally transmitted in the spectrum for a short period of time and a sensor device attempts to utilize the spectrum opportunistically when the spectrum is empty. For an opportunistic channel access, the device requires to do spectrum sensing based on energy detection to determine whether the spectrum is busy or empty.

Fig. 1 illustrates a burst signal, where L is the regular sensing duration used by the conventional receiver in terms of the number of samples and L_B is the length of the burst signal, where $L_B \ll L$. If energy measurement is done over the sensing duration L as in the conventional detection scheme, then it is hard to detect the presence of the burst signal with high confidence since the burst signal energy is relatively small (the average energy over L is not distinguishable from the noise average as shown in the figure). Thus, if energy measurement is performed and averaged for each short window, then the burst signal energy can be properly captured by the short window, which results in

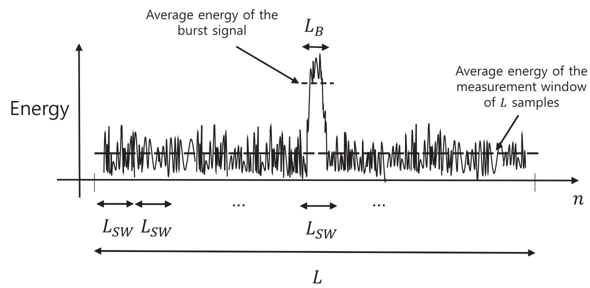

Fig. 1. Illustration of a burst signal in time, where L is the sensing duration, L_{SW} is the length of a short window, and L_B is the length of the burst signal in terms of samples.

a higher detection probability (the average energy over L_{SW} is shown as a dotted line).

The n-th received sample during the energy measurement follows a binary hypothesis that is given as

$$y(n) = \begin{cases} w(n), 0 \le n \le L-1 & : H_0 \\ z(n), 0 \le n \le L-1 & : H_1, \end{cases} \quad (1)$$

where $z(n)$ is a received sample in the presence of burst signal defined as

$$z(n) = \begin{cases} hx(n) + w(n), & n_s \le n < n_s + L_B \\ w(n), & n < n_s \text{ or } n_s + L_B \le n, \end{cases} \quad (2)$$

where $x(n)$ is a burst signal whose power is σ_x^2, h is complex Rayleigh block fading whose power is σ_h^2, $w(n)$ is additive white Gaussian noise (AWGN) with variance σ_w^2, H_0 and H_1 refer to the hypotheses of signal absence and signal presence, and n_s is an arbitrary starting sample index of a burst signal. Note that n_s is uniformly distributed between 0 and $L - L_B + 1$.

The proposed scheme splits the sensing duration into short windows, where L_{SW} is the length of a short window. There are $\frac{L}{L_{SW}}$ short windows in the sensing duration. Average energy is measured for each short window, which results in L/L_{SW} average energies. From those, the proposed scheme selects the one with maximum energy and compares it with a pre-determined threshold to decide the presence or the absence of a burst signal. The test statistics for deciding on the existence of a burst signal is given as

$$T = \frac{1}{L_{SW}} \max\left\{ \sum_{n=0}^{L_{SW}-1} |y(n)|^2, \ldots, \sum_{n=L-L_{SW}}^{L-1} |y(n)|^2 \right\} \underset{H_0}{\overset{H_1}{\gtrless}} \gamma, \quad (3)$$

where T is the maximum average energy, γ is a pre-determined threshold, and $|x|$ is absolute value of x.

The goal of the proposed detection scheme is to detect the presence of a burst signal within the sensing duration. Even if more than one burst signals are present in the sensing duration, the operation of the proposed scheme is identical.

B. Simple Computational Method for Threshold

To detect the presence of a burst signal while satisfying target false alarm probability, the threshold with which the average energy is compared is of prime importance. Given that a burst signal is possibly present, the proposed energy detection scheme needs to compute the threshold for proper burst signal detection as simply as possible.

To derive the expression for the threshold, a cumulative density function (CDF) of T under H_0 has to be provided. In (3), each average energy during the short window follows a Chi-square distribution with L_{SW} degrees of freedom. Since T in (3) is the maximum average energy selected from L/L_{SW} short windows, the CDF of T under H_0 is obtained as

$$\begin{aligned} F_T(t) &= \left(\int_0^t \frac{1}{(\frac{2\sigma_w^2}{L_{SW}})^{L_{SW}} \Gamma(L_{SW})} w^{L_{SW}-1} e^{-\frac{w}{\frac{2\sigma_w^2}{L_{SW}}}} dw \right)^{\frac{L}{L_{SW}}} \\ &= \left(1 - \frac{\Gamma(L_{SW}, \frac{L_{SW}\, t}{2\sigma_w^2})}{\Gamma(L_{SW})} \right)^{\frac{L}{L_{SW}}}, \end{aligned} \quad (4)$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ denote the complete and incomplete gamma function, respectively. Given a certain threshold γ, a false alarm probability P_{FA} is computed as

$$P_{FA} = 1 - F_T(\gamma) = 1 - \left(1 - \frac{\Gamma(L_{SW}, \frac{L_{SW}\,\gamma}{2\sigma_w^2})}{\Gamma(L_{SW})} \right)^{\frac{L}{L_{SW}}}. \quad (5)$$

Finally, by arranging (5), the threshold to satisfy P_{FA} is simply obtained as

$$\gamma = \frac{2\sigma_w^2}{L_{SW}} \Gamma^{-1}\left(L_{SW}, (1 - (1 - P_{FA})^{\frac{L_{SW}}{L}} \Gamma(L_{SW})) \right), \quad (6)$$

where $\Gamma^{-1}(\cdot,\cdot)$ is an inverse incomplete Gamma function.

C. Optimal Length of Short Window (L_{SW})

The proposed energy detection selects the maximum among the average of short windows and compares it with a threshold pre-determined to satisfy target false alarm probability to detect the presence of the burst signal. The optimal length of the short window in the proposed scheme is determined by maximizing the average energy of burst signals (AEBS). In other words, the optimal length of the short window that maximizes AEBS is obtained as

$$L_{SW-opt} = \arg\max_{L_{SW}} \text{AEBS}(L_{SW}), \quad (7)$$

where $\text{AEBS}(L_{SW})$ is defined differently for the cases of $L_{SW} \le L_B$ and $L_{SW} > L_B$.

In the case of $L_{SW} \le L_B$, when the short window with the highest average energy is selected among many short windows, the value of the average energy of the burst signal is in the range between $\lceil L_B/2 \rceil \sigma_x^2$ and $L_{SW}\sigma_x^2$. Because at least a half of the burst signal samples or at most the full burst signal samples are included in the short window. Thus, $\text{AEBS}(L_{SW})$ in the case of $L_{SW} \le L_B$ is given as

$$\begin{aligned} \text{AEBS}(L_{SW}) &= \frac{2\sum_{k=\lceil L_B/2 \rceil}^{L_{SW}-1} k + (L_B - L_{SW} + 1)L_{SW}}{2(L_{SW} - \lceil L_B/2 \rceil) + L_B - L_{SW} + 1} \sigma_x^2 \\ &= \frac{L_B L_{SW} - \lceil L_B/2 \rceil (\lceil L_B/2 \rceil - 1)}{L_{SW} - 2\lceil L_B/2 \rceil + L_B + 1} \sigma_x^2, \end{aligned} \quad (8)$$

where σ_x^2 is the average energy of the burst signal. Similarly, in the case of $L_{SW} > L_B$, the value of the average energy of the selected short window is in the range between $\lceil L_B/2 \rceil \sigma_x^2$ and

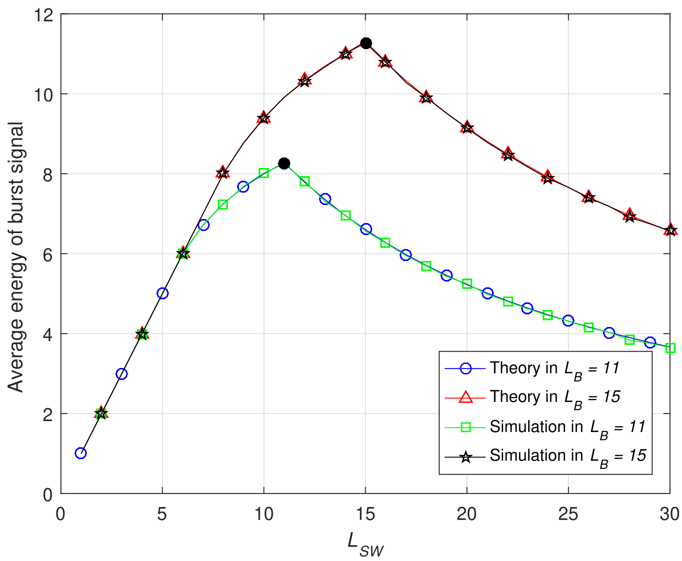

Fig. 2. Illustration of an average SNR with various L_{SW} in SNR = 0 dB, $L_B = 11$ and 15. Two dots in the figure indicate the optimal L_{SW} s for the proposed energy detection.

$L_B\sigma_x^2$. So, AEBS(L_{SW}) in the case of $L_{SW} > L_B$ is given as

$$\begin{aligned}&\text{AEBS}(L_{SW})\\&= \sigma_x^2 \frac{2\sum_{k=\lceil L_B/2\rceil}^{L_B-1} k + (L_{SW} - L_B + 1)L_B}{2(L_B - \lceil L_{SW}/2\rceil) + (L_{SW} - L_B + 1)} \frac{L_B}{L_{SW}} \\&= \sigma_x^2 \frac{L_B L_{SW} - \lceil L_{SW}/2\rceil(\lceil L_{SW}/2\rceil - 1)}{L_B - 2\lceil L_{SW}/2\rceil + L_{SW} + 1} \frac{L_B}{L_{SW}}.\end{aligned} \quad (9)$$

$\frac{L_B}{L_{SW}}$ is multiplied in (9), since the burst signal energy is averaged over the short window, where the length of the short window is longer than the burst signal.

To evaluate the optimal short window size, numerous simulations are performed for various burst signal sizes. Fig. 2 illustrates AEBSs with various L_{SW} when $L_B = 11$ and 15, where two dots show the optimal short window sizes ($L_{SW-opt} = L_B$) with the maximum AEBSs. SNR is defined as σ_x^2/σ_w^2. This observation can be explained as follows. AEBS grows proportional to L_{SW} in the range of $L_{SW} < L_B$, because more burst signal samples are included as L_{SW} increases. But as L_{SW} increases beyond L_B, AEBS is reduced since the constant burst signal energy is diluted over the short window that is getting longer than the burst signal size.

III. Performance Analysis

A. Average Miss Detection Probability

Based on the threshold computed in (6), miss detection probability is analyzed as follows. Suppose the short window size is same as the length of the burst signal, $L_B = L_{SW}$, since it is the optimal window size as discussed in subsection II-C. The burst signal comes at random and thus is unlikely to be time aligned with the short window boundaries. Thus, a distribution of the time offset between the short window and the burst signal is uniformly distributed from 0 to $\lfloor L_B/2\rfloor$, where $\lfloor x\rfloor$ is the greatest integer which is less than or equal to x. Substituting L_B into L_{SW} in (8), the average number of the burst signal samples during the short window is given as

$$m = \frac{L_B^2 - \lceil L_B/2\rceil(\lceil L_B/2\rceil - 1)}{2(L_B - \lceil L_B/2\rceil) + 1}. \quad (10)$$

Based on the average number of the burst signal samples and L_{SW}, T under H_1 follows a non-central chi-square distribution defined as

$$\begin{aligned}f_T(t) = &\frac{L_{SW}}{2\sigma_w^2}\left(\frac{L_{SW}t}{m\cdot x}\right)^{\frac{L_{SW}-1}{2}}\\&\cdot e^{-\frac{m\cdot x + L_{SW}t}{2\sigma_w^2}} I_{L_{SW}-1}\left(\frac{\sqrt{L_{SW}m\cdot x\cdot t}}{\sigma_w^2}\right),\end{aligned} \quad (11)$$

where x is an instantaneous burst signal power and I_ν is the ν-th order modified Bessel function of the first kind [8, 8.43]. Note that x in (11) is multiplied by $\frac{m}{L_{SW}}$ in order to consider the effect of the time offset. By integrating (11) from 0 to γ, the miss detection probability over AWGN channels, which is a probability that γ is less than T under H_1, is computed as

$$P_{MD} = \int_0^\gamma f_T(t)dt = 1 - Q_{L_{SW}}\left(\sqrt{\frac{m\cdot x}{\sigma_w^2}}, \sqrt{\frac{L_{SW}\gamma}{\sigma_w^2}}\right), \quad (12)$$

where $Q_N(a,b)$ is the generalized Marcum Q function defined as

$$Q_N(a,b) = \frac{1}{a^{N-1}}\int_b^\infty x^N e^{-\frac{x^2+a^2}{2}} I_{N-1}(ax)dx. \quad (13)$$

Averaging (12) over an exponential distribution with the mean of $1/(\sigma_x^2\sigma_h^2)$, the average miss detection probability of the proposed energy detection is calculated as

$$\begin{aligned}P_{MD,Ray} &= \int_0^\infty P_{MD}\frac{1}{\sigma_x^2\sigma_h^2}e^{-\frac{x}{\sigma_x^2\sigma_h^2}}dx\\&= 1 - e^{-\frac{L_{SW}\gamma}{2\sigma_w^2}}\sum_{i=0}^{L_{SW}-2}\frac{(\frac{L_{SW}\gamma}{2\sigma_w^2})^i}{i!} - \left(\frac{2\sigma_w^2 + m\sigma_x^2\sigma_h^2}{m\sigma_x^2\sigma_h^2}\right)^{L_{SW}-1}\\&\cdot\left(e^{-\frac{L_{SW}\gamma}{2\sigma_w^2 + m\sigma_x^2\sigma_h^2}} - e^{-\frac{L_{SW}\gamma}{2\sigma_w^2}}\sum_{i=0}^{L_{SW}-2}\frac{\left(\frac{L_{SW}\gamma m\sigma_x^2\sigma_h^2}{2\sigma_w^2(2\sigma_w^2 + m\sigma_x^2\sigma_h^2)}\right)^i}{i!}\right).\end{aligned} \quad (14)$$

Note that the manipulation for (14) is performed by Appendix A in [9].

B. Energy Efficiency

The energy efficiency is defined as [10]

$$E_e = \frac{F}{C}, \quad (15)$$

where F is average throughput and C is energy cost for the spectrum sensing composed of sensing and transmission frames whose lengths are τ_s and $\tau - \tau_s$, respectively, and τ is one frame length. There are four possible scenarios between the activities of primary user (PU) and secondary user (SU): PUs are absent and SUs detect the absence of PU correctly; false alarm happens; PUs are present and SUs detect the presence of PU successfully; and miss detection occurs. When $P(H_0)$ and $P(H_1)$ are the probabilities of H_0 and H_1, respectively, the *a priori* probabilities for the four scenarios are as follows:

TABLE I
PARAMETER VALUES FOR SIMULATION

Parameter	Value
the transmit power E_t	3 Watt
the sensing power E_s	0.1 Watt
the occurrence probability of H_1 Pr(H_1)	0.2
the occurrence probability of H_0 Pr(H_0)	0.8
the bandwidth of the licensed band W	3MHz
the sampling frequency f_s	6 MHz
the energy detection throughput F_0	0.6658 bits/sec/Hz
the length of one time frame τ	300 ms
the symbol duration for burst signal	100 μs

$P_1 = P(H_0)(1 - P_{FA})$; $P_2 = P(H_0)P_{FA}$; $P_3 = P(H_1)(1 - P_{MD})$; and $P_4 = P(H_1)P_{MD}$.

In the first scenario, SUs transmits their data after spectrum sensing. When F_0 is the throughput of SU in the case of H_0, the energy cost C_1 and the throughput F_1 for this scenario are obtained as

$$C_1 = E_s\tau_s + E_t(\tau - \tau_s), F_1 = \frac{\tau - \tau_s}{\tau}F_0. \quad (16)$$

SUs do not transmit their data in the second and third scenarios. For these scenarios, the energy costs C_i and the throughput F_i are obtained as

$$C_i = E_s\tau_s, F_i = 0, \quad (17)$$

where $i = 2, 3$ for the second and third scenarios, respectively.

In the last scenario, SUs transmit their data due to miss detection. However, the transmitted data cannot be correctly decoded due to a high power burst signal, so the throughput may be zero. For this scenario, the energy cost C_4 and the throughput F_4 are obtained as

$$C_4 = E_s\tau_s + E_t(\tau - \tau_s), F_4 = 0. \quad (18)$$

By combining the whole scenarios, the energy efficiency for the spectrum sensing is computed as

$$E_e = \frac{P_1F_1}{\sum_{i=1}^{4} P_iC_i} = \frac{P_1\frac{\tau-\tau_s}{T}F_0}{E_s\tau_s + (P_1 + P_4)E_t(\tau - \tau_s)}. \quad (19)$$

Note that the energy efficiency is decreased as P_4 increases.

IV. Simulation Results

Numerous simulations are performed to evaluate the performance of the proposed scheme in the presence of the burst signal regarding miss detection probability and energy efficiency. For comparison purposes, the thresholds for the conventional scheme and the proposed scheme are computed by [7] and (6), respectively. For the proposed and the conventional schemes with a burst signal, parameter values in Table I are used [4], [10]–[12]. The number of samples for sensing and transmission frames are computed as $\tau_s f_s$ and $(\tau - \tau_s)f_s$, respectively. Rayleigh fading with normalized power is present.

Fig. 3 compares the performance of the proposed detection scheme with that of the conventional scheme in terms of miss detection probability in the presence of a burst signal such as $(\tau_s, T_F) = (5\text{ ms}, 10^{-3})$. The figure also shows that the analysis in (14) matches very well with simulation results. Note that the conventional detection scheme has a higher miss detection probability, because the burst signal energy is diluted when L samples are measured and averaged out.

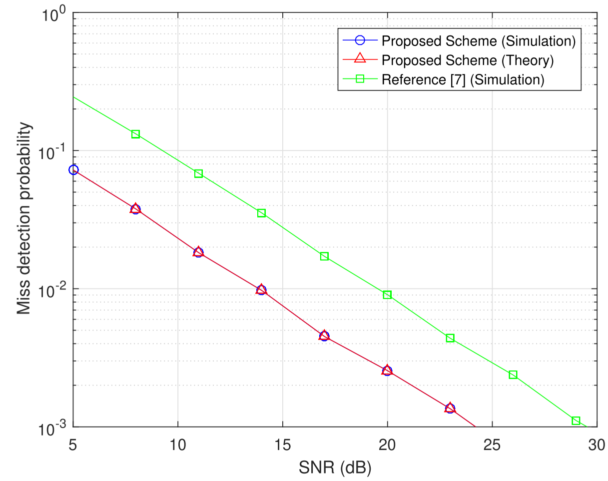

Fig. 3. Illustration of simulation results of the proposed scheme and reference [7], and performance analysis of the proposed scheme in the presence of Rayleigh fading with the normalized power. $\tau_s = 5$ ms and $T_F = 10^{-3}$.

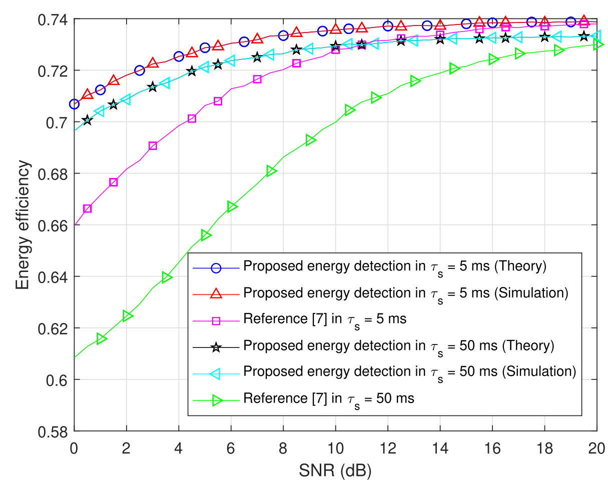

Fig. 4. Illustration of simulation results of the proposed scheme and reference and energy efficiency of the proposed scheme in $T_F = 10^{-2}$ and $\tau_s = 5$ ms and 50 ms when the Rayleigh fading channel with normalized power is present.

Fig. 4 shows energy efficiencies of the conventional and proposed energy detection schemes. As shown in Fig. 4, the energy efficiency of the proposed energy detection outperforms that of the conventional energy detection due to the lower miss detection probability of the proposed energy detection. In low SNR regime, the proposed scheme with τ_s of even 50 ms outperforms the conventional scheme with τ_s of 5 ms because miss detection probability of the proposed scheme is sufficiently low in low SNR regime.

V. Conclusion

This paper proposes an energy detection scheme based on short windows to detect a burst signal. For practical use of the scheme, it provides a simple computational method for threshold that satisfies target false alarm probability. In addition, it presents the optimal length of the short window that maximizes the average energy of a burst signal captured by the short window. The analyses of miss detection probability and energy efficiency confirm that the proposed scheme has better performance than the conventional scheme.

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