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Cognitive Radio Unified Spectral Efficiency and Energy Efficiency Trade-off Analysis

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***Abstract*—Spectral efficiency and energy efficiency are fundamental trade-off in wireless communications. Spectral efficiency (SE), defined as the average data rate per unit bandwidth, quantifies how efficiently the available spectrum is utilized. Energy efficiency (EE), defined as the successful transmitted information bits per unit energy from transmitter to receiver, quantifies how efficiently the energy is utilized. Basically, with higher average energy per bit to noise power spectral density ratio at the receiver, the packet can be more successfully detected, thus utilizing the spectrum more efficiently, giving higher SE; however, in this case, it requires more energy, lowering EE, and vice versa. In this paper, we study the trade-off between SE and EE, specifically for the cognitive radio considering its configurability. We propose a general metric SEE (Spectral/Energy Efficiency) to facilitate the analysis which quantifies the preference of SE or EE. Closed-form solutions for symbol transmission energy and the length of information bits per frame are obtained for various combined modulation and channel coding schemes. The closed-form solutions further facilitate the adaptivity of cognitive radio considering both SE and EE in various scenarios. Using the proposed metric shows that our scheme is capable to perform balanced trade-off between SE and EE. Considering only maximizing SE, our scheme gains much larger EE while only sacrificing little SE; and comparing with maximizing EE, larger SE can be obtained while sacrificing a small amount EE.**

I. Introduction

In wireless communications for either commercial or tactical services, spectral efficiency (SE) improvement is an eternal topic, due to the strong demand of high data rate transmissions but limited spectrum resources. The SE is defined as the average data rate per unit bandwidth; therefore, when SE is larger, higher data rates can be supported with a fixed spectrum bandwidth. Currently, SE is even more important with the large pervasive utilizations of mobile devices, such as smart phones, tablets, sensors, and small clouds, where huge volumes of data are generated and need to be transmitted. The wide spread of devices also has size, weight, and power (SWaP) requirements to make them convenient for various applications. To quantify the power consumption for information transmission, the energy efficiency (EE) is defined as the successful transmitted information bits per unit energy from a transmitter to a receiver. Therefore, for a larger EE, more information can be transmitted with a fixed amount of energy resource. However, SE and EE construct the fundamental trade-off in wireless communications [1] [2]. To efficiently utilize spectrum resources for a larger SE, it requires a packet can be more successfully transmitted, which in turn requires more energy consumption, thus reducing EE, and vice versa.

Recently, by combining both SE and EE, the trade-off analysis between the two metrics has attracted growing interest in the design of a communication system [1], [3]– [11]. In [1], the SE/EE trade-off has been analyzed for wideband systems. In [11], the trade-off has been analyzed for orthogonal frequency division multiple access (OFDMA) system. However, most works focus on the trade-off analysis using the Shannon channel capacity, without providing insights for direct practical guidance, especially for the agile configuration of cognitive radios.

In this paper, we focus the trade-off analysis between SE and EE from another perspective, to provide direct guidelines for cognitive radio design. A detail of the SE and EE models are first developed, considering the length of information transmission bits, overhead bits, practical modulation and channel coding schemes, hardware energy consumption, both large-scale power path-loss and small-scale signal fluctuations, and frame retransmissions, etc. A general metric is then proposed to facilitate the trade-off analysis, by incorporating both SE and EE. It can provide the balanced SE and EE trade-off design, with adjustable weights for the preference of SE/EE to fit for various scenarios. Closed-form solutions for both optimum transmission symbol energy and the length of information bits are provided for practical cognitive radio adaptivity. The analytical and simulation results demonstrate that our proposed scheme can achieve the balanced trade-off, under the conditions of different interests of SE and EE for various scenarios.

The rest of the paper is organized as follows. In Section II, the system model of SE and EE are first presented. Our proposed SEE (Spectral/Energy Efficiency η_{SEE}) metric is then given, by incorporating both SE and EE, to facilitate the trade-off analysis. In Section III, the optimum design with respect to η_{SEE} is performed; and the closed-form solutions of both transmission symbol energy and the length of information bits are obtained. Numerical and simulation results are carried out to validate our analysis in Section IV. Finally, the conclusions are presented in Section V.

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II. SYSTEM MODEL

Considering a cognitive radio transmitter and a receiver communicate with radio frequency (RF). They are separated with distance d. The information bits at the transmitter are divided into frames. In each frame, there are L uncoded information bits and L_0 overhead bits. The information bits and overhead bits are encoded with a channel encoder with coding rate r. For a system employing M-ary modulation scheme, there is the number of symbols in each frame $L_s = (L + L_0)/(r \log_2 M)$, where L is chosen in a way such that L_s is an integer. Note that for the cognitive radio transmitter, the uncoded information bits L in each frame, channel coding scheme with coding rate r, and modulation scheme with constellation size M can be adaptive to ensure the required communication quality of services (QoS). The impacting factors to the cognitive radio adaptivity include the quality of wireless channel, interferences, and the transmitted information type, etc.

The received signal samples in discrete-time at receiver can be represented as

$$y_m = \sqrt{E_r} h_m x_m + z_m, m = 1, 2, \cdots, L_s, \quad (1)$$

where E_r is received average energy per symbol, $x_m \in \mathcal{S}$ is the m-th modulated symbol in a frame, with $\mathcal{S}$ being the modulation constellation set with the cardinality $M = |\mathcal{S}|$, y_m, h_m, and z_m, correspond to the m-th transmitted symbol at the transmitter, are the received symbol, the fading coefficient between the transmitter and the receiver, and additive white Gaussian noise (AWGN) with single-sided power spectral density N_0; respectively.

A. Spectral Efficiency

The spectral efficiency (SE), is defined as the average data rate per unit bandwidth, which can be represented as [5]

$$\eta_{\text{SE}} = \frac{R_d}{(1+\alpha)R_s}, \quad (2)$$

where R_d is the net data rate of the successfully transmitted information bit, $(1 + \alpha)R_s$ is the signal bandwidth with α being the roll-off factor of the pulse shaping filter and R_s is the gross symbol rate. Note that in wireless communications, each frame cannot be guaranteed to be successfully transmitted in one transmission attempt, due to the effects of channel fading, intentional/unintentional interferences, and noise, etc. Therefore, retransmissions must be analyzed to obtain the η_{SE}.

The probability that a frame can be successfully transmitted equals to $1-\text{FER}$, where FER is the frame error rate that qualifies the frame transmission QoS. Note that FER depends on many system parameters, such as received signal-to-noise ratio (SNR) at the receiver, the frame length L_s, the transmission modulation and demodulation scheme, and channel encoding and decoding scheme. For an automatic repeat request (ARQ) protocol, the frame at the transmitter will be retransmitted if the transmitter receives a negative acknowledgement (NACK) which represents that the receiver cannot successfully recover the information bits in the frame. Since the retransmissions are independent, the number of retransmissions follow a geometric distribution with the parameter FER. The average number of retransmissions is therefore

$$\Lambda = \frac{1}{1 - \text{FER}}. \quad (3)$$

With the analysis of retransmissions, the average time to transmit L information bits is

$$T = \frac{\Lambda(L + L_0)}{r \log_2 M R_s}. \quad (4)$$

Therefore, R_d in (2) can be represented as

$$R_d = \frac{rL \log_2 M R_s}{\Lambda(L + L_0)} = \frac{L}{L + L_0} \frac{rR_s \log_2 M}{\Lambda}. \quad (5)$$

The spectrum efficiency of the system can then be calculated, by substituting (5) to (2), as

$$\eta_{\text{SE}} = \frac{L}{L + L_0} \frac{r \log_2 M}{1 + \alpha}(1 - \text{FER}). \quad (6)$$

B. Energy Efficiency

The energy efficiency (EE), η_{EE}, is defined as the successfully transmitted information bits per unit energy. EE can be measured as the average energy consumption to successfully deliver one uncoded information bit from the transmitter to the receiver. Note that the energy consumption for frame retransmissions must be included when measuring the energy efficiency.

Denote E_b is the average energy per uncoded information bit observed at the receiver during one transmission attempt. Therefore, the average E_b/N_0 at the receiver is

$$\gamma_b \triangleq \frac{E_b}{N_0} = \frac{E_r}{rN_0 \log_2 M}. \quad (7)$$

Using a large-scale power path-loss model [5], the energy consumption for each symbol at transmitter is

$$E_s = E_r G_1 d^\kappa M_l, \quad (8)$$

where κ is the path-loss exponent, G_1 is the gain factor at a unit distance including path-loss and antenna gain, and M_l is the link margin compensating the hardware process variations and other additive background noise or interference.

Besides considering the energy consumption for information transmission, we also include the hardware energy consumption to calculate the complete energy efficiency of a communication system. The hardware energy consumption is positive proportional to the transmission energy consumption, which can be modeled as [10]

$$E_c = \left(\frac{\xi_M}{\eta_A} - 1\right) E_s + \frac{\beta}{R_s}, \quad (9)$$

where η_A is the drain efficiency of the power amplifier, ξ_M is the peak-to-average power ratio (PAPR) of an M-ary modulation signal, and β incorporates the effects of baseband processing in both transmitter and receiver, such as signal processing, modulation and demodulation, encoding and decoding, and it can be treated as a constant in a frame with designed transceiver structure. For M-ary quadrature amplitude modulation (MQAM) systems, $\xi_M \cong 3(\sqrt{M}-1/\sqrt{M}+1)$ for $M \geq 4$ [10].

From (7), (8), and (9), the energy consumption to transmit an information bit in a transmission attempt, $E_0 = (E_s+E_c)L_s/L$ can be represented as

$$E_0 = \frac{L+L_0}{L}\frac{\gamma_b \xi_M N_0 G_d}{\eta} + \frac{\beta}{R_b}, \tag{10}$$

where $G_d = G_1 d^\kappa M_l$ and $R_b = R_s L/L_s$ is the net bit rate of the uncoded information bits.

The total energy consumption to successfully transmit an information bit from the transmitter to the receiver is then

$$E_t = \frac{1}{1-\text{FER}}\left[\frac{L+L_0}{L}\frac{\gamma_b \xi_M N_0 G_d}{\eta} + \frac{\beta}{R_b}\right]. \tag{11}$$

Finally, the EE can be obtained from the inverse of E_t as

$$\eta_{\text{EE}} \triangleq \frac{1}{E_t} = \frac{1-\text{FER}}{\frac{L+L_0}{L}\frac{\gamma_b \xi_M N_0 G_d}{\eta} + \frac{\beta}{R_b}}. \tag{12}$$

C. Trade-off Configuration between SE and EE

For the SE and EE, it exists a trade-off between the two efficiency metrics. To achieve a larger SE, it is better for the transmitter to ensure the successful transmission probability of each frame by utilizing spectrum efficiently, which however requires more energy support, causing smaller EE. It can be shown from (6) that with larger received γ_b at receiver, the frame can be more successfully detected, causing smaller FER, which gives larger η_{SE}; however, to provide the larger γ_b, it requires more energy consumption at the transmitter, which can cause larger E_t, and thus results in a smaller EE.

In this paper, instead of maximizing SE or EE, without considering the other one, we do the general trade-off configuration between SE and EE to fit for various scenarios and different requirements for both SE and EE. A new metric SEE (Spectral/Energy Efficiency) is proposed and defined as

$$\eta_{\text{SEE}} \triangleq \eta_{\text{SE}}^{1-\lambda}\eta_{\text{EE}}^{\lambda} = \eta_{\text{SE}}^{1-\lambda}/E_t^{\lambda}, \tag{13}$$

where λ is the weight represents the preference of SE and EE, satisfying $0 \leq \lambda \leq 1$. It can be seen that maximizing the new metric η_{SEE} will increase η_{SE} or reduce energy consumption E_t, thus achieve a balanced trade-off between the SE and EE. Besides, it is general and can be simply reduced to considering only the maximization of SE or EE for different scenario requirements. When only maximizing EE, the λ can be set to 1, and vice versa. Furthermore, the new metric provides different adjustable weight λ for SE and EE, to make it general for numerous applications with different requirements of SE and EE. Combining (6), (12), and with some calculations, η_{SEE} is expressed as

$$\eta_{SEE} = (1-\text{FER})\frac{L}{L+L_0}\left(A\gamma_b + \frac{L}{L+L_0}B\right)^{-\lambda} C^{1-\lambda}, \tag{14}$$

where $A = (\xi_M N_0 G_d)/\eta$, $B = \beta/R_b$, and $C = (r log_2 M)/(1+\alpha)$.

The new metric η_{SEE} relies on a number of system parameters, including E_b/N_0 at the receiver (denoted as γ_b), the number of information bits L in each frame, the information transmission modulation and coding scheme, and the FER which inherently depends on all the above parameters, with the weight coefficient λ to adjust weights between SE and EE.

In (14), we can see that γ_b has two opposite effects on η_{SEE}. On one hand, FER is a decreasing function of γ_b, giving $(1-\text{FER})$ increase with γ_b, which shows the positive relationship between γ_b and η_{SEE}. However, on the other hand, $(A\gamma_b + BL/(L+L_0))^{-\lambda}$ monotonically decrease with γ_b. Therefore, increasing γ_b will reduce η_{SEE}. The similar observation is applied for the relationship between η_{SEE} and L. Therefore, it is critical to determine the optimum values of γ_b and L to maximize η_{SEE}, thus achieving the configurable balanced trade-off between SE and EE.

III. OPTIMUM SYSTEM DESIGN

In this section, the optimum system design with respect to η_{SEE} under the constraints of fixed L_0, R_b, and a chosen modulation and coding scheme is analyzed.

From (14), it can be seen that the analysis of η_{SEE} relies on the FER expression, which is a function of many system parameters. It shows that the FER for numerous modulation and coding schemes in block fading channel can be represented as [12]

$$\text{FER} \cong 1 - \exp\left(-\frac{\gamma_\omega}{\gamma_b}\right), \tag{15}$$

where γ_b is the received average E_b/N_0 at receiver, and γ_ω is a threshold value which can be calculated as

$$\gamma_\omega \cong k_M \log(L+L_0) + b_M, \tag{16}$$

where k_M and b_M are determined by the transmission modulation and channel coding schemes. It is shown in [12] that (15) and (16) provide very accurate approximations for a large range of modulation and channel coding schemes. The modulation schemes include MQAM, and the channel coding schemes including convolutional codes with different coding rates, generator polynomials, and constraint lengths; turbo codes; and low-density parity-check (LDPC) codes. For instance, when a quadrature phase-shift keying (QPSK) modulation scheme and a convolutional code with coding rate $r = 1/2$, generator polynomial $[171, 133]_8$, and a constraint length 7 is chosen, there is $k_M = 0.209$ and $b_M = 0.207$. The complete table of k_M and b_M for various modulation and channel coding schemes can be seen in [12].

A. Optimum γ_b

The optimum value of γ_b that maximizes η_{SEE} is studied in this subsection.

Lemma 1: The optimum γ_b which maximizes η_{SEE} to achieve a balanced trade-off between SE and EE for a communication system in block fading channel is

$$\hat{\gamma}_b = \frac{1}{2\lambda}\left(\gamma_\omega + \sqrt{\gamma_\omega^2 + 4\lambda\gamma_\omega \frac{B}{A}\frac{L}{L+L_0}}\right), \tag{17}$$

where $A = (\xi_M N_0 G_d)/\eta$ and $B = \beta/R_b$.

Proof: Substituting (15) into (14), and with some simplifications, η_{SEE} can be represented as

$$\eta_{\text{SEE}}=\exp\left(-\frac{\gamma_\omega}{\gamma_b}\right)\frac{L}{L+L_0}\left(A\gamma_b+\frac{L}{L+L_0}B\right)^{-\lambda}C^{1-\lambda}. \quad (18)$$

Setting $\partial\eta_{\text{SEE}}/\partial\gamma_b=0$ and with the facts that $\exp(\gamma_\omega/\gamma_b)>0$, $(L+L_0)/L>0$, $C^{\lambda-1}>0$, and $(A\gamma_b+BL/(L+L_0))^{\lambda-1}>0$, there is

$$\lambda A-\frac{\gamma_\omega}{\gamma_b^2}\left(A\gamma_b+\frac{L}{L+L_0}B\right)=0. \quad (19)$$

With some investigations, (19) can be rewritten as

$$\lambda\gamma_b^2-\gamma_\omega\gamma_b-\gamma_\omega\frac{L}{L+L_0}\frac{B}{A}=0, \quad (20)$$

which is a quadratic function with two solutions. By omitting the negative solution since $\gamma_b>0$, there is the unique solution of γ_b shown in (17). Note that the solution of γ_b in (17) can be global maximum or minimum. However, since $\lim_{\gamma_b\to 0}\eta_{\text{SEE}}=0$, the γ_b in (17) gives global maximum η_{SEE}. ■

It should be mentioned here that the obtained γ_b is the average E_b/N_0 at the receiver. The required transmission symbol energy at the transmitter can then be obtained with (7) and (8), gives

$$\hat{E}_s=\hat{\gamma}_b\times rN_0\log_2 M\times G_d, \quad (21)$$

where $\hat{\gamma}_b$ is the optimum value calculated from (17).

B. Optimum Length of Information Bits L

The optimum length of information bits L which maximizes the η_{SEE}, thus achieving the balanced trade-off between SE and EE are analyzed in this subsection.

Substituting (15) and (16) into (14), and with some simplifications, there is the function of η_{SEE} to L as

$$\eta_{\text{SEE}}=\exp\left(-\frac{b_M}{\gamma_b}\right)\frac{L}{(L+L_0)^{\frac{k_M}{\gamma_b}+1}}\left(A\gamma_b+\frac{L}{L+L_0}B\right)^{-\lambda}C^{1-\lambda}. \quad (22)$$

Lemma 2: The optimum L which maximize η_{SEE} to achieve a balanced trade-off between SE and EE for a communication system in block fading channel is

$$L=\frac{A\gamma_b+B-k_MA-\lambda B}{2k_M(A\gamma_b+B)}\gamma_bL_0 +\frac{\sqrt{(k_MA+\lambda B)^2+(A\gamma_b+B)^2+2(A\gamma_b+B)(Ak_M-\lambda B)}}{2k_M(A\gamma_b+B)}\gamma_bL_0, \quad (23)$$

where $A=(\xi_MN_0G_d)/\eta$ and $B=\beta/R_b$.

Proof: It is not easy to directly obtain the optimum L for the maximum η_{SEE} due to the complex expression of η_{SEE} to L. We set $\Psi=\log\eta_{\text{SEE}}$, which gives

$$\Psi=\log L-\left(\frac{k_M}{\gamma_b}+1\right)\log(L+L_0)-\lambda\left(A\gamma_b+\frac{L}{L+L_0}B\right)-(\lambda-1)\log C-\frac{b_M}{\gamma_b}.$$

Due to the monotonically increasing function of $y=\log x$ with $x>0$, the value of L which gives the maximum of Ψ also gives the maximum of η_{SEE}.

Setting $\partial\Psi/\partial L=0$ and with some calculations, then

$$(L+L_0)\left(\frac{k_M}{\gamma_b}-\frac{L_0}{L}\right)+\frac{\lambda BL_0}{A\gamma_b+\frac{L}{L+L_0}B}=0. \quad (24)$$

With some observations of (24), we further simplify it to

$$k_M(A\gamma_b+B)L^2+\gamma_bL_0(k_MA+\lambda B-A\gamma_b-B)L-AL_0^2\gamma_b^2=0, \quad (25)$$

which is a quadratic function gives two solutions. With the physical meaning of $L>0$, the unique solution of L is shown in (23). Note that the obtained optimum η_{SEE} with L in (23) could be global maximum or minimum. Since $\lim_{L\to 0}\eta_{\text{SEE}}=0$, the η_{SEE} obtained from (23) is thus global maximum, which concludes the proof. ■

C. Joint Optimum γ_b and L

In (17) and (23), the closed-form solution of γ_b is expressed as a function of the length of information bits L, and vice versa. Therefore, for a communication system with fixed values of either of the two system parameters, the optimum value of another one can be directly calculated. However, for a cognitive transmitter, which may has the capability to adjust both system parameters, where the joint optimization of γ_b and L is required.

To obtain the joint optimum values of γ_b and L, (17) and (23) can be treated as two system equations of the two parameters. However, due to the nonlinear functions of both (17) and (23), the solution is not easy to be directly obtained. An effective iterative algorithm has been developed to obtain the joint optimum values of γ_b and L as shown in Algorithm 1.

Algorithm 1 Iterative solution calculations for $\hat{\gamma}_b$ and $\hat{L}$

```
1: Input: System parameters L_0, R_b, d, η_A, M, α, β, weight
   λ for SE and EE, and convergence parameters ε_γ with ε_L.
2: Set an initial point γ'_b = +∞, L' = 10^6, γ̂_b = 0, and
   L̂ = 0.
3: Calculate A, B, and γ_ω.
4: while |γ̂_b − γ'_b| < ε_γ and |L̂ − L'| < ε_L do
5:     Set γ'_b ← γ̂_b and L' ← L̂,
6:     Calculate γ̂_b from (17),
7:     Calculate L̂ from (23).
8: end while
9: Output: γ̂_b and L̂.
```

IV. Numerical Results

Numerical results are presented in this section to demonstrate our closed-form solutions and algorithm for configurable SE and EE trade-off analysis. The system parameters are shown in Table 1. The channel coding is a rate $r=1/2$ convolutional code, generator polynomial $[171,133]_8$, and a constraint length 7, which is commonly utilized in space communications. To facilitate the results analysis and description, energy consumption per information bit E_t, which has the physical meaning, is utilized, to represent the energy efficiency η_{EE}, which satisfying $\eta_{\text{EE}} = 1/E_t$. Therefore, the larger of EE, the smaller of E_t.

In Figure 1, we first validate our closed-form solutions of γ_b in (17) and the length of information bits L in (23), by comparing simulation results with analytical results. The proposed metric η_{SEE} is plotted as a function of γ_b under various values of frame length $L+L_0$. The distance is $d = 100$ m. The η_{SEE} obtained from simulation results are plotted in lines, and the corresponding analytical results are marked in the Figure 1. It shows that our analytical results match well with the simulation results.

In Figures 2 and 3, the effects of weight λ for EE and SE are analyzed. The energy consumption per information bit E_t and spectral efficiency η_{SE} versus different frame length $L+L_0$ are plotted, with various weights of λ. The QPSK modulation scheme and previous described channel coding are chosen. The distance is set $d = 100$ m. When λ is set to 1, the maximization of η_{SEE} equals to the minimization of energy consumption E_t. It shows in Figure 2 that the minimum E_t is achieved; however, the cost is spectral efficiency that it also provides the minimum SE in Figure 3. With the decrease of λ, especially set λ to a small value, such as 0.1, the maximization of η_{SEE} will tend to maximize more spectral efficiency than energy efficiency. Figure 3 shows that the SE for $\lambda = 0.1$ is the largest; however, its corresponding energy consumption is also the largest, shown in Figure 2. Therefore, the results verify the trade-off between SE and EE.

Another advantage of our proposed maximization of η_{SEE} is obtaining the balanced trade-off between SE and EE. When setting $\lambda = 0.5$, the SE and EE are given the same priority. Comparing the results with that of $\lambda = 0.1$, huge energy savings is achieved while sacrificing medium SE. For instance, when $L + L_0 = 1000$ bits, the energy consumption E_t is decreased from -34.8 dB to -40 dB, while SE decreases from 0.71 bits/s/Hz to 0.48 bits/s/Hz. Therefore, 5.2 dB of E_t is gained while sacrificing only 1.7 dB of SE. At the same time, while comparing the results of $\lambda = 0.5$ with that of $\lambda = 1$, a huge SE is gained while sacrificing little energy consumption. For instance, when $L + L_0 = 1000$ bits, SE is increased by 61% while sacrificing only 0.18 dB of energy consumption. Furthermore, for users who prefer either more EE or more SE in various scenarios, the balanced trade-off can be achieved while

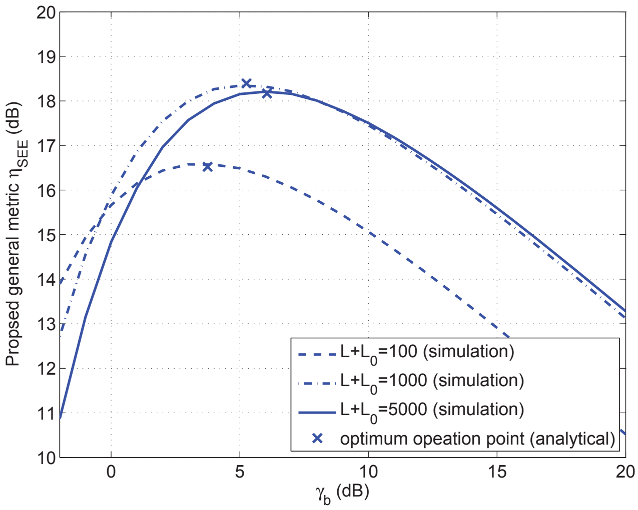

Fig. 1. Proposed general metric η_{SEE} v.s. average E_b/N_0 at the receiver γ_b.

TABLE I
SIMULATION SYSTEM PARAMETERS

Overhead bits L_0	48 bits
Bit rate R_b	300 kbps
Power amplifier drain efficiency η_A	0.35
Pulse shaping filter roll-off factor α	0.22
Baseband processing power β	310.014 mW
AWGN single-sided power spectral density $N_0/2$	-174 dBm/Hz
Transmission gain factor at a unit distance G_1	30 dB
Large scale path-loss exponent κ	3.5
Link margin compensating gain M_l	40 dB

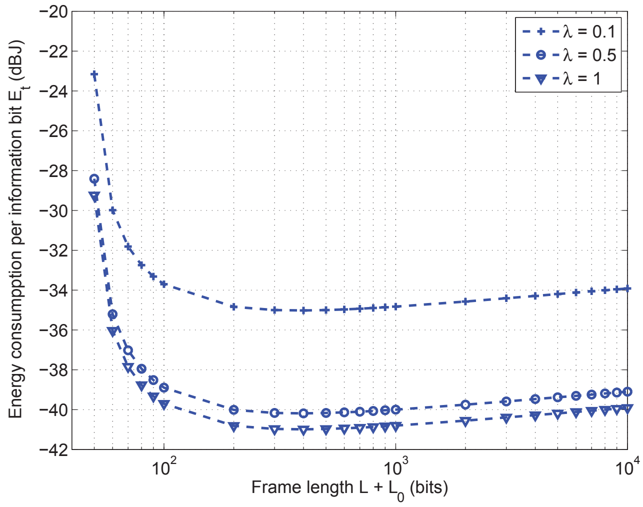

Fig. 2. Energy consumption per informaiton bit E_t v.s. frame length $L+L_0$ bits.

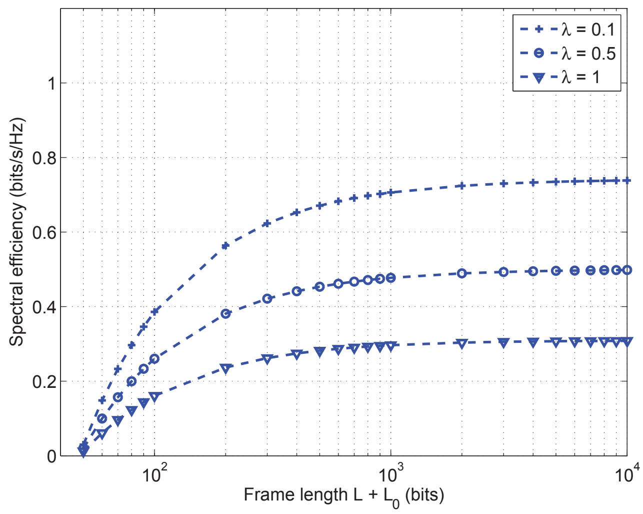

Fig. 3. Spectral efficiency η_{SE} v.s. frame length $L + L_0$ bits.

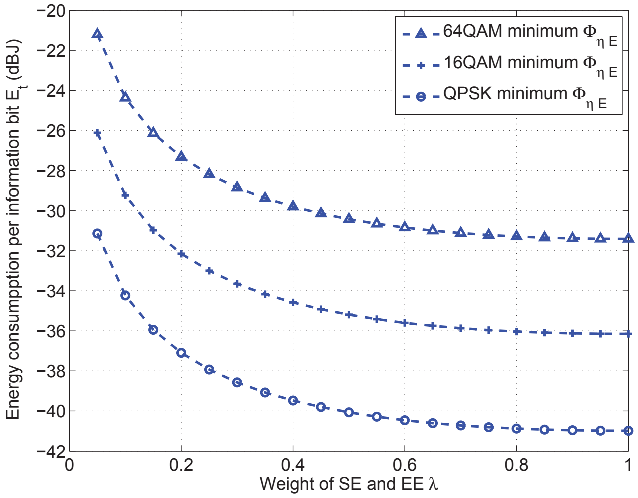

Fig. 4. Energy consumption per information bit E_t v.s. weight of SE and EE λ.

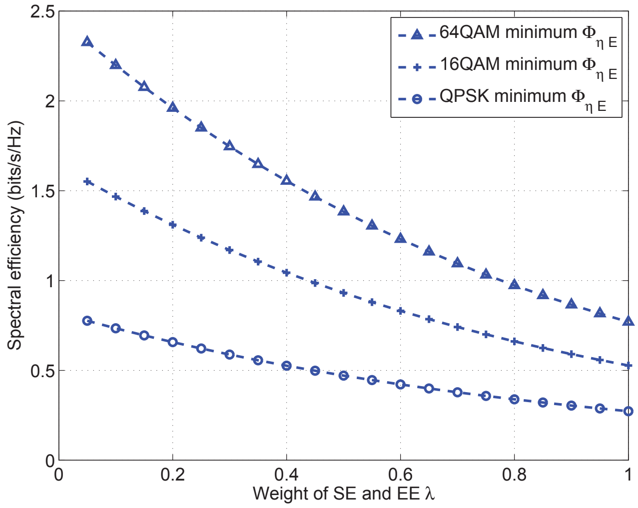

Fig. 5. Spectral efficiency η_{SE} v.s. weight of SE and EE λ.

easily tuning the weight λ value, such as if preferring more SE, the λ can be set to 0.8, or setting $\lambda = 0.2$ if preferring more EE.

In Figures 4 and 5, the performances of EE and SE for combination of various modulation and channel coding are analyzed. The energy consumption per information bit E_t and spectral efficiency η_{SE} versus different value of weight λ are plotted respectively, with different transmission waveforms. The distance is set $d = 100$ m. The E_t and η_{SE} are obtained with maximum η_{SEE} where joint γ_b and L are optimized with Algorithm 1. It shows that energy consumption E_t is reduced while increasing λ, since energy reduction is desired. However, at the same time, the SE is reduced due to this tendency. In addition, the larger of constellation size M, the larger spectral efficiency is shown in Figure 5; however, which also requires larger E_t. Therefore, with different requirements of SE and EE, an appropriate waveform could be selected at the cognitive transmitter, with the jointly optimized transmission symbol energy and the length of information bits.

V. Conclusions

The configurable balanced trade-off between spectral efficiency (SE) and energy efficiency (EE) for cognitive radios has been investigated in this paper. A general metric, η_{SEE}, has been proposed for the configurable balanced trade-off analysis. The weight for different preferment between SE and EE is introduced to facilitate the configuration. The closed-form solutions for optimum transmission symbol energy and the length of information bits are provided, which affords convenient cognitive radio configurations. The analytical and simulation results verified the trade-off between SE and EE. Also, our balanced trade-off analysis under the condition of different interests of SE and EE for various scenarios is demonstrated. When giving the equal interest of SE and EE, our scheme can achieve energy consumption reduction as large as 5.2 dB while sacrificing 1.7 dB of SE, compared with the maximization of SE; and at the same time, relating to energy consumption minimization case, a large SE can be increased by 61% while only sacrificing 0.18 dB of energy consumption.

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