Energy-Efficient Management of Cognitive Radio Terminals With Quality-Based Activation

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***Abstract*— In cooperative cognitive radio systems (CRSs), where battery-powered cognitive radio terminals (CTs) frequently sense and report primary user's (PU's) existence to exploit a spectrum hole, *energy efficiency* (EE) is a challenging design issue. To improve EE in CRSs, letting only some of the CTs be active in sensing and reporting [called a quality-based activation (QBA)] is proposed in this letter. With QBA, CTs that have good channel quality in a data channel (DCH) as well as a reporting channel (RCH) are allowed to sense and report. A possible drawback of such conditional activation is that it could limit the participation of CTs in a scheduling procedure, and hence, may result in losing certain system throughput. Throughput and EE of CRSs with the proposed QBA are investigated and it is shown, with numerical examples, that QBA does not decrease the throughput and provides significant improvement in EE.**

***Index Terms*— Cogntive radio system, energy efficiency, throughput.**

I. INTRODUCTION

IN COOPERATIVE cognitive radio system (CRS), battery-powered cognitive users sense a spectrum hole and report the results to a centralized fusion center known as cognitive base station (CBS) [1]. All the sensed results successfully received at CBS are combined and used to determine whether the spectrum is unoccupied [2]. When it is unoccupied, CBS feeds back which cognitive terminal (usually the best cognitive terminal (CT) in *so-called* greedy scheduling [3]) could actively use the spectrum. If the sensing is perfect, CRS could achieve the full diversity gain as the number of CTs increases [4]. In the CRS, "sensing and reporting" every time slot is however a big overhead in energy management of CT (CT is used interchangeably for cognitive terminals and cognitive transmitter in this letter). Letting only a part of CTs activated to sense and report, while the other CTs remain in a sleep mode, may improve the energy efficiency (EE) [5]. EE is considered as an important performance metric in wide areas of wireless communications research. For examples, a goal of [6] and [7] is to maximize EE in downlink orthogonal frequency division multiple access (OFDMA) systems and in wireless powered communication networks, respectively. In cooperative spectrum sensing, making a subset of sensors turn to a sleep mode and thus improving EE is known as a *node selection* approach [8]. However, an impact of the selection by relieving congestion in RCH to EE has been rarely studied.

A possible drawback of such selective activation is however that it could limit the participation of CTs in a scheduling procedure and may result in losing certain multi-user diversity gain and hence the system throughput. On the other hand, if taking the observation that too many reports could diminish the diversity gain by decreasing the number of successful reports due to congestion in reporting channel (RCH), a certain conditional activation scheme seems plausible [9], [10].

This letter proposes quality-based activation (QBA) of cooperative cognitive user (CU) pairs (consisting of CTs and cognitive receiver (CRs)), in which sensing and reporting is allowed only for CTs that have greater or equal values in the magnitude of two channels: data channel (DCH) and RCH compared to given thresholds, respectively. The contribution of QBA in improving EE is twofold: QBA lets a subset of CTs turn to a sleep mode and save the energy; and, at the same time, it reduces possible congestion in RCH and contributes to increasing throughput and hence improving EE. Throughput and EE of CRS with the proposed QBA are derived in terms of the thresholds. With numerical investigation, it is shown that QBA, compared with the every time "sensing and reporting" scheme, achieves more than 50% improvement in EE. Moreover, QBA also increases the throughput more than 30% since it prevents CTs from losing their reports by reducing traffic load in RCH.

II. SYSTEM MODEL

We consider a CRS that consists of a CBS and N pairs of cognitive user. $\mathrm{CT_i}$ acts as a sensing node and, if selected, a data transmitter for $\mathrm{CR_i}$ where $i = 1, 2, \ldots, N$. It is assumed that primary user (PU) with transmitting power P is either active or inactive with probability ϕ_1 and ϕ_0 ($\phi_1 + \phi_0 = 1$) during time T, respectively. Fig. 1 shows the system model along with a CRS time frame structure. Initially, during time t_c, CBS broadcasts beacon signals giving the time synchronization to CTs and requesting CTs to initiate sensing. CTs sense PU's activity during time t_s and then report the sensing result as well as their respective DCH quality to CBS over RCH in reporting time t_r. RCH is a random access channel and modeled as a direct-sequence/spread-spectrum multiple access (DS/SSMA) channel with coherent binary phase-shift keying (BPSK) modulation in the simulation [9]. During time t_p, CBS decides whether PU is present or not by the received sensing results and send the decision to CU pairs. We assume that the decision is based on a soft-scheme fusion rule [11]. In the soft scheme, CBS compares an averaged SNR (signal-to-noise ratio) obtained from the reports with a pre-defined threshold to make a final decision. Quality of the

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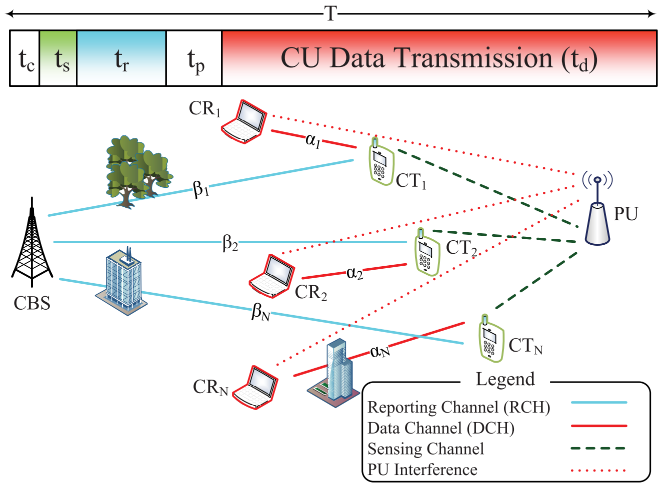

Fig. 1. System model and CRS time frame.

final decision is usually characterized in terms of the detection probability and the false alarm probability, which are denoted by $\mathcal{P}_d(L,\lambda)$ and $\mathcal{P}_f(L,\lambda)$, respectively. If PU is determined to be inactive, CBS allocates the vacant spectrum to a CU pair that has the best DCH quality based on greedy scheduling [3]. The allocation is informed to the CU user pair by CBS on a control channel (CCH) during time t_p. It is noted that the probability of selecting a cognitive user pair is $\phi_1(1-\mathcal{P}_d(L,\lambda))$ plus $\phi_0(1-\mathcal{P}_f(L,\lambda))$. The beacon signal from CBS, RCH and CCH are assumed to use an independent and non-overlapping spectrum that does not interfere with the PU network [12]. The selected CT transmits its data in DCH on PU's spectrum during time t_d. Therefore, the effective time $\bar{T}$ for the CRS to occupy the PU's spectrum is given by

$$\bar{T} = \frac{T-(t_c+t_s+t_r+t_p)}{T}. \tag{1}$$

A. Energy Efficiency (EE)

Let P^c be the circuit power consumed by an individual CT when listening to the beacon signal from CBS. Since all of the N CTs in the system should hear the beacon during t_c, the total energy consumption in this initial stage is NP^ct_c. Let P^s be the circuit power consumed while sensing the PU channel, P^r be transmitting power for sending the sensed result to CBS by an individual CT and let P^p be the processing power consumed at CT while receiving the decision on spectrum allocation by CBS. If $L(\leq N)$ CTs among N CTs sense and report the result during t_s and t_r, respectively, and hence listen to the CBS's decision during t_p, the total energy consumption in $t_s+t_r+t_p$ is $L(P^st_s+P^rt_r+P^pt_p)$. The data transmission from a selected CT is possible only when the PU channel is sensed to be idle. Let P^a be the transmitting power of the selected CT in its respective DCH. Thus, the total average energy consumption E at CTs during time T can be modeled by

$$\begin{aligned} E &= N(P^ct_c) + L(P^st_s+P^rt_r+P^pt_p) \\ &\quad + \Big[\phi_1(1-\mathcal{P}_d(L,\lambda)) + \phi_0(1-\mathcal{P}_f(L,\lambda))\Big]P^at_d. \end{aligned} \tag{2}$$

EE of a communication system is usually defined as a ratio of the achievable system throughput to the energy consumed [5], [8], [13]. For a given CRS throughput C (bps/Hz) to be defined in the following section, EE η is then obtained by

$$\eta = \frac{C}{E/T}, \quad \text{bit/Hz/Joule.} \tag{3}$$

B. CRS Throughput

Let γ_d^i be the instantaneous SNR received at CR$_\text{i}$ given as:

$$\gamma_d^i = \frac{|\alpha_i|^2P^a}{N_o}, \tag{4}$$

where $|\alpha_i|$ denotes instantaneous fading magnitude modeled as a random variable (RV) and N_0 is an identical noise-density at receivers. Let L be the number of CTs' reports successfully received at CBS. The instantaneous capacity with greedy scheduling, if PU is inactive is then expressed by

$$C_0 = \bar{T}\log_2\left(1+\gamma_{\max}^{(L)}\right), \tag{5}$$

where $\gamma_{\max}^{(L)} = \max\left[\gamma_d^1, \gamma_d^2, \ldots, \gamma_d^L\right]$. $\gamma_{\max}^{(L)}$ introduces a new RV. Let us assume that γ_d^i's are independent but not identically distributed (inid) and let $f_{\gamma_d^i}(x)$ be the probability density function (pdf) of γ_d^i. Then the pdf of $\gamma_{max}^{(L)}$ according to the order statistics is given by

$$f_{\gamma_{max}^{(L)}}(x) = \sum_{i=1}^{L} f_{\gamma_d^i}(x)\prod_{j\neq i}\mathcal{F}_{\gamma_d^j}(x), \tag{6}$$

where $\mathcal{F}_{\gamma_d^j}(x)$ denotes the cumulative distribution function (cdf) of γ_d^j. When PU is active but miss-detected, the DCH transmission by the selected best CU pair is interfered by PU's signal. Let p denote an index of the selected cognitive user pair and $|\sigma_p|$ denote the instantaneous fading magnitude between PU and CR$_\text{p}$. It is noted that $\gamma_{max}^{(L)}$ and $|\sigma_p|^2$ are independent RVs. Then the instantaneous capacity, when PU is miss-detected is expressed by

$$C_1 = \bar{T}\log_2\left(1+\frac{\gamma_{max}^{(L)}}{|\sigma_p|^2P/N_o+1}\right), \tag{7}$$

Then average CRS throughput C_L is then expressed as

$$\begin{aligned} C_L &= \phi_0(1-\mathcal{P}_f(L,\lambda))\left[\int_0^\infty C_0 f_{\gamma_{max}^{(L)}}(x)dx\right] + \phi_1 \\ &\quad \times(1-\mathcal{P}_d(L,\lambda))\left[\int_0^\infty\int_0^\infty C_1 f_{\gamma_{max}^{(L)}}(x)f_{|\sigma_p|^2}(y)dxdy\right], \end{aligned} \tag{8}$$

where $f_{|\sigma_p|^2}(y)$ denotes the pdf of $|\sigma_p|^2$.

The number of reports from CTs correctly received and hence available at CBS mainly depends on the offered load in RCH. Let ρ_L be the loss probability of a reporting packet when L CTs are transmitting in RCH and K be the length of reporting packet in bits. Then

$$\rho_L = 1-(1-P_e(L))^K, \tag{9}$$

where $P_e(L)$ denotes the probability of bit error and can be computed from [9, eq. (17)]. When L CTs are reporting, CRS throughput with loss probability is then obtained by

$$\begin{aligned} C_\rho = \sum_{i=0}^{L} \binom{L}{i} \rho_L^i (1-\rho_L)^{L-i} \Bigg[& \phi_0 (1 - \mathcal{P}_f(L-i,\lambda)) \\ & \cdot \left[\int_0^\infty C_0 f_{\gamma_{max}^{(L-i)}}(x) dx \right] + \phi_1 (1 - \mathcal{P}_d(L-i,\lambda)) \\ & \cdot \left[\int_0^\infty \int_0^\infty C_1 f_{\gamma_{max}^{(L-i)}}(x) f_{|\sigma_p|^2}(y) dx dy \right] \Bigg]. \end{aligned} \tag{10}$$

From (8) and (10), it is obvious that $C_\rho \leq C_L$.

III. Quality-Based Activation (QBA)

If too many CTs are activated and send their reports, not only the energy consumption but also the reporting loss probability increases. QBA could limit the number of activated CTs and improve the energy consumption as well the throughput. Let $|\beta_i|$ denote the instantaneous fading magnitude of the i^{th} CT's RCH. $|\beta_i|$ could be estimated by measuring the instantaneous SNR of the beacon signals from CBS received at $\mathrm{CT_i}$ and is given by

$$\gamma_c^i = \frac{|\beta_i|^2 P^{CBS}}{N_o}, \tag{11}$$

where P^{CBS} is CBS transmitting power for beacon signals. Let ξ_d and ξ_c be two engineering thresholds for DCH and RCH, respectively. QBA is then defined by a rule: a CT is activated (i.e. senses PU, reports on RCH and waits for the scheduling result) only if;

$$|\alpha_i|^2 \geq \xi_d \quad \text{and } |\beta_i|^2 \geq \xi_c. \tag{12}$$

The rationale behind QBA is:

- if $|\alpha_i|^2 < \xi_d$, $\mathrm{CT_i}$ could not be selected in scheduling and thus activation of $\mathrm{CT_i}$ results in wasting the energy as well as increasing the congestion in RCH;
- and if $|\beta_i|^2 < \xi_c$, the report from $\mathrm{CT_i}$ is likely to be lost since it should contend with other reports possibly on a stronger channel.

However, QBA certainly diminishes the multi-user diversity gain due to limiting the participation of CTs, which might decrease the system throughput unless ξ_d and ξ_c are adequately obtained.

A. CRS Throughput With QBA

When ξ_d and ξ_c are given and L CTs are assumed to be activated, the average CRS throughput, $C(L;\xi_d,\xi_c)$, is then expressed as

$$\begin{aligned} C(L;\xi_d,\xi_c) = \phi_0(1-\mathcal{P}_f(L,\lambda)) & \left[\int_{\xi_d P^a/N_o}^\infty C_0 f_{\gamma_{max}^{(L)}}(x) dx \right] \\ + \phi_1 & (1-\mathcal{P}_d(L,\lambda)) \\ & \times \left[\int_0^\infty \int_{\xi_d P^a/N_o}^\infty C_1 f_{\gamma_{max}^{(L)}}(x) f_{|\sigma_p|^2}(y) dx dy \right]. \end{aligned} \tag{13}$$

When $\xi_d = 0, \xi_c = 0$, $C(N;0,0) = C_N$ implies the average CRS throughput without QBA. The fusion rule as well as the order statistics in the throughput expression in (13) depends on the number of correctly received reports at the CBS.

When ξ_d and ξ_c are given, the number of active CTs L is also a RV. Let ρ_d^i and ρ_c^i be probabilities of the ith CT having DCH and RCH channel powers greater than or equal to ξ_d and ξ_c, respectively. That is,

$$\rho_d^i = \int_{\xi_d P^a/N_o}^\infty f_{\gamma_d^i}(x)\, dx \tag{14}$$

and

$$\rho_c^i = \int_{\xi_c P^{\mathrm{CBS}}/N_o}^\infty f_{\gamma_c^i}(x) dx, \tag{15}$$

where $f_{\gamma_c^i}(x)$ denotes the pdf of γ_c^i. Since γ_d^i and γ_c^i are SNRs of independent channels, $\rho_a^i = \rho_d^i \rho_c^i$ is the probability of the ith CT to be active. Let $\Lambda^{(L)}$ denote a set of indexes of L active CTs. Then there are $\binom{N}{L}$ possible combinations of $\Lambda^{(L)}$. Let $\Lambda_j^{(L)}$ denote the jth set among the combinations. Then the probability that L CTs are active is

$$P_{\mathrm{act}}(L) = \sum_{\text{all } j} \prod_{i \in \Lambda_j^{(L)}} \rho_a^i \prod_{i \in \Lambda_j^{(L)c}} (1-\rho_a^i), \tag{16}$$

where $\Lambda_j^{(L)^c}$ is the complement of $\Lambda_j^{(L)}$.

Now the average CRS throughput with QBA is given by

$$\begin{aligned} C_{\mathrm{QBA}}(\xi_d,\xi_c) = \sum_{L=1}^{N} & P_{\mathrm{act}}(L) \\ & \cdot \sum_{i=0}^{L} \binom{L}{i} \rho_L^i (1-\rho_L)^{L-i} C(L-i;\xi_d,\xi_c). \end{aligned} \tag{17}$$

C_{QBA} obviously depends on the screening thresholds ξ_d and ξ_c. In order to maximize C_{QBA}, it is important to find optimal values of the thresholds (i.e. ξ_d and ξ_c). With numerical investigation, we have shown that CRS throughput C_{QBA}^{opt} with optimal screening thresholds approaches to an ideal CRS throughput $C = C(N;0,0)$ for which every CT senses and sends its result to CBS and each report is assumed to be received successfully.

B. Energy Efficiency With QBA

Using $P_{\mathrm{act}}(L)$ in (16), the average energy consumption at CTs with QBA during time T, E_{QBA}, is given by

$$\begin{aligned} E_{QBA} = NP^c t_c + \sum_{L=1}^{N} \Bigg[P_{\mathrm{act}}(L) \Bigg(& L(P^s t_s + P^r t_r + P^p t_p) \\ & + [\phi_1(1-\mathcal{P}_d(L,\lambda)) + \phi_0(1-\mathcal{P}_f(L,\lambda))] P^a t_d \Bigg) \Bigg]. \end{aligned} \tag{18}$$

EE for CRS with QBA, η_{QBA}, is then obtained by

$$\eta_{\mathrm{QBA}} = \frac{C_{\mathrm{QBA}}}{E_{QBA}/T}, \quad \text{bit/Hz/Joule.} \tag{19}$$

IV. Numerical Results

For numerical investigation, instantaneous fading amplitude $|\alpha_i|$, $|\beta_i|$ and $|\sigma_p|$ are assumed to be iid Rayleigh RVs and an equal combining gain for the soft-scheme fusion rule is

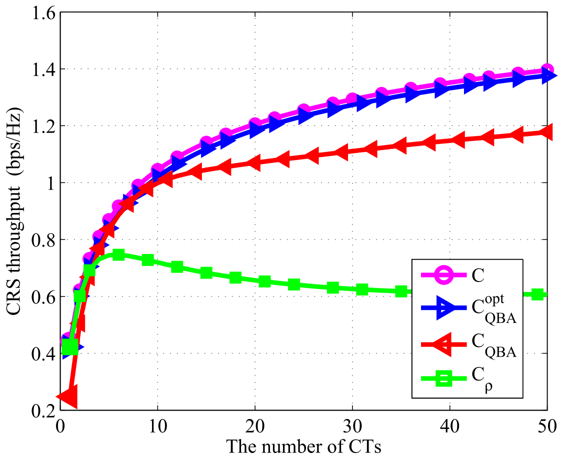

Fig. 2. CRS throughput versus the number of cognitive terminals.

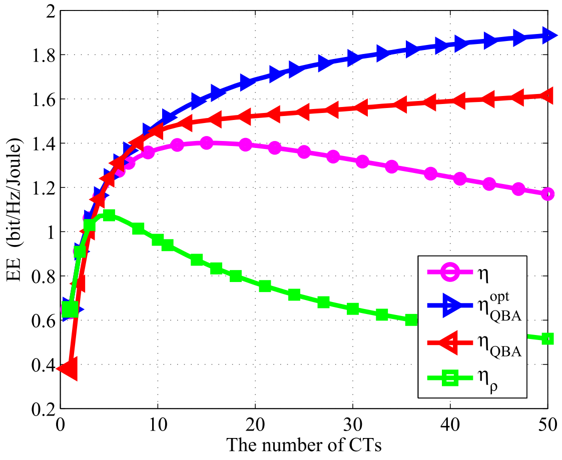

Fig. 3. CRS energy efficiency versus the number of cognitive terminals.

used [11]. For computing loss probability we set $K = 8$ with spreading factor 4 in RCH [9]. Power values were set as $P = 0.8W$, $P^{CBS} = 0.25W$, $P^c = P^s = P^p = 0.01W$, $P^c = 0.01W$, $P^a = 0.5W$, $N_o = 10^{-13}W$. $T = 3ms$, $t_s = 0.15ms$, $t_r = 0.2ms$, $t_c = t_p = 0.002ms$ for time values and $\phi_1 = 0.2$ for PU's activity are assumed. In the simulation, the probability of detection is maintained as $\mathcal{P}_d(L, \lambda) = 0.9$ by adjusting λ [14].

Fig. 2 shows CRS throughput for increasing N. Optimal values of screening thresholds ξ_d and ξ_c for C_{QBA}^{opt} are found by exhaustive searches. For example, when $N = 20$, optimal QBA thresholds for DCH $\xi_d = 0.0798$ and RCH $\xi_c = 0.05$ are numerically achieved, which gives $\rho_a = 0.2952$. For C_{QBA}, fixed values $\xi_d = 0.21$ and $\xi_c = 0.01$ are used for varying number of N. For $N \geq 4$, C_{QBA}^{opt} and C_{QBA} achieve greater throughput compared to C_ρ. More precisely it can be seen that for $N \geq 10$, C_{QBA} and C_{QBA}^{opt} get more than 30% and 40% increase in throughput compared to C_ρ, respectively. Moreover, as N increases C_{QBA}^{opt} approaches to the ideal throughput C for which all the CTs are assumed to sense and report without reporting loss.

Fig. 3 shows EE corresponding to the throughput depicted in Fig. 2. η, η_{QBA}^{opt}, η_{QBA} and η_ρ correspond to C, C_{QBA}^{opt}, C_{QBA} and C_ρ, respectively. At a moderate value of N, EE starts to decrease in η and η_ρ since the energy consumption is proportional to the number of CTs and furthermore the throughput of C_ρ decreases as shown in Fig. 2. However, QBA (in η_{QBA} and η_{QBA}^{opt}) gives much better EE compared to the others. QBA increases EE as N increases since the number of CTs activated are limited depending on the screening thresholds but QBA still enjoys multi-users diversity. It is noted that η_{QBA}^{opt} as well as η_{QBA} attains significant improvement in EE compared to η that is obtained from the ideal throughput. Furthermore, it can be seen from Fig. 3 that for $N \geq 11$, η_{QBA} and η_{QBA}^{opt} provide more than 50% and 60% increase in EE compared to η_ρ, respectively.

V. CONCLUSION

The proposed QBA limits the number of activated CTs by measuring the DCH and RCH channel quality in order to preserve the multi-user diversity and hence the CRS throughput. Numerical investigation shows that QBA provides significant improvement in EE (more than 50%) as well as throughput (more than 30%), compared with the every time "sensing and reporting" approach. When a large number of battery-powered CTs are involved in communication like in Internet-of-Things applications, QBA is a promising approach.

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