Access Strategy for Hybrid Underlay-Overlay Cognitive Radios With Energy Harvesting

Muhammad Usman and Insoo Koo, *Member, IEEE*

***Abstract*— In this paper, we consider a hybrid underlay-overlay cognitive radio with energy harvesting. In the considered system, secondary user can harvest energy from the primary user's signal as well as from the other ambient sources, such as solar, wind, vibration and so on. Energy is harvested from the primary user's signal when the primary channel is found in busy state. The secondary user either operates in one of the two transmission modes; overlay and underlay in order to maximize the throughput, remains in the sleep mode in order to conserve energy, or harvests energy from the primary channel in order to maximize the remaining energy. To maximize long-term throughput of the system, we propose an access strategy in which the partially observable Markov decision process framework is used to determine action of the secondary user, and energy threshold is used to determine the transmission mode (overlay or underlay) of secondary user. Simulations show that for certain values of the system parameters, the considered system provides 60% improved throughput than overlay-only cognitive radio and 43% enhanced throughput than a hybrid cognitive radio system harvesting energy only from the ambient sources. However, increasing the throughput also increases computational burden on the secondary user, which may increase latency and energy requirements of the system.**

***Index Terms*— Access strategy, cognitive radio, energy harvesting, hybrid cognitive radio, POMDP, primary channel energy harvesting.**

I. Introduction

BANDWIDTH demand for limited spectrum has been greatly increasing in recent years due to the growing number of wireless devices and services. The problem of spectrum scarcity is further worsened by the inefficient utilization of the fixed allocation of spectra. According to the Federal Communications Commission (FCC), spatial and temporal variations in the utilization of the assigned spectrum range from 15% to 85% [1], [2].

Cognitive radio is a communication paradigm conceived to cope up with the looming spectrum problem: it allows non-licensed users, also known as secondary users (SU), to opportunistically use a spectrum that is primarily allocated to licensed users, also known as primary users (PU) [3]. Cognitive radio efficiently uses scarce spectrum by adopting an overlay or underlay transmission mode without causing harmful interference to the primary user [7], [12]. In the overlay transmission mode, SUs exclusively and opportunistically use a spectrum when it is not used by the PU. Whereas, in the underlay mode, PU is in a limited 'friendly' state which allows SU to coexist with PU, as long as the interference caused by SU remains below a certain threshold, called the "interference temperature".

We assume that the SU is equipped with a rechargeable energy harvested finite capacity battery. In addition to replenishing energy from other ambient sources such as wind, solar, vibration, and others [13], we also consider scavenging energy from the primary channel [9]. To the best of our knowledge, this is the first time that harvesting energy from the primary channel, as presented in this paper, has been considered in spectrum access. Although the amount of energy harvested from the primary channel is very small, it is still sufficient to operate the device in sleep mode because an active sensor consumes 34mW but in the sleep mode it consumes only 0.4mW [15]. So at least the energy consumed in sleep mode is compensated by the energy harvested from the wireless primary channel. Energy is harvested stochastically from the primary channel as well as from other ambient energy sources. Energy harvesting from the primary channel occurs when the channel is busy. Energy is consumed during spectrum sensing, subsequent processing and transmission of the data. A small amount of energy is also consumed in sleep mode. If the SU does not have enough energy or an energy outage may occur in the near future, the SU refrains from transmission.

In [12], a statistical analysis of the past-sensed data of PU is used for the access strategy. However, the decision of accessing a mode does not consider energy of the SU. Occasional switches from overlay to underlay mode are considered in [7] in order to achieve stable SU transmission. However, switching is probabilistically controlled and is not based on sensing results. Energy harvesting with few sensing observations is considered in [6]. Energy harvested in a sensor node with a finite data buffer is studied in [11]. In [10] variable sensing time and a stationary Markovian process is used to switch between idle and active states. In all these works, only the overlay transmission mode is considered.

Our focus in this work is to take advantage of the waiting time of the SU. Typically when the PU occupies a channel, the SU is restricted from transmission and has to wait until the PU stops its transmission. The waiting time of SU can be used in two ways: First to allow the SU to continue its transmission

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The authors are with the School of Electrical and Computer Engineering, University of Ulsan 680-749, Korea (e-mail: usman@nwfpuet.edu.pk; iskoo@ulsan.ac.kr).

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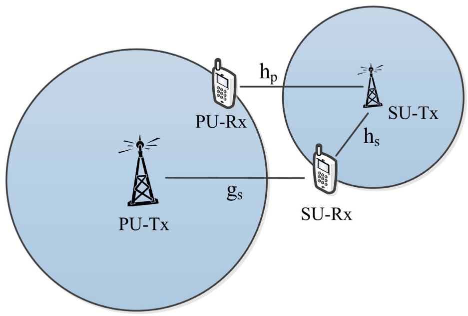

Fig. 1. System model.

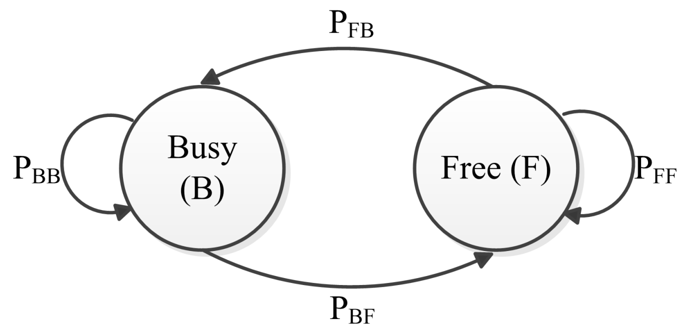

Fig. 2. Markov channel model.

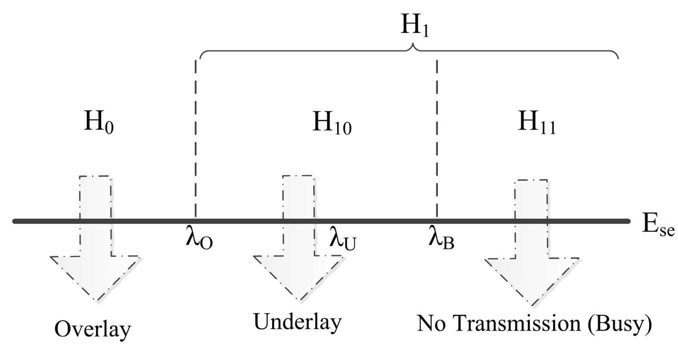

Fig. 3. Sensing energy thresholds for the proposed strategy where λ_O is the overlay sensing energy threshold, λ_U is the underlay sensing energy threshold, and λ_B is the underlay maximum sensing energy threshold and E_{se} is the signal energy.

in underlay mode with controlled power if the interference generated is under a certain threshold. Second if the generated interference exceeds the threshold, then instead of just waiting, the SU can harvest energy from the PU signal. So the SU is always busy either transmitting in overlay/underlay mode, or replenishing energy from the primary channel.

We assume that the SU operates in a time slotted manner. In each time slot, of duration T, the SU starts by deciding optimally to sense the channel or to stay idle, based on the available energy and belief about the inactivity of the PU. The Partially Observable Markov Decision Process (POMDP) framework is used for action selection. After the spectrum sensing, energy thresholds and required transmission energy are considered for mode selection and transmission. The SU transmits in hybrid mode (overlay-underlay) to achieve the maximum throughput and maintain the quality of service (QoS) of the PU at the same time.

The remainder of the paper is outlined as follows. First, in Section II, the system model is described, which consists of energy harvesting and throughput calculations. In Section III, we present our proposed access strategy using POMDP. Simulations results and their discussion are presented in Section IV. Finally the paper is concluded in Section V.

II. System Model

We consider a secondary transmitter-receiver pair which operates in the coverage area of primary network as shown in Fig. 1. In each time slot, the SU first decides which action to take: to sense the channel or to stay idle. Whenever it chooses to sense the channel, the SU uses an energy detection technique for spectrum sensing. The channel may be found in one of the two states, free (F) or busy (B), which is modelled by a two state Markov chain as shown in Fig. 2. The channel state corresponds to the PU activity. That is, state F indicates that the PU is silent/inactive whereas, state B indicates the presence of the PU. The transition probability from state F to itself is denoted by p_{FF} and from state B to state F is given by p_{BF}. We consider a positive correlation of the PU traffic [12], i.e. $p_{FF} > p_{FB}$ and $p_{BB} > p_{BF}$.

We assume that the secondary transmitter has certain information: the channel gain (h_s) between the secondary transmitter and the secondary receiver, the channel gain (h_p) between the secondary transmitter and the primary receiver, and the channel gain (g_s) between the primary transmitter and the secondary receiver [7]. All the channels suffer from Rayleigh fading gains, i.e channel gains are assumed to be *iid* (independent and identically distributed) exponential random variables with unit mean. The secondary receiver provides the channel state information (CSI) including the channel gain h_s as feedback to the transmitter [11]. The channel gain h_p can be obtained by taking advantage of the local oscillator leakage power or using a sensor node detector [14].

The SU harvests energy from the primary channel as well as from ambient sources as explained in the following subsection.

A. Energy Harvesting

We assume that a finite capacity rechargeable energy harvested battery (energy queue) is attached to each SU. SU has the capability to harvest packets of energy (e_p) from the primary channel when detected in state B and signal energy (E_{se}) is greater than the underlay maximum sensing energy threshold (λ_B), i.e. $E_{se} > \lambda_B$ as shown in Fig. 3.

$$e_p \in \mathrm{E}_p = \{e_1^p, e_2^p, \ldots, e_n^p\} \tag{1}$$

The energy harvested packets from the primary channel follow a Poisson process with mean $e_{p\mu}$. Then the probability distribution of the energy is given below

$$\Pr(e_p = i) = e^{-e_{p\mu}} \frac{(e_{p\mu})^i}{i!} \quad i = 1, 2, \ldots, n. \tag{2}$$

Similar to e_p, note that SU also harvests packets of energy (e_h) from other sources.

$$e_h \in \mathrm{E}_h = \{e_1^h, e_2^h, \ldots, e_m^h\} \tag{3}$$

The energy harvested packets from the other sources also follow a Poisson process with mean $e_{h\mu}$. Its probability distribution is given as

$$\Pr(e_h = j) = e^{-e_{h\mu}} \frac{(e_{h\mu})^j}{j!} \quad j = 1, 2, 3, \ldots, m. \tag{4}$$

The secondary transmitter adjusts its transmission energy according to the feedback (CSI) of the channel gain h_s provided by the secondary receiver.

$$h_s \in H_s = \left\{h_1^s, h_2^s, \ldots, h_K^s\right\} \quad h_1^s > h_2^s >, \ldots, > h_K^s. \tag{5}$$

Assuming that the channel gain follows a Poisson random variable with mean $h_{s\mu}$, we have

$$\Pr(h_s = k) = e^{-h_{s\mu}} \frac{(h_{s\mu})^k}{k!} \quad k = 1, 2, \ldots, K. \tag{6}$$

For higher channel gain less transmission energy (e_t) would be required which is given as

$$\begin{aligned} &e_t \in \mathrm{E}_t = \{e_1^t, e_2^t, \ldots, e_K^t\} \quad e_1^t < e_2^t <, \ldots, < e_K^t \\ &\Pr\left(e_t = e_k^t\right) = \Pr\left(h_s = h_k^s\right) \quad k = 1, 2, \ldots, K. \end{aligned} \tag{7}$$

At the beginning of a time slot, SU has some available energy (e_a), such that $0 < e_a \leq e_{max}$, where e_{max} is the maximum capacity of the battery. In case of staying idle, the energy consumed by SU in idle mode is e_i. If SU decides to sense the channel, it consumes the sensing energy (e_s). If SU is allowed to transmit with energy e_t, the updated energy (e') for the next slot becomes [8]

$$e' = \min[e_a + e_h + e_p - (e_t + e_s) - e_i, e_{\max}] \tag{8}$$

such that $e_t + e_s \leq e_a$, $e_t \leq e_{to}$ (in overlay mode) and $e_t \leq e_{tu}$ (in underlay mode), and $e_a + e_h + e_p \leq e_{max}$. e_{to} is the overlay transmission energy threshold and e_{tu} is the underlay transmission energy threshold.

The objective of our considered system and proposed access strategy is to improve throughput which is given in the following subsection.

B. Throughput Calculations

Successful transmission between the secondary transmitter and receiver occurs when there is no outage. The throughput of the SU is described in terms of the outage as [7]

$$C = 1 - p_{out} \tag{9}$$

where C is one of C_O, the throughput in overlay mode, or C_U, the throughput in underlay mode and p_{Out} is the outage probability. The throughput in overlay mode, C_O, is given by

$$C_O = p_t(1 - p_f)(1 - p_{out}^O) + (1 - p_t)p_m(1 - p_{out}^{OI}) \tag{10}$$

where p_t is the probability that PU is idle, p_f is the probability of false alarm, p_{out}^O is the outage probability of the secondary link when there is no interference from PU, p_m is the probability of misdetection, and p_{out}^{OI} is the outage probability of the secondary link when there is interference from PU due to misdetection. p_{out}^O and p_{out}^{OI} can be calculated as follows

$$\begin{aligned} p_{out}^O &= \Pr[\log_2(1 + h_s P_s^O) < R_s] \\ &= 1 - \exp(-\frac{2^{R_s} - 1}{P_s^O}) \end{aligned} \tag{11}$$

where R_s is the required data rate of secondary link and P_s^O is the transmission power of SU in overlay mode.

$$\begin{aligned} p_{out}^{OI} &= \Pr[\log_2(1 + \frac{h_s P_s^O}{1 + g_s P_p}) < R_s] \\ &= 1 - \frac{\exp(-\frac{2^{R_s}-1}{P_s^O})}{1 + \frac{2^{R_s}-1}{P_s^O} P_p} \end{aligned} \tag{12}$$

where P_p is the peak transmit power of primary link.
The throughput in underlay mode, C_U, is given as

$$C_U = p_t p_f(1 - p_{out}^U) + (1 - p_t)(1 - p_m)(1 - p_{out}^{UI}) \tag{13}$$

where p_{out}^U is the outage probability of the secondary link when the SU switches to underlay by false alarm and p_{out}^{UI} is the outage probability in underlay when the PU is actually present. Similarly, p_{out}^U and p_{out}^{UI} can be calculated as follows.

$$\begin{aligned} p_{out}^U &= \Pr\left[\log_2(1 + h_s P_s^U) < R_s\right] \\ &= \left(1 - \exp\left(-\frac{I_T}{P_{s,\max}}\right)\right)\left(1 - \exp\left(-\frac{2^{R_s} - 1}{P_{s,\max}}\right)\right) \\ &\quad + \exp\left(-\frac{I_T}{P_{s,\max}}\right) - \frac{\exp\left(-\frac{I_T}{P_{s,\max}}\left(1 + \frac{2^{R_s}-1}{I_T}\right)\right)}{1 + \frac{2^{R_s}-1}{I_T}} \end{aligned} \tag{14}$$

where P_s^U is the transmission power of SU in underlay mode, I_T is the interference temperature, and $P_{s,max}$ is the maximum transmit power of SU.

$$\begin{aligned} p_{out}^{UI} &= \Pr\left[\log_2\left(1 + \frac{h_s P_s^U}{1+g_s P_p}\right) < R_s\right] \\ &= \left(1 - \exp\left(-\frac{I_T}{P_{s,\max}}\right)\right)\left(1 - \frac{\exp\left(-\frac{2^{R_s}-1}{P_{s,\max}}\right)}{1 + \frac{P_p}{P_{s,\max}}(2^{R_s} - 1)}\right) \\ &\quad + \exp\left(-\frac{I_T}{P_{s,\max}}\right) - \frac{\exp\left(\frac{1}{P_p} - \frac{I_T}{P_p(2^{R_s}-1)}\right) I_T}{P_p(2^{R_s} - 1)} \\ &\quad \times E_1\left(\frac{(I_T + 2^{R_s} - 1)(P_{s,\max} + P_p(2^{R_s} - 1))}{P_{s,\max} P_p(2^{R_s} - 1)}\right) \end{aligned} \tag{15}$$

where E_1 is the exponential integral function.

III. Proposed Access Strategy Using POMDP

We propose an access strategy that uses predefined energy thresholds to determine the transmission mode (overlay or underlay) and uses POMDP framework to determine an optimal action. The main goal of this work is to enhance throughput of the SU. Even though it may also increase computational complexity and energy requirements, however the availability of energy efficient and highly computational units will lessen the problem.

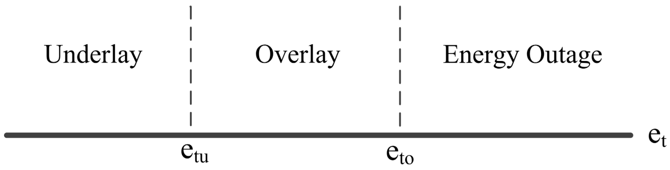

Fig. 4. Transmission energy thresholds for the proposed strategy where e_{tO} is the overlay transmission energy threshold, e_{tu} is the underlay transmission energy threshold, and e_t is the required transmission energy.

As stated above, SUs determine the transmission mode based on the spectrum sensing result and predefined energy thresholds. Let E_{se} be the signal energy and λ_O and λ_U be the predefined overlay sensing energy threshold and underlay sensing energy threshold, respectively, and λ_B be the underlay maximum sensing energy threshold. The value of λ_O is determined so as to satisfy the required detection probability. On the other hand, the value of λ_U can have any value between λ_O and λ_B. The value of λ_B can be chosen experimentally by observing the throughput according to λ_U between λ_O and 1, and finding a certain value of λ_U above which the throughput does not improve further. For example, when the target detection probability p_d is 0.87, the value of λ_O is set to 0.3 based on (17). To set λ_B, we observe the throughput as λ_U is changed from 0.3 to 1 as like Fig. 8. In this case, the value of λ_B can be set to 0.76 since the throughput does not increase with a further increase in λ_U after 0.76. Finally, λ_U can have any value between 0.3 and 0.76. As shown in Figs. 3 and 4, if the signal energy is below the overlay sensing energy threshold, i.e. $E_{se} < \lambda_O$, and the required transmission energy is also below the overlay transmission energy threshold, i.e. $e_t < e_{to}$, then the SU will transmit in overlay mode. However, if energy of the signal is above the overlay sensing energy threshold but lower than the underlay sensing energy threshold, i.e. $\lambda_O < E_{se} < \lambda_U$ and further, the required transmission energy is also below the underlay transmission energy threshold, i.e. $e_t < e_{tu}$, then SU will adopt the underlay transmission mode. Notice that to keep the interference caused by SU in the underlay mode below the interference temperature, the underlay transmission energy threshold is kept below the overlay transmission energy threshold, i.e. $e_{tu} < e_{to}$. Transmission power of the SU in underlay mode is given as

$$P_s^U = \begin{cases} P_{s,\max}, & h_p \le \frac{I_T}{P_{s,\max}} \\ \frac{I_T}{h_p}, & h_p > \frac{I_T}{P_{s,\max}} \end{cases} \tag{16}$$

The transmission power of SU in underlay mode is immediately adjusted to the interference channel gain (h_p) in order to keep the interference below the interference temperature (I_T). If the signal energy is greater than the underlay maximum sensing energy threshold, i.e. $\lambda_B < E_{se}$, then the channel is in state B, meaning that SU is not allowed to transmit, and the SU will harvest energy from the channel. If the channel is determined to be free but the required transmission energy is above the overlay transmission energy threshold, i.e. $e_t > e_{to}$, then SU will refrain from transmission to evade the energy outage problem.

In order to transmit, the SU must first determine whether the PU is present or absent by consuming sensing energy in the sensing time (τ). Under the binary hypothesis test and Neyman-Pearson (NP) criteria, H_0 means that the PU is absent (the channel is free and there is an opportunity for overlay transmission), and H_1 means PU is present (the channel is busy but there may be an opportunity for underlay transmission). To allow SU to transmit in underlay mode, underlay sensing energy threshold λ_U is used to divide H_1 into two subsections: H_{10} (underlay transmission) and H_{11} (no transmission) as shown in Fig. 3.

The detection performance of SU is determined by the probability of detection (p_d) and the probability of false alarm (p_f). Correct detection of the primary signal protects the QoS of PU, whereas the false alarm, i.e. PU is actually absent but reported as present, results in a wasted opportunity for the SU to make a transmission. To maintain the QoS of the PU, the probability of detection is fixed as defined in IEEE 802.22. The relationship between p_d, and the overlay sensing energy threshold, λ_O, is given below

$$p_d = Q_M\left(\sqrt{2\beta}, \sqrt{\lambda_O}\right) \tag{17}$$

where Q_M is the Marcum Q-function and β is the signal-to-noise (SNR) of the primary signal measured at the SU. For a fixed detection probability, the probability of a false alarm is a function of the sensing time [4] and is given by

$$p_f(\tau) = Q\left(\sqrt{2\beta+1}\,Q^{-1}(P_d) + \sqrt{\tau}\beta\right) \tag{18}$$

where $Q(.)$ is the complementary distribution function of a standard Gaussian variable. Based on the sensing result, if the channel status is H_0 or H_{10}, SU would transmit data in the remaining time slot (T$-\tau$) by adopting either the overlay or underlay mode respectively. H_0 may be obtained from the correct detection or misdetection of PU which is ensured by an ACK signal from the concerned secondary receiver. Similarly H_{10} may also be obtained either correctly or incorrectly (misdetection) which is confirmed by an ACK signal from the receiver.

At the start of each time slot, based on the previous actions and observations, SU has a belief, p_t, about the channel that it is in state F which can also be described as the idle probability of the primary channel. Depending on the belief and available energy, SU takes an optimal action using POMDP and further updates its belief, energy, and other parameters for the next time slot. The action taken by SU may either be to stay idle (SI) or sense (S). The choice of action is driven by a reward or throughput. Selection of the action and transmission mode is shown graphically in the flow chart given in Fig. 5.

For every action $a_i(e_a, p_t, s) \in A = \{SI, S\}$ in the state space $s = \{B, F\}$, SU gets a reward $R(e_a, p_t, a_i)$. If SU decides to stay idle ($\tau = 0$), the reward (in fact a penalty because of no transmission) obtained is

$$R(e_a, p_t, SI) = 0. \tag{19}$$

Staying idle is beneficial for energy conservation but it wastes the opportunity for transmission, which has a negative impact

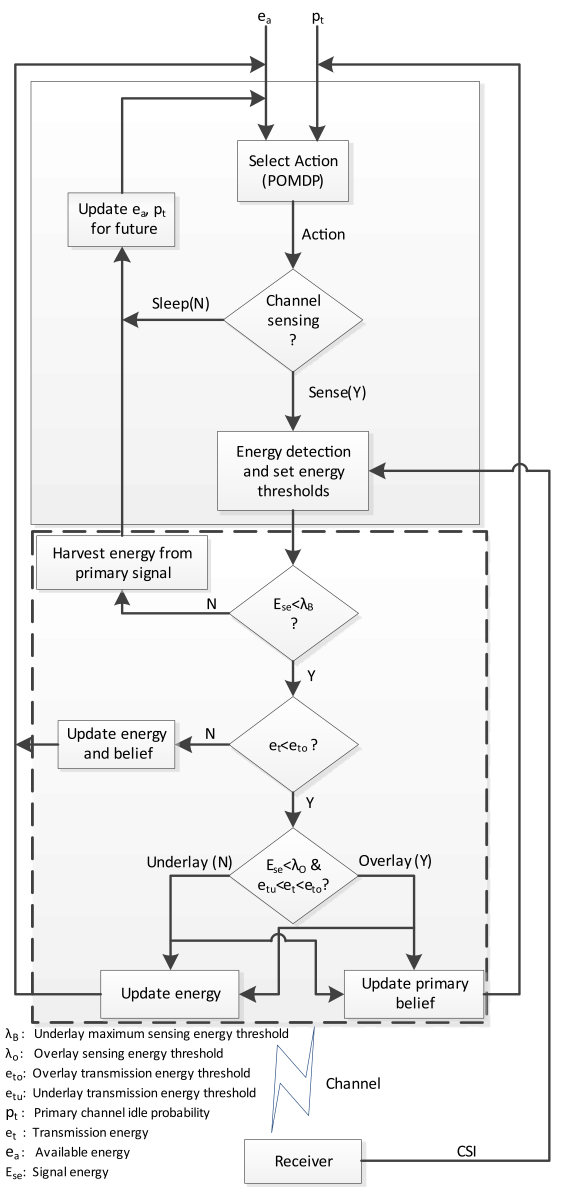

Fig. 5. Flow chart of the proposed access strategy.

on the throughput. On the other hand, SU will get the following reward when channel sensing ($\tau > 0$) is chosen.

$$R(e_a, p_t, S) = \frac{T-\tau}{T}C \tag{20}$$

where C is the throughput and its value is dependent on the observation. Spectrum sensing and transmission results in the consumption of energy but it increases the opportunity for the throughput. POMDP is used to take an action i.e. to stay idle or to sense the channel, which maximizes the throughput based on the available energy and primary network dynamics. Our objective is to maximize the discounted reward function in a particular time slot. In POMDP, the expected value of a policy or the maximum achievable reward function starting from the current slot is represented by the value function $V(e_a, p_t)$, and is given by

$$\begin{aligned} &V(e_a, p_t) \\ &= \min_{a_k, a_{k+1} \dots \varepsilon A} \mathrm{E}\left\{\sum_{n=k}^{\infty}\left(\gamma^{n-k} R(e_{an}, p_{tn}, a_n) | e_k = e_a, p_k = p_t\right)\right\} \\ &\qquad\qquad\qquad 0 \le \gamma < 1 \end{aligned} \tag{21}$$

where γ is the discount factor and is used to value the current reward more than future rewards. The value function satisfies the following Bellman equation and is solved by the value iteration method [5].

$$\begin{aligned} &V(e_a, p_t) = R(e_a, p_t, a_i) \\ &+ \left\{\sum_{e'}^{\infty} \gamma^{t-k} \sum_{i=1}^{7} \Pr(Z_i) \Pr(e_a \to e' | Z_i) V(e', p_{t+1}) | e_a, p_t\right\} \end{aligned} \tag{22}$$

where $\Pr(Z_i)$ is the probability of observation Z_i and $\Pr\left(e_a \to e^{'} | Z_i\right)$ is the transition probability from e_a to e' (updated energy state for the next slot) where $i = 1, 2, \dots, 7$.

When SU decides an action, one of the following observations may occur.

Observation 1(Z_1)**:** SU does not carry out spectrum sensing either due to insufficient energy or due to the SU's belief about the channel. An updated belief, p_{t+1}, that channel would be free in the next time slot is given as

$$p_{t+1} = p_t p_{FF} + (1 - p_t) p_{BF}. \tag{23}$$

SU does not get any reward, as it does not transmit in the idle mode. Therefore, we have

$$R(e_a, p_t, SI | Z_1) = 0. \tag{24}$$

The energy and transition probability, $\Pr\left(e_a \to e^{'} | Z_1\right)$, will be updated, respectively, as follows

$$\begin{aligned} &e' = e_a + e_h - e_i \\ &\Pr(e_a \to e' | Z_1) = \Pr\left(e_h = e_j^h\right) \quad j = 1, 2, \dots, m. \end{aligned} \tag{25}$$

The remaining energy is increased by e_h which increases the chances of spectrum sensing in the next slot (if PU is idle) to avail the opportunity of transmission in either of the modes.

Observation 2(Z_2)**:** SU decides to sense the channel consuming energy e_s in time τ, and finds the channel in state F. If $E_{se} < \lambda_o, e_t < e_{to}$, and SU transmission (in overlay mode) is successful in receiving an ACK signal from the receiver, the belief is updated as follows

$$p_{t+1} = p_{FF}. \tag{26}$$

In this case, SU gets a reward in the form of transmission as given below

$$R(e_a, p_t, S | Z_2) = \frac{T-\tau}{T} C_O. \tag{27}$$

The probability of observation-2 is computed as

$$\Pr(Z_2) = p_t(1 - p_f) \Pr(e_t \le e_{to}). \tag{28}$$

The updated energy and transition probability is given by

$$e' = e_a + e_h - e_s - e_t$$
$$\Pr(e_a \to e' \big| Z_2) = \Pr(e_h = e_j^h)\Pr(e_t = e_k^t) \tag{29}$$

where $j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, K$.

Observation 3 (Z_3)**:** This is similar to observation-2 except no ACK is received from the receiver, which implies that PU has been misdetected. The updated belief would become

$$p_{t+1} = p_{BF}. \tag{30}$$

Then SU gets the following reward

$$R(e_a, p_t, S|\, Z_3) = 0 \tag{31}$$

and the probability of observation-3 is given by

$$\Pr(Z_3) = (1 - p_t)(1 - p_d)\Pr(e_t \le e_{to}). \tag{32}$$

The updated energy and transition probability are computed, respectively, as

$$e' = e_a + e_h - e_s - e_t$$
$$\Pr(e_a \to e' \big| Z_3) = \Pr(e_h = e_j^h)\Pr(e_t = e_k^t) \tag{33}$$

where $j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, K$.

Observation 4 (Z_4)**:** SU senses the channel and finds it in state F, but the transmission energy is greater than the overlay transmission energy threshold, i.e. $e_t > e_{to}$, which may lead to an energy outage, therefore SU refrains from transmission and updates its belief along with energy. The updated belief state is given as

$$p_{t+1} = p_t^u p_{FF} + (1 - p_t^u)p_{BF} \tag{34}$$

where p_t^u is the posterior probability and is obtained by using Bayes' rule as below

$$p_t^u = \frac{p_t(1 - p_f)}{p_t(1 - p_f) + (1 - p_t)(1 - p_d)}. \tag{35}$$

The data transmitted is given by

$$R(e_a, p_t, S|\, Z_4) = 0. \tag{36}$$

The probability of observation-4 is computed as

$$\Pr(Z_4) = [p_t(1 - p_f) + (1 - p_t)(1 - p_d)]\Pr(e_t > e_{to}). \tag{37}$$

The updated energy and transition probability are obtained, respectively, as below

$$e' = e_a + e_h - e_s$$
$$\Pr(e_a \to e' \big| Z_4) = \Pr(e_h = e_k^h). \tag{38}$$

Observation 5(Z_5)**:** SU finds the channel in the busy state but SU can coexist with PU i.e. $\lambda_o < E_{se} < \lambda_u$. If the required transmission energy is also less than the underlay transmission energy threshold, i.e. $e_t < e_{tu} < e_{to}$, then SU transmits in underlay mode and receives ACK from the receiver updating belief for the next slot as

$$p_{t+1} = p_{BF}. \tag{39}$$

The reward in the form of data transmitted is given by

$$R(e_a, p_t, S|\, Z_5) = \frac{T - \tau}{T} C_U. \tag{40}$$

The probability of observation-5 is computed as

$$\Pr(Z_5) = (1 - p_t)(p_d)\Pr(e_t \le e_{tu}). \tag{41}$$

The updated energy and transition probability are given, respectively, by

$$e' = e_a + e_h - e_s - e_t$$
$$\Pr(e_a \to e' \big| Z_5) = \Pr(e_h = e_j^h)\Pr(e_t = e_k^t) \tag{42}$$

where $j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, K$.

Observation 6 (Z_6)**:** This is similar to observation-5 except that SU does not receive ACK from the receiver, which means that PU has been misdetected (reported H_{10} but actually H_{11}). Hence, the updated belief would become

$$p_{t+1} = p_{BF}. \tag{43}$$

The data transmitted is given by

$$R(e_a, p_t, S|\, Z_6) = 0. \tag{44}$$

The probability of observation-6 is computed as

$$\Pr(Z_6) = p_t(p_f)\Pr(e_t \le e_{tu}). \tag{45}$$

The updated energy and transition probability are given, respectively, as

$$e' = e_a + e_h - e_s - e_t$$
$$\Pr(e_a \to e' \big| Z_6) = \Pr(e_h = e_j^h)\Pr(e_t = e_k^t) \tag{46}$$

where $j = 1, 2, \ldots, m$ and $k = 1, 2, \ldots, K$.

Observation 7(Z_7)**:** SU senses the channel, finds it in state B i.e. $E_{se} > \lambda_B$, and harvests energy from the primary signal and also refrains from transmission for the remaining time slot. The updated belief is given as

$$p_{t+1} = p_t^u p_{FF} + (1 - p_t^u)p_{BF} \tag{47}$$

where $p_t^u = \frac{p_t p_f}{p_t p_f + (1 - p_t)p_d}$.

As no data transmission occurs so the reward is given as

$$R(e_a, p_t, S|\, Z_7) = 0. \tag{48}$$

The probability of observation-7 is given as

$$\Pr(Z_7) = p_t p_f(e_s) + (1 - p_t)p_d. \tag{49}$$

The updated energy and transition probability are computed, respectively, as

$$e' = e_a + e_h + e_p - e_s$$
$$\Pr(e_a \to e' \big| Z_7) = \Pr(e_h = e_j^h)\Pr(e_p = e_i^p) \tag{50}$$

where $j = 1, 2, \ldots, m$ and $i = 1, 2, \ldots, n$.

From the above observations, it is obvious that the probability of observation depends on the transmission energy and idle probability (belief) of the PU. The transition probability from available to updated energy depends on harvested and transmission energy. Both of these probabilities are used to calculate the value function. In summary, value function is

TABLE I
SYSTEM PARAMETERS

Description	Symbol	Value
Primary Channel Idle Probability	p_t	0.7
Transition Probability from State F to Itself	p_{FF}	0.7
Transition Probability from State B to State F	p_{BF}	0.3
Signal to Noise Ratio	β	$-10dB$
Required Data Rate	R_s	$0.4bps/Hz$
Interference Temperature	I_T	$2dB$
SU Transmission Power in Overlay Mode	P_s^O	$10dB$
Peak Transmit Power	P_p	$10dB$
Number of Iterations	N	2000
Slot Duration	T	$30ms$
Battery Maximum Capacity	e_{max}	20
Mean Energy Harvested from Primary Channel	$e_{p\mu}$	1
Mean Energy Harvested from Other Sources	$e_{h\mu}$	3
Sensing Energy	e_s	1

related with the harvested energy. Throughput is dependent on transmission (no transmission would lead to no throughput) which in turn depends on the spectrum sensing and available energy for transmission. If there is not sufficient energy for sensing, SU would stay idle rather than doing transmission. Similarly, if the existing energy is not enough for transmission, the SU would not be able to transmit which will result in a decrease in the throughput.

IV. SIMULATION RESULTS

In this section simulation results are provided to show the performance of the proposed hybrid (overlay-underlay) cognitive radio with energy harvesting in terms of throughput. Throughput is calculated in the form of reward when successful transmission occurs in overlay mode or in underlay mode. That is, in the proposed scheme, after sensing action is selected through POMDP, the transmission mode is chosen between the overlay mode and the underlay mode on the basis of the sensing energy (E_{se}). If the overlay mode is chosen, then throughput is computed by (27) in Observation 2 when the transmission is successful. If the underlay mode is chosen, then throughput is given by (40) in Observation 5 when the transmission is successful. Collectively, throughput of the hybrid overlay-underlay system with energy harvesting is obtained by summing the throughputs obtained in the overlay mode and underlay mode at each frame. System parameters for simulation are summarized in Table I. In the simulations, effect of the detection probability, underlay sensing energy threshold and channel occupancy (related with the idle probability of the PU) on the throughput are shown.

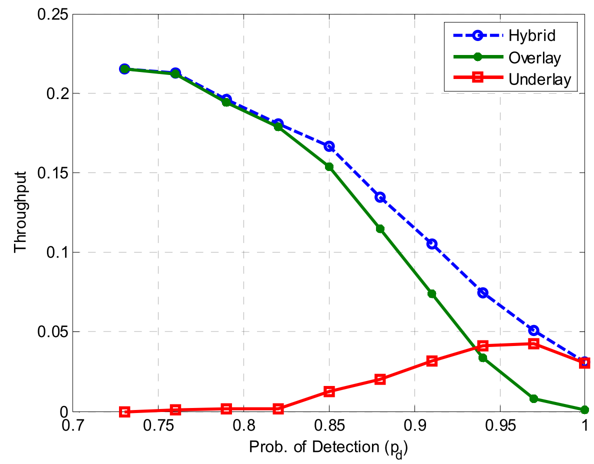

Fig. 6. Throughput of the SU in the hybrid, overlay and underlay modes versus the probability of detection.

Fig. 6 shows the throughput of SU according to the probability of detection when cognitive radio is operated in the following access modes: hybrid overlay-underlay mode, overlay mode, and underlay mode, which are denoted as "Hybrid", "Overlay", and "Underlay" respectively. As can be seen from the figure that with the increase in the probability of detection (p_d), throughput of the SU decreases in the overlay mode and increases in the underlay mode. It is due to the fact that high detection probability means more protection of the QoS of the PU which restricts SU from transmission in the overlay mode. However, SU can coexist with the PU in the underlay mode and transmit simultaneously with controlled power so throughput increases with increasing the detection probability in the underlay mode. It can be observed from the figure that the underlay transmission outperforms overlay transmission for $p_d > 0.935$. To increase the throughput in the underlay mode, SU transmits with more power that also increases interference to the PU. The throughput increases for rise in p_d as long as p_d is below 0.975 and slightly decreases for further increase in p_d. The reason is that the interference generated by the SU at this point exceeds the maximum interference to the PU, called interference temperature, so the transmission power in the underlay mode is lowered to avoid interference to the PU which slightly reduces throughput in the underlay mode.

Fig. 7 illustrates throughput of the hybrid overlay-underlay energy harvested (our proposed system), overlay-only, and overlay-optimal cognitive radio systems. Our proposed system harvests energy from the wireless primary signal as well as from the ambient sources and uses POMDP for action selection. Overlay-only and overlay-optimal cognitive radio systems both harvest energy from the ambient sources only. Furthermore, they do not use any access strategy i.e. POMDP for selecting an action to sense the channel. However, for calculating the throughput, overlay-only system uses an arbitrary sensing time while overlay-optimal system uses an optimal sensing time. It is evident from the figure that our proposed scheme performs better than the overlay-only and overlay-optimal cognitive radio systems. The reason is that

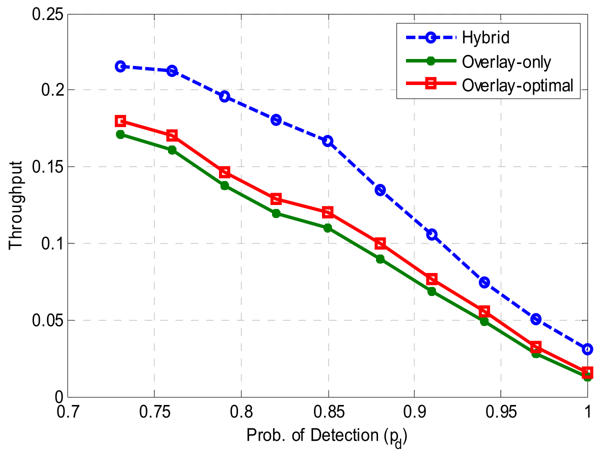

Fig. 7. Comparison of the throughput of hybrid cognitive radio with overlay-only and overlay-optimal cognitive radios.

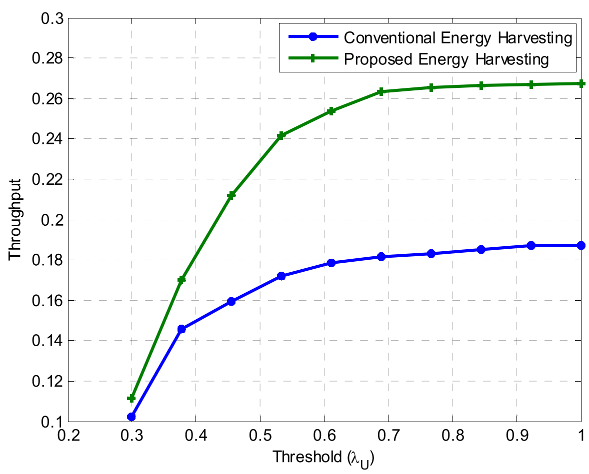

Fig. 8. Comparison of the proposed energy harvesting with conventional energy harvesting when $p_d = 0.87$.

our proposed scheme uses POMDP to decide the action of channel sensing and subsequent transmission by considering both the transmission energy and harvested energy and hence maximizes the value function (throughput). For example, in the proposed scheme if the available energy is not enough for transmission, SU would refrain from channel sensing and would harvest energy from the channel which will be utilized for transmission in the next slot. Whereas, in the overlay-only and overlay-optimal systems, the user spends energy in channel sensing that further reduces the available insufficient energy for transmission. In next time slot, SU would not be able again to transmit due to insufficient energy even if the channel is free. The hybrid approach enhances the throughput by 60% (approximately) and 50% (approximately) compared to overlay-only and overlay-optimal cognitive radios, respectively when $p_d = 0.9$.

Fig. 8 shows the throughput of hybrid underlay-overlay cognitive radio when the following two energy harvesting strategies are used; in the first case, SU harvests energy from the primary channel as well as from the ambient sources, which is denoted as "Proposed Energy Harvesting". In the

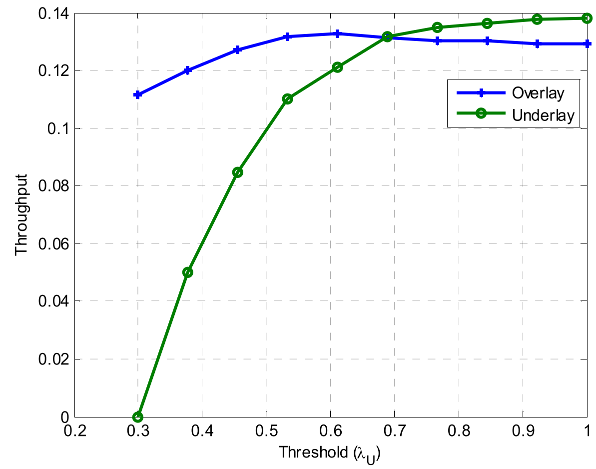

Fig. 9. Effect of the underlay sensing energy threshold on the throughput of SU in overlay and underlay modes when $p_d = 0.87$.

second case, SU harvests energy only from the ambient sources, which is denoted as "Conventional Energy Harvesting". It can be observed from the figure that the throughput of our proposed energy harvesting is 43% (approximately) greater than that of the conventional energy harvesting for $\lambda_U \geq 0.76$. In case of the proposed energy harvesting strategy, extra energy is harvested from the primary channel compared to harvesting energy only from the ambient sources. The increased energy is utilized for channel sensing and transmission which consequently enhances throughput of the system.

Fig. 9 shows the effect of underlay sensing energy threshold (λ_U) on throughput when the hybrid overlay-underlay cognitive radio with energy harvesting is operated in the "Overlay" and "Underlay" modes. It can be seen from the figure that throughput in the overlay mode does not change significantly with underlay sensing energy threshold (λ_U). It is because the overlay transmission does not depend on the difference between λ_O and λ_U. On the other side, throughput increases in the underlay mode as λ_U increases. By keeping the value of λ_O fixed and increasing λ_U from λ_O to 1, SU gets more opportunities by transmitting in the underlay mode to increase the throughput. However, we do not see further increase in the throughput after a certain value of the underlay sensing energy threshold such as $\lambda_U = 0.76$. The reason is that in the underlay mode, SU has to keep interference below the interference temperature and transmit with a controlled power. In this case, the value of λ_O is set to 0.3 based on (17) since the given target detection probability p_d is 0.87. From the figure, the underlay maximum sensing energy threshold λ_B is set to 0.76 since the underlay throughput does not increase with a further increase in λ_U after 0.76. When $\lambda_O = \lambda_U$, it means that there is no transmission in the underlay mode and all the throughput is due to transmission in the overlay mode. As the difference between these two thresholds increases, throughput in underlay mode increases, which results in a larger combined throughput.

Fig. 10 depicts the throughput of the hybrid overlay-underlay cognitive radio with energy harvesting for different

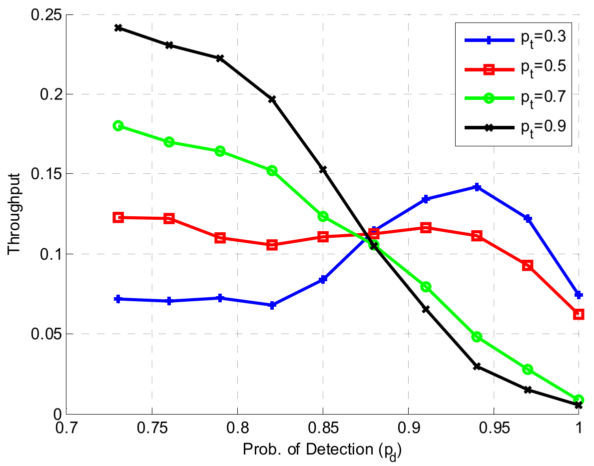

Fig. 10. Throughput of the SU in hybrid mode for different values of p_t.

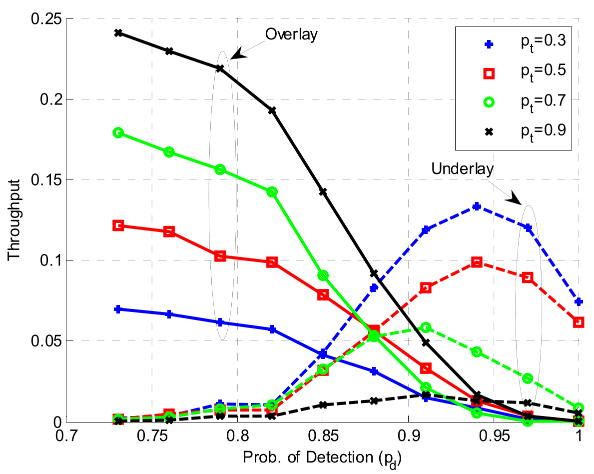

Fig. 11. Overlay and underlay throughput detail of the hybrid mode (in Fig. 10) for different values of p_t.

values of the channel idle probability p_t. It is observed from the figure that for the higher values of channel idle probability i.e. $p_t = 0.7$ and $p_t = 0.9$, throughput of system is higher at the smaller values of the probability of detection and decreases for higher values of detection probability. On the other hand, for the smaller values of idle probability i.e. $p_t = 0.3$ throughput is lower at lower values of detection probability and decreases after reaching a certain maximum value for further increase in the probability of detection. This phenomenon is due to the overlay and underlay effect which is further clarified in Fig. 11.

Fig. 11 is a detailed version of Fig. 10 and shows the throughput of hybrid cognitive radio in overlay and underlay modes for different values of channel idle probability p_t. Higher throughput is observed in the overlay mode for higher value of channel idle probability. At the same time lower throughput is observed in the underlay mode for the higher value of channel idle probability. On the other hand, lower throughput is observed in the overlay mode while higher throughput is observed in the underlay mode for smaller values of p_t. The obvious reason for the above observed phenomenon is that the SU can transmit in the overlay mode only if the primary channel is free. When the channel occupancy increases, such that the probability of a free channel decreases, transmission in the overlay mode decreases and vice versa. On the other hand, SU in the underlay mode can transmit even in the presence of the PU. When the channel occupancy increases, i.e. probability of a free channel decreases, transmission in the underlay mode increases and vice versa.

So far, we have shown that the proposed access strategy can increase throughput of the SU. However, the throughput improvement comes along with a computational burden on the SU which may require more processing time and would result in an increase in the latency and energy consumption. There is a need to obtain an optimal solution between throughput, latency and energy which is an interesting work for future.

V. Conclusion

In this paper, we have considered a hybrid (overlay and underlay) cognitive radio system that harvests energy from the wireless communication channel as well as from other ambient sources of energy. Our proposed strategy performs better in terms of throughput than a cognitive radio which operates only in the overlay mode, a non-hybrid cognitive radio which does not use POMDP or any other action selection policy, and a cognitive radio harvesting energy only from the ambient sources.

We have shown that throughput is maximized when energy is harvested from the primary channel as well as from ambient sources. We have also shown that by increasing the underlay sensing energy threshold, the opportunities for underlay transmission increase which are wasted in an overlay-only access scheme. We also investigated the effect of the channel occupancy on the throughput. Our proposed system performs better than a conventional overlay system by utilizing the underlay mode for transmission when the channel idle probability decreases.

Tradeoff between throughput, latency and energy will be investigated in future. Furthermore, this work can be extended to multi-channel scenario and similar to POMDP framework which is used for action selection, MDP framework can be used to select the transmission mode in future.

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Muhammad Usman is currently pursuing the Ph.D. degree at the Multimedia Communication Systems Laboratory, University of Ulsan, Ulsan, Korea. He received the M.Sc. degree in computer engineering from the Center of Advanced Studies in Engineering, Islamabad, Pakistan, in 2007, and the B.Sc. degree in computer information systems engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2004. His research interests include spectrum sensing and energy efficiency in cognitive radio networks, next generation networks, and wireless sensor networks.

Insoo Koo received the B.E. degree from Kon-Kuk University, Seoul, Korea, in 1996, and the M.S. and Ph.D. degrees from the Gwangju Institute of Science and Technology (GIST), Gwangju, Korea, in 1998 and 2002, respectively. From 2002 to 2004, he was with the Ultrafast Fiber-Optic Networks Research Center, GIST, as a Research Professor. In 2003, he was a Visiting Scholar with the Royal Institute of Science and Technology, Stockholm, Sweden. In 2005, he joined the University of Ulsan, Ulsan, Korea, where he is currently a Full Professor. His current research interests include next generation wireless communication systems and wireless sensor networks.