Performance Comparison between Adaptive and Fixed Transmit Power in Underlay Cognitive Radio Networks

Hela Hakim, *Student Member, IEEE,* Hatem Boujemaa, *Member, IEEE,* and Wessam Ajib, *Member, IEEE*

***Abstract*—In this paper, we compare the performance in terms of symbol error probability, data rate and power consumption of the use of fixed transmit power (FTP) and adaptive transmit power (ATP) in underlay cognitive radio networks. The use of FTP alleviates the signaling requirements of underlay cognitive radio networks compared to the ATP. Nevertheless, the use of FTP influences the performances of the underlay cognitive radio networks. To study this influence, we consider three relay selection schemes using FTP: opportunistic decode and forward with FTP (O-DF with FTP), opportunistic amplify and forward with FTP (O-AF with FTP) and partial relay selection with FTP (PR with FTP). We compare the performances of these schemes in terms of symbol error probability, data rate and power consumption with three relay selection schemes using ATP: opportunistic decode and forward with ATP (O-DF with ATP), opportunistic amplify and forward with ATP (O-AF with ATP) and partial relay selection with ATP (PR with ATP). We provide exact and/or lower bound expressions of the symbol error probabilities of O-DF, O-AF and PR with FTP. The analytical study for the data rate and the power consumption is also provided. Our comparison study shows that FTP has a positive impact on the data rate and power consumption performance while it deteriorates the symbol error probability performance.**

***Index Terms*—Cognitive radio, relaying, fixed transmit power, adaptive transmit power, symbol error probability, data rate, power consumption.**

I. Introduction

EVER increasing demand for high data rate wireless services burdens the available spectrum resources which become unable to satisfy this demand and suffer from severe scarcity. Cognitive radio has emerged as a promising technology to optimize spectrum resources exploitation by using the licensed spectrum in an opportunistic fashion [1]. In this technology, any cognitive secondary user may share the spectrum with a licensed primary user as long as the latter fulfills its Quality of Service (QoS) requirement. The protocols settling the coexistence of primary and secondary users are classified into three approaches [2]: (i) interweave approach where the secondary user can operate as long as the primary user is idle and must switch off whenever this latter becomes active; (ii) overlay approach where the secondary and primary users share simultaneously the spectrum whereas the secondary nodes must implement and perform some techniques in order to assist the primary communications; (iii) finally, an underlay approach where secondary users share the spectrum with the primary one but have to adjust their transmit power to keep the induced interference always below a given allowable threshold. To fulfill the interference constraint, the secondary transmitter uses generally low transmit power which limits largely the performances of the cognitive radio network and hence this network may suffer from low data rate and high symbol error probability (SEP). A way to ameliorate the performances of the secondary network is the use of relaying. Recently, several works have focused on relaying techniques in cognitive radio network [3]-[9]. In [3], Zou *et al.* have proposed to select the relay with the largest signal-to-noise ratio (SNR) in relay-destination link under the constraint of satisfying a required primary outage probability. In [4], Chen *et al.* have proposed a distributed relay selection scheme while considering adaptive modulation and coding and energy states of relay nodes. The same authors have proposed in [5] a relay selection scheme that maximizes the secondary data rate whilst ensuring a minimum required primary data rate. In [6], a distributed relay selection concurrently considering the channel states of all related links and residual energy state of the relay nodes have been proposed. In [7], krishna *et al.* have proposed that relays use beam steering capability to impose a target signal to interference plus noise ratio (SINR) whilst fulfilling the primary requirement. In [8], Lin *et al.* have used the pricing function in game theory to propose a novel low-interference relay selection derived from the conventional max-min relay selection. In [9], amplify-and-forward relay selection scheme is investigated in the presence of interference from primary transmitter.

All previous works assume that secondary transmitters can adjust their transmit power. Recently, some efforts have focused on the use of secondary transmitter nodes using fixed transmit power (FTP) [10]-[13]. In these works, several relaying schemes are investigated where secondary transmitters (source and relay) use their maximum available power when the primary interference constraint is verified and remain silent otherwise. This approach is solely proposed in [10]-[13] and is different from the approach where the relay remains silent when the direct link is of high quality [14].

In this paper, we consider a secondary network composed by simple nodes transmitting with FTP. The secondary network consists of a source, a destination and several available

Manuscript received August 7, 2012; revised January 20 and June 18, 2013. The editor coordinating the review of this paper and approving it for publication was L. Husheng

H. Hakim is with the Department of Applied Mathematics, Communications and Signals, Higher School of Communication of Tunis, Ariana 2083, Tunisia, and with the Department of Computer Science, Université de Québec à Montréal, Montreal, QC H2X 3Y7, Canada (e-mail: hela.hakim@supcom.tn).

H. Boujemaa is with the Department of Applied Mathematics, Communications and Signals, Higher School of Communication of Tunis, Ariana 2083, Tunisia (e-mail: boujemaa.hatem@supcom.rnu.tn).

W. Ajib is with the Department of Computer Science, Université de Québec à Montréal, Montreal, QC H2X 3Y7, Canada (e-mail: ajib.wessam@uqam.ca).

Digital Object Identifier 10.1109/TCOMM.2013.110413.120578

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

relays. We investigate the use of FTP which requires less signaling than the use of ATP. We investigate and compare the performances of three relay selection schemes: opportunistic DF relaying with FTP (O-DF with FTP), Opportunistic AF relaying with FTP (O-AF with FTP) and partial relay selection with FTP (PR with FTP). We study the performances of the considered relay selection schemes in terms of SEP, data rate and power consumption. Using FTP in underlay cognitive radio network alleviates the signaling requirements compared to the ATP nodes. But, it influences the performance of the cognitive radio system. The target of our work is to study this by comparing the performances of FTP and ATP in terms of symbol error probability, data rate and power consumption. This gives insights to cognitive network architectures if using ATP or FTP is worthy. The relaying schemes when ATP is used are called: O-DF with ATP, O-AF with ATP and PR with ATP. Our comparison study shows that FTP has a positive impact on the data rate and power consumption performance while it deteriorates the symbol error probability performance.

In [10]-[13], authors have considered only the FTP and have not provided a performance comparison between FTP and ATP. Also they have considered only amplify and forward (AF) relaying and have omitted the interference caused by the primary transmitter to the secondary receivers. Moreover, they have analysed only the SEP and the outage probability performances. In addition, in these works, all relays are assumed to be equidistant from primary receiver. The contribution of our work compared to [10]-[13] consists in providing performance comparison between the FTP and ATP in terms of SEP, data rate and power consumption. Moreover, we have considered both decode and forward (DF) and AF relaying modes. In addition, we have provided analytical study and simulation results of SEP, data rate and power consumption of the secondary network in the presence and absence of interference from the primary transmitter. The relays positions in our work are uniformly generated in a square 3x3 and simulation and numerical results are averaged over many topologies.

The remainder of this paper is organized as follows. In section II, we describe our system model. In section III, we present the new relaying schemes. Section IV is dedicated to present the SEP analysis of each relaying scheme using FTP. Section V is dedicated for the data rate and power consumption analysis. Section VI shows and discusses with theoretical and simulation results. Finally, section VII draws some concluding remarks.

II. System Model

We consider an underlay cognitive radio network operating near a primary network. The primary network consists of a primary transmitter (PT) communicating with a primary destination (PD). The cognitive radio network consists of a source S communicating with a destination D simultaneously with the primary communication. We assume that M_r relays are available to assist S. The system model is depicted in Fig.1. We denote the set of the M_r available relays by $\mathcal{R}$. We assume that each transmission is subject to an additive white Gaussian noise (AWGN) with zero mean and variance N_0. The channel coefficient of the link *X*-*Y* is denoted by $h_{X,Y}$ and is assumed to consist of path loss and independent fading effect

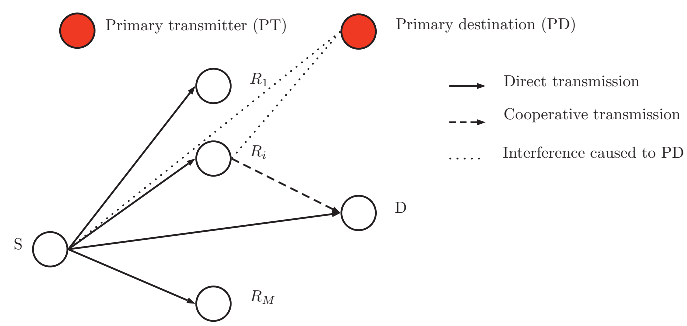


Fig. 1. System model.

as $h_{X,Y} = \mathcal{X}_{X,Y} d_{X,Y}^{-\frac{\alpha}{2}}$, where $d_{X,Y}$ is the distance between X and Y and α is the path loss exponent. $\mathcal{X}_{X,Y}$ is the fading coefficient modeled as a circular symmetric complex Gaussian random variable with variance 1. We assume that the channels coefficients are invariant during two time slots and may change independently each two time slots. Nodes are assumed to be half duplex.

The communication time is divided into two time slots. In the first time slot, S sends its signal while the M relays listen as shown by bold arrows in Fig. 1. The transmitted signal is also perceived by PD and hence causes some interference. In underlay cognitive radio network, the interference level at PD caused by the secondary transmitters (source and relays) must be below an interference threshold noted I_{th}. The interference caused by a transmitter X, noted $\mathcal{I}_X$ using a fixed transmit power P_X^F is as follows

$$\mathcal{I}_X = \mathcal{P}_X^F \mid h_{X,PD} \mid^2 \leq I_{th}, \tag{1}$$

where $\mathcal{P}_X^F$ denotes the FTP used by the transmitter X. If the secondary transmitter X (S or R_i) finds that the constraint (1) is satisfied, then it transmits with $\mathcal{P}_X^F$. Hence, the SINR of the link *X*-*Y* is given by

$$\Gamma_{X,Y} = \frac{\mathcal{P}_X^F |h_{X,Y}|^2}{\mathcal{P}_p |h_{PT,Y}|^2 + N_0}. \tag{2}$$

If the secondary transmitter is unable to satisfy the primary interference constraint, then it remains silent. This implies that the transmission process starts only if S satisfies the interference constraint in (1). S transmits with a fixed power noted $\mathcal{P}_S^F$ and each relay $R_i \in \mathcal{R}$, transmits with a fixed power noted $\mathcal{P}_{R_i}^F$. The values of $\mathcal{P}_S^F$ and $\mathcal{P}_{R_i}^F$ are set at the activation of the cognitive radio network and remains fixed during all the transmissions.

The relays and D receive useful data from S and interference from PT as shown in Fig. 1. Thereby, the received signal at D during the first time slot can be written as follows.

$$y_D = \sqrt{\mathcal{P}_S^F} h_{S,D} x_s + \sqrt{\mathcal{P}_P} h_{PT,D} x_p^1 + n_D^1, \tag{3}$$

where x_s is the secondary symbol, x_p^1 and n_D^1 are the primary transmitted symbol and the noise at D during the first time slot. Some relays, with the use of their FTP, will fall short of the interference constraint and thus they can not be selected to forward the secondary signal. The set of relays satisfying the interference constraint is denoted by U.

In the second time slot, one relay belonging to U is selected to forward the received signal. Two relaying modes can be used: DF and AF.

If DF relaying is used, a subset from U, denoted by C gathering decoding relays is formed, i.e., the relays that have correctly decoded the received signal. The selected relay from C, denoted by $R_s^{\text{O-DF}}$, decodes the received signal then regenerates and forwards it. The received signal at D during the second time slot is given by

$$y_D^{\text{O-DF},2} = \sqrt{\mathcal{P}^F_{R_s^{\text{O-DF}}}} h_{R_s^{\text{O-DF}},D} x_s + \sqrt{\mathcal{P}_P} h_{PT,D} x_p^2 + n_D^2. \quad (4)$$

where x_p^2 and n_D^2 are the primary transmitted symbol and the noise at D during the second time slot.

If AF relaying is used, the selected relay from U, denoted by $R_s^{\text{O-AF}}$, amplifies the received signal using an amplification factor $G = \sqrt{\frac{\mathcal{P}^F_{R_s^{\text{O-AF}}}}{\mathcal{P}_S^F |h_{S,R_s^{\text{O-AF}}}|^2 + \mathcal{P}_p |h_{PT,R_s^{\text{O-AF}}}|^2 + N0}}$. Then, the selected relay forwards the amplified signal to D. The received signal at D during the first and second time slots are respectively given by

$$y_D^{\text{O-AF},2} = G h_{R_S^{\text{O-AF}},D} y^1_{R_s^{\text{O-AF}}} + \sqrt{\mathcal{P}_P} h_{PT,D} x_p^2 + n_D^{22},$$

where $y^1_{R_s^{\text{O-AF}}} = \sqrt{\mathcal{P}_S} h_{S,R_s^{\text{O-AF}}} x_s + \sqrt{\mathcal{P}_P} h_{PT,R_s^{\text{O-AF}}} x_p^1 + n_{R_s^{\text{O-AF}}}$, is the signal received by the selected relay during the first time slot.

The transmission during the second time slot is shown by a dashed arrow in Fig.1.

III. Relaying Schemes in Underlay Cognitive Radio Network

The relay selection process must respect the end-to-end SINR as well as the interference constraint imposed by the primary system. In the following, we present the three relaying schemes using FTP: namely the O-DF with FTP, O-AF with FTP and PR with FTP. Then, we present the corresponding relaying schemes using ATP: namely O-DF with ATP, O-AF with ATP and PR with ATP.

A. Opportunistic DF Relaying with FTP (O-DF with FTP)

In underlay cognitive radio network operating in DF mode, the selected relay must respect the three following constraints:

- Interference constraint: the level of the interference caused by the selected relay should be below the threshold allowed by the primary receiver.
- Decoding constraint: the selected relay should correctly decode the secondary signal.
- Finally, the selected relay should maximize the SINR of the relay-destination link.

To select a relay, we first determine the set U, then, the subset C ($C \subset U$). Finally, the selected relay is the one in C maximizing the SINR of the relay-destination link. Hence $R_s^{\text{O-DF}} = \underset{R_i \in C}{\text{argmax}}\, \Gamma_{R_i D}$, where $\Gamma_{R_i D}$ is defined in (2).

B. Opportunistic AF Relaying with FTP (O-AF with FTP)

When the network operates in AF mode, the selected relay must respect two constraints:

- Interference constraint: the interference perceived by the primary receiver is lower than I_{th}.
- The selected relay maximizes the SINR of the source-relay-destination link.

The SINR of the relaying link source-relay-destination is given by

$$\Gamma_{SR_i D} = \frac{\Gamma_{SR_i} \Gamma_{R_i D}}{\Gamma_{SR_i} + \Gamma_{R_i D} + 1}. \quad (5)$$

For the relay selection, we first determine the set U. Then, the selected relay for O-AF with FTP, denoted by $R_s^{\text{O-AF}}$, is chosen as $R_s^{\text{O-AF}} = \underset{R_i \in U}{\text{argmax}}\, \Gamma_{SR_i D}$.

C. Partial relay selection with FTP (PR with FTP)

The proposed O-AF scheme requires knowing the state of source-relay and relay-destination channels. When the number of available relays increases, the amount of required signaling becomes important. This increases the complexity and may constitute an implementation bottleneck. An alternative solution is to rely only on the SINR of source-relay link to moderate signaling requirement. This idea was first proposed for non-cognitive radio network in [15]. The new scheme is called partial relay selection. Consequently, the selected relay should

- Satisfy the interference constraint imposed by the primary user.
- Maximize the SINR of the source-relay link.

Hence, the selected relay for PR with FTP, denoted by R_s^{PR}, is chosen as $R_s^{\text{PR}} = \underset{R_i \in U}{\text{argmax}}\, \Gamma_{SR_i}$.

D. Opportunistic DF relaying with adjustable transmit power (O-DF with ATP)

In this scheme, in order to maximize the system performance while respecting the interference constraint, each transmitter adjusts its power before each transmission as follows

$$\mathcal{P}_X^A = \min\left(\frac{I_{th}}{|h_{X,PD}|^2}, P_X^{max}\right), \quad (6)$$

where $\mathcal{P}_X^A$ denotes the ATP used by the transmitter X, P_X^{max} is the maximum available power for the transmitter X. To select a relay, the decoding set of relays C is first formed. Then, each relay R_i in C adjusts its power as in (6). The selected relay, denoted by $R_s^{\text{O-DF, ATP}}$, is the one that maximizes the SINR of the relay-destination link such as: $R_s^{\text{O-DF, ATP}} = \underset{R_i \in C}{\text{argmax}}\, \Gamma_{R_i D}$.

E. Opportunistic AF relaying with adjustable transmit power (O-AF with ATP)

In this scheme, each relay $R_i \in \mathcal{R}$, adjusts its power as in (6). Then, the relay maximizing the SINR of the relaying link source-relay-destination denoted by $R_s^{\text{O-AF, ATP}}$ is selected as follows $R_s^{\text{O-AF, ATP}} = \underset{R_i \in U}{\text{argmax}}\, \Gamma_{SR_i D}$, where $\Gamma_{SR_i D}$ is defined in (5).

F. Partial relay selection with adjustable transmit power (PR with ATP)

In this scheme, each relay $R_i \in \mathcal{R}$, adjusts its power as in (6). Then, the relay which maximizes the SINR of the relaying link source-relay is selected. The selected relay is denoted by $R_s^{\text{PR, ATP}}$ and is given by $R_s^{\text{PR, ATP}} = \underset{R_i \in \mathcal{R}}{\text{argmax}}\, \Gamma_{SR_i}$.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Relay node Id	CSI of R_i-D link

Fig. 2. Signaling overhead structure used by fixed transmit power relays.

Relay node Id	CSI of R_i-D link	value of $P_{R_i}^A$

Fig. 3. Signaling overhead structure used by adaptive transmit power relays.

G. Signaling requirements comparison

We compare the signaling requirements of FTP and ATP and we show that FTP requires less signaling than ATP. When the signaling requirements increases, extra resources must be provided to carry more signaling information. This increases the practical implementation complexity of the designed wireless system. We assume that S is the central scheduler that collects information and selects the relay.

1) Fixed Transmit Power: If FTP nodes are used, each relay R_i compares the amount $P_{\mathrm{R}_i}^F|h_{\mathrm{R}_i,\mathrm{PD}}|^2$ to the interference threshold I_{th}. If R_i finds that $P_{\mathrm{R}_i}^F|h_{\mathrm{R}_i,\mathrm{PD}}|^2 < I_{th}$, then it sends its identity and the value of $h_{\mathrm{R}_i,\mathrm{D}}$ to S. The signaling overhead structure used by FTP relays is shown in Fig. 2. S then collects the identities of the relays verifying the interference constraint and since it is assumed to have a prior knowledge about the values of $P_{\mathrm{R}_i}^F, \forall\ \mathrm{R}_i \in \mathcal{R}$, it can selects the best relay.

2) Adaptive transmit Power: If ATP nodes are used, to select the best relays, each relay R_i verifying $P_{\mathrm{R}_i}^A|h_{\mathrm{R}_i,\mathrm{PR}}|^2 < I_{th}$, has to send its identity, the value of $h_{\mathrm{R}_i,\mathrm{D}}$ and the value of its transmit power $P_{\mathrm{R}_i}^A$ to S. The signaling overhead structure of ATP is shown in Fig. 3.

In Table. 1, we compare the signaling requirements of the use of FTP and ATP. We can easily see that comparing to FTP, in ATP, relays have to further send the values of their adapted transmit powers to S. Obviously, when the number of relays increases. the signaling amount required to transmit this information becomes huge.

TABLE I
REQUIRED CSI FOR THE DIFFERENT RS SCHEMES

Fixed transmit Power nodes	Adaptive Transmit Power nodes
• Identity of R_i • The CSI of R_i-SR link	• Identity of R_i • The CSI of R_i-D link • The transmit power $P_{R_i}^A$

IV. SEP ANALYSIS OF THE RELAYING PROTOCOLS

In this section, we derive the exact form expression of the SEP of O-DF with FTP and exact and lower bound form of the SEP of O-AF and PR with FTP in the absence of interference from PT. The exact SEP expression of the O-DF with FTP in the presence of interference from PT is also derived while for O-AF and PR with FTP, only lower bound expressions are given, due to the intractability of the exact form expressions.

To derive the SEP at a node X, we use the moment generating function (MGF) of the SINR at X, Γ_X, defined as follows

$$M_{\Gamma_X}(s) \quad = \quad E(e^{-s\Gamma_X}), \tag{7}$$

where $E(.)$ is the expectation operator. For M-PSK modulation, the SEP at X can be deduced from the MGF of Γ_X as follows [16]

$$\mathbb{P}_{s,X} = \frac{1}{\pi}\int_0^{\pi\frac{M-1}{M}} M_{\Gamma_X}\left(\frac{\text{gpsk}}{\sin^2(\theta)}\right)d\theta, \tag{8}$$

where $\text{gpsk} = \sin^2(\frac{\pi}{M})$. Similar expressions can be obtained for M-QAM modulations.

A. SEP analysis of the O-DF with FTP

For the O-DF, the SEP at D can be written as

$$\mathbb{P}_{s,D}^{\text{O-DF}} \quad = \sum_{\Theta\subset\mathcal{R}} \mathbb{P}_{s,D|U=\Theta}^{\text{O-DF}}\mathbb{P}(U=\Theta). \tag{9}$$

The probability $\mathbb{P}(U=\Theta)$ is given by

$$\mathbb{P}(U=\Theta) \quad = \prod_{R_i\in\Theta}\mathbb{P}(I_{R_i,PD}\leq I_{th})\prod_{R_j\in\overline{\Theta}}\mathbb{P}(I_{R_j,PD}>I_{th}), \tag{10}$$

where $\overline{\Theta} = \mathcal{R}\backslash\Theta$ and

$$\mathbb{P}(I_{R_i,PD}\leq I_{th}) = 1-\exp(-\frac{I_{th}}{\overline{I_{R_i,PD}}}), \tag{11}$$

where $\overline{I_{R_i,PD}} = \mathcal{P}_{R_i}E(|h_{R_i,PD}|^2)$. To derive $\mathbb{P}_{s,D|U=\Theta}^{\text{O-DF}}$, two cases arise.

Case 1: if $U=\emptyset$, then the conditional probability $P_{s,D|U=\Theta}^{\text{O-DF}}$ is given by

$$\mathbb{P}_{s,D|U=\Theta}^{\text{O-DF}} = \frac{1}{\pi}\int_0^{\pi\frac{M-1}{M}} M_{\Gamma_{S,D}}\left(\frac{\text{gpsk}}{\sin^2(\theta)}\right)d\theta, \tag{12}$$

where $M_{\Gamma_{S,D}}(s)$ can be obtained by using the probability density function (PDF) of the SINR $\Gamma_{S,D}$ given in (38) in Appendix A and equation (7). In the absence of interference (i.e., the interference from PT is negligible and could be approximated by 0, $M_{\Gamma_{S,D}}(s)$, can simply be written as $M_{\Gamma_{S,D}}(s) = \frac{1}{1+\lambda_{S,D}^2 s}$, where $\lambda_{XY}^2 = \frac{P_X^F}{d_{xy}^\alpha N_0}$.

Case 2: if $U\neq\emptyset$, then given that in O-DF with FTP, only relays belonging to U and having correctly decoded the signal are retained as candidate relays, $\mathbb{P}_{s,D|U=\Theta}^{\text{O-DF}}$ can be written as

$$\mathbb{P}_{s,D|U=\Theta}^{\text{O-DF}} = \sum_{J\subset U}\mathbb{P}_{s,D|U=\Theta,C=J}^{\text{O-DF}}\mathbb{P}(C=J|U=\Theta). \tag{13}$$

Next, we derive each term of (13).

$\mathbb{P}_{s,D|U=\Theta,C=J}^{\text{O-DF}}$, is given by (12), if $C=\emptyset$. Otherwise, it is given by

$$\begin{aligned}\mathbb{P}_{s,D|U=\Theta,C=J}^{\text{O-DF}} \quad &= \quad \frac{1}{\pi}\int_0^{\pi\frac{M-1}{M}} M_{\Gamma_{S,D}}\left(\frac{\text{gpsk}}{\sin^2(\theta)}\right)\\ &\quad \times M_{\Gamma_{R_s^{\text{O-DF}}D}}\left(\frac{\text{gpsk}}{\sin^2(\theta)}\right)d\theta,\end{aligned} \tag{14}$$

where the expression of $M_{\Gamma_{R_s^{\text{O-DF}}D}}(s)$ is derived in Appendix A. In the absence of interference, $M_{\Gamma_{R_s^{\text{O-DF}}D}}(s)$ is derived in Appendix B.

$\mathbb{P}(C = J|U = \Theta)$, is given by

$$\mathbb{P}(C = J|U = \Theta) = \prod_{R_i \in J} (1 - \mathbb{P}_{s,R_i}) \prod_{R_j \in \overline{J}} (\mathbb{P}_{s,R_j}), \quad (15)$$

where $\overline{J} = U \backslash J$ and $\mathbb{P}_{s,X}$ is the SEP at X given by (12) by replacing D by node X.

B. SEP Analysis of the O-AF with FTP

In this subsection, we provide an exact form and a lower bound expression of the SEP for the O-AF with FTP in the absence of primary interference. The lower bound expression is derived to provide which is simpler than the exact one since this latter is given in the form of double integral. Due to the intractability of the exact form expression of the SEP in the presence of interference from PT, only the lower bound expression is derived.

1) Exact form expression: The SEP at D can be written as

$$\mathbb{P}^{\text{O-AF}}_{s,D} = \sum_{\theta \subset \mathcal{R}} \mathbb{P}^{\text{O-AF}}_{s,D|U=\theta} \mathbb{P}(U = \theta), \quad (16)$$

where $\mathbb{P}(U = \theta)$ is given by (10). Next, we derive the exact form expression of the first term of (16). To derive $\mathbb{P}^{\text{O-AF}}_{s,D|U=\theta}$, two cases arise.

Case 1: if $U = \emptyset$, then $\mathbb{P}^{\text{O-AF}}_{s,D|U=\theta}$ is given by (12), where $M_{\Gamma_{S,D}}(s) = \frac{1}{1+\lambda^2_{S,D}s}$.

Case 2: if $U \neq \emptyset$, then we have

$$\mathbb{P}^{\text{O-AF}}_{s,D|U=\theta} = \frac{1}{\pi} \int_0^{\pi \frac{M-1}{M}} M_{\Gamma_{S,D}} \left(\frac{\text{gpsk}}{\sin^2(\theta)} \right) M_{\Gamma_{SR^{\text{O-AF}}_s D}} \left(\frac{\text{gpsk}}{\sin^2(\theta)} \right) d\theta, \quad (17)$$

where $M_{\Gamma_{SR^{\text{O-AF}}_s D}}(s)$ can be computed as in (7) using the PDF of $\Gamma_{SR^{\text{O-AF}}_s D}$ which can be written as [17]

$$f_{\Gamma_{SR^{\text{O-AF}}_s D}}(\gamma) = \sum_{R_i \in U} f_{\Gamma_{SR_i D}}(\gamma) \prod_{\substack{R_j \in U \\ R_j \neq R_i}} F_{\Gamma_{SR_j D}}(\gamma), \quad (18)$$

where $f_{\Gamma_{SR_i D}}(\gamma)$ and $\mathrm{F}_{\Gamma_{SR_i D}}(\gamma)$ are the PDF and the cumulative distribution function (CDF) of $\Gamma_{SR_i D}$.

$\mathrm{f}_{\Gamma_{SR_i D}}(\gamma)$ and $\mathrm{F}_{\Gamma_{SR_i D}}(\gamma)$ are given respectively by [18](19) and (20), where $\nu_{R_i} = \frac{1}{\lambda^2_{SR_i}}$, $\mu_{R_i} = \frac{1}{\lambda^2_{R_i D}}$ and $\mathrm{K}_v(.)$ is the *v-th* order modified Bessel function of the second kind.

2) Lower Bound expression: $\Gamma_{SR_i D}$ can be upper-bounded as follows

$$\Gamma_{SR_i D} < \min(\Gamma_{SR_i}, \Gamma_{R_i D}) \triangleq \Gamma^{R_i}_{up}. \quad (21)$$

Next, we derive the lower bound expression in the absence and in the presence of interference from PT.

a) Absence of interference from PT: When the interference from PT is not considered, we have Γ_{SR_i} and $\Gamma_{R_i D}$ are two exponential random variables with mean $\lambda^2_{SR_i}$ and $\lambda^2_{R_i D}$, respectively. Thus, $\Gamma^{R_i}_{up}$ is an exponential random variable with mean $\frac{\lambda^2_{SR_i}\lambda^2_{R_i D}}{\lambda^2_{SR_i}+\lambda^2_{R_i D}}$.

Let Γ^{Sel}_{up} denotes the maximum of $\Gamma^{R_i}_{up}, R_i \in U$. Hence, the MGF of Γ^{Sel}_{up} can be deduced from (41) as follows

$$M_{\Gamma^{Sel}_{up}}(s) = \sum_{i \in U} \sum_{p=0}^{2^{|U|-1}-1} \frac{(-1)^{\xi(p)}}{\omega_{R_i} s + 1 + \sum\limits_{k=1}^{|U|-1} \frac{\omega_{R_i} \xi_p(k)}{\omega_{R_{l_{R_i,k}}}}}, \quad (22)$$

where $\omega_{R_i} = \frac{\lambda^2_{SR_i}\lambda^2_{R_i D}}{\lambda^2_{SR_i}+\lambda^2_{R_i D}}$ and $\{l_{R_i,k}\}_{k=1}^{|U|-1}$ is the set of relays indices in $U \backslash \{R_i\}$.

b) Presence of interference from PT: In the presence of interference from PT, the CDF of $\Gamma^{R_i}_{up}$ can be written as

$$F_{\Gamma^{R_i}_{up}}(\gamma) = 1 - \left(\frac{\sigma^2_{S,R_i}}{\sigma^2_{S,R_i} + \sigma^2_{PT,R_i}\gamma} \exp(-\frac{N_0\gamma}{\sigma^2_{S,R_i}}) \right) \times \left(\frac{\sigma^2_{R_i.D}}{\sigma^2_{R_i,D} + \sigma^2_{PT,D}\gamma} \exp(-\frac{N_0\gamma}{\sigma^2_{R_i,D}}) \right), \quad (23)$$

where $\sigma^2_{X,Y} = P^F_X d^{-\alpha}_{X,Y}$. The PDF of $\Gamma^{R_i}_{up}$ denoted by $f_{\Gamma^{R_i}_{up}}$ can be found by deriving the CDF of $\Gamma^{R_i}_{up}$ given above. Finally, the PDF of Γ^{Sel}_{up} can be computed as

$$f_{\Gamma^{Sel}_{up}}(\gamma) = \sum_{R_i \in U} f_{\Gamma^{R_i}_{up}}(\gamma) \prod_{\substack{R_j \in U \\ R_j \neq R_i}} F_{\Gamma^{R_i}_{up}}(\gamma), \quad (24)$$

and the $M_{\Gamma^{Sel}_{up}}(s)$ can be deduced from (24) as in (7).

Using these results, a lower bound of $\mathbb{P}^{\text{O-AF}}_{s,D|U=\Theta}$ is given by

$$B^{\text{O-AF}}_{low} = \frac{1}{\pi} \int_0^{\pi \frac{M-1}{M}} M_{\Gamma_{S,D}} \left(\frac{\text{gpsk}}{\sin^2(\theta)} \right) M_{\gamma^{Sel}_{up}} \left(\frac{\text{gpsk}}{\sin^2(\theta)} \right) d\theta. \quad (25)$$

Substituting the lower bound of $\mathbb{P}^{\text{O-AF}}_{s,D|U=\Theta}$ given in (25) and (10) in (16), we obtain a lower bound for the SEP of O-AF with FTP.

C. SEP Analysis of the PR with FTP

We first give the exact form expression of the SEP of PR with FTP in the absence of interference from PT. Lower bound expressions are derived in the presence and in the absence of interference from PT.

1) Exact form expression: Considering the PR with FTP scheme, the SEP at D can be written as

$$\mathbb{P}^{\text{PR}}_{s,D} = \sum_{\Theta \subset \mathcal{R}} \mathbb{P}^{\text{PR}}_{s,D|U=\Theta} \mathbb{P}(U = \Theta), \quad (26)$$

where $\mathbb{P}(U = \Theta)$ is given by (10). To derive $\mathbb{P}^{\text{PR}}_{s,D|U=\Theta}$, two cases arise.

If $U = \emptyset$, then $P^{\text{PR}}_{s,D|J=U}$ is given by (12). Otherwise, if $U = \emptyset$, then, $P^{\text{PR}}_{s,D|J=U}$ is given by

$$\mathbb{P}^{\text{PR}}_{s,D|J=U} = \frac{1}{\pi} \int_0^{\pi \frac{M-1}{M}} M_{\Gamma_{S,D}} \left(\frac{\text{gpsk}}{\sin^2(\theta)} \right) \times M_{\Gamma_{SR^{\text{PR}}_s D}} \left(\frac{\text{gpsk}}{\sin^2(\theta)} \right) d\theta, \quad (27)$$

where $M_{\Gamma_{SR^{\text{PR}}_s D}}(s)$ is derived in appendix C.

$$f_{\Gamma_{SR_iD}}(\gamma) = 2\mathrm{e}^{-(\nu_{R_i}+\mu_{R_i})\gamma}\Big[\nu_{R_i}\mu_{R_i}(2\gamma+1)K_0\left(2\sqrt{\nu_{R_i}\mu_{R_i}\gamma(\gamma+1)}\right) +(\nu_{R_i}+\mu_{R_i})\sqrt{\nu_{R_i}\mu_{R_i}\gamma(\gamma+1)}K_1\left(2\sqrt{\nu_{R_i}\mu_{R_i}\gamma(\gamma+1)}\right)\Big], \quad (19)$$

$$F_{\Gamma_{SR_iD}}(\gamma) = 1 - 2\mathrm{e}^{-(\nu_{R_i}+\mu_{R_i})\gamma}\sqrt{\nu_{R_i}\mu_{R_i}\gamma(\gamma+1)}K_1\left(2\sqrt{\nu_{R_i}\mu_{R_i}\gamma(\gamma+1)}\right), \quad (20)$$

2) Lower Bound expression: Γ_{SR_iD} can be upper-bounded as (21). Let the upper bound of Γ_{SR_iD} be denoted by Γ_{up}^{Sel}. The MGF of Γ_{up}^{Sel}, can be expressed as follows

$$M_{\Gamma_{up}^{Sel}}(s) = \sum_{R_i\in U} M_{\Gamma_{up}^{R_i}}(s)\mathbb{P}(R_s^{\text{PR}} = R_i), \quad (28)$$

where $P(R_s^{\text{PR}} = R_i)$ is given by (44) and $M_{\Gamma_{up}^{R_i}}(s)$ is the MGF of $\Gamma_{up}^{R_i}$. In the presence of interference from PT, the expression of $\Gamma_{up}^{R_i}$ is computed similar to the previous section while in the absence of interference it is given by $M_{\Gamma_{up}^{R_i}}(s) = \frac{1}{1+\omega_{R_i}s}$. Hence, a lower bound of $P_{s,D|J=U}^{\text{PR}}$ is given by

$$B_{low}^{PR} = \sum_{R_i\in U}\mathbb{P}(R_s^{\text{PR}} = R_i)\frac{1}{\pi}\int_0^{\pi\frac{M-1}{M}}\frac{1}{1+\omega_{R_i}\left(\frac{\text{gpsk}}{\sin^2(\theta)}\right)}d\theta. \quad (29)$$

Substituting the lower bound of $P_{s,D|J=U}^{\text{PR}}$ given in (29) and (10) in (26), we obtain a lower bound for the SEP of PR with FTP.

V. Data Rate and Power Consumption Analysis

We derive the data rate and power consumption expressions for the three relaying protocols, O-DF with FTP, O-AF with FTP and PR with FTP.

A. Data rate Analysis

The data rate is defined to be the amount of data successfully delivered per time unit. For the direct transmission, the data rate can be written as

$$th^x = \frac{\rho(1-\mathbb{P}_{s,D}^x)}{E(T)}, \quad (30)$$

where ρ (bits/s/Hz) is the target transmission rate, $x \in \{$'O-DF','O-AF','PR', 'd'$\}$, where $x =$ 'd' stands for the direct transmission, $\mathbb{P}_{s,D}^x$ is the SEP of the relaying scheme $'x'$. The exact form expression of $\mathbb{P}_{s,D}^{\text{O-DF}}$ is derived in IV-A, in the presence and absence of primary interference. The exact form expressions of $\mathbb{P}_{s,D}^{\text{O-AF}}$ and $\mathbb{P}_{s,D}^{\text{O-PR}}$ in the absence of primary interference are derived in IV-B and IV-C, respectively. The upper bounds of the data rate expressions of O-AF and PR with FTP in the presence of interference are also given in IV-B2 and IV-C2, respectively. $\mathbb{P}_{s,D}^d$ is given in (12).

$E(T)$ is the expected number of time slots to transmit one symbol. According to our system setup, $E(T)$ for O-DF with FTP can be computed as follows

$$E(T) = \mathbb{P}(I_{S,PD} > I_{th}) + \mathbb{P}(I_{S,PD} \le I_{th}) \times\left[(1-\mathbb{P}(C=\emptyset))\left(\mathbb{P}(U=\emptyset)+2(1-\mathbb{P}(U=\emptyset))\right) +\mathbb{P}(C=\emptyset)\right]. \quad (31)$$

For O-AF and PR with FTP, $E(T)$ can be computed as follows

$$E(T) = \mathbb{P}(I_{S,PD} > I_{th}) + \mathbb{P}(I_{S,PD} \le I_{th} \times\left[\mathbb{P}(U=\emptyset)+2(1-\mathbb{P}(U=\emptyset))\right]. \quad (32)$$

B. Power Consumption Analysis

The power consumption is the power consumed by the source and the selected relay to transmit one symbol. For O-DF with FTP, the power consumption can be computed as follows

$$\mathcal{P}_{Consumed}^{\text{O-DF}} = \mathbb{P}(I_{S,PD} \le I_{th}) \times\left[\mathcal{P}_s + \sum_{\substack{\Theta\subset\mathcal{R}\\ \Theta\neq\emptyset}}\mathbb{P}(U=\Theta)\left[\sum_{\substack{J\subset U\\ J\neq\emptyset}}\mathbb{P}(C=J|U=\Theta) \times\left(\sum_{R_i\in C}\mathbb{P}(R_i = R_s^x|U=\Theta, C=J)\mathcal{P}_{R_i}\right)\right]\right], \quad (33)$$

where $\mathbb{P}(R_i = R_s^{\text{O-DF}}|U=\Theta, C=J)$ is given by (34). For O-AF and PR with FTP, the power consumption can be computed as follows

$$\mathcal{P}_{Consumed}^x = \mathbb{P}(I_{S,PD} \le I_{th}) \times\left[\mathcal{P}_s + \sum_{\substack{\Theta\subset\mathcal{R}\\ \Theta\neq\emptyset}}\mathbb{P}(U=\Theta) \times\left[\sum_{R_i\in U}\mathbb{P}(R_i = R_s^x|U=\Theta)\times\mathcal{P}_{R_i}\right]\right], \quad (35)$$

where $x \in \{$'O-AF', 'PR'$\}$; $\mathbb{P}(R_s^{\text{PR}} = R_i)$ is given in (44) in appendix C and the expression of $\mathbb{P}(R_i = R_s^{\text{O-AF}}|U=\Theta)$ is given by

$$\mathbb{P}(R_i = R_s^{\text{O-AF}}|U=\Theta) = \prod_{\substack{R_k\in C\\ R_k\neq R_i}}\int_0^\infty(1-F_{\Gamma_{SR_iD}}(\gamma)) \times f_{\Gamma_{SR_kD}}(\gamma)d\gamma. \quad (36)$$

VI. Numerical Results

In this section, we present theoretical and simulation results carried out in order to compare the performance of relaying schemes using FTP nodes with those using ATP nodes. Simulation results are averaged over many random topologies generated in a square 3×3. The path loss exponent is set to 3. Without loss of generality, we have considered a simple binary phase shift keying (BPSK) modulation. The maximum

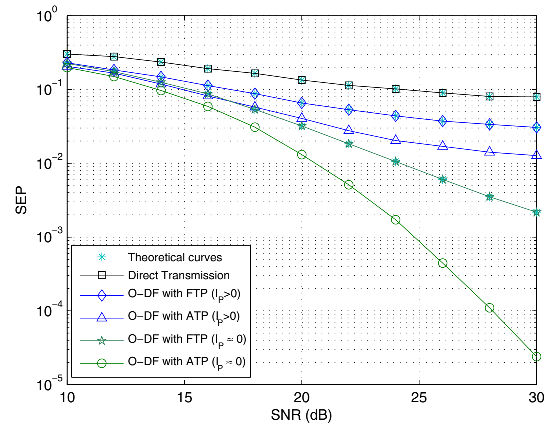
$$\mathbb{P}(R_i = R_s^{\text{O-DF}} | U = \Theta, C = J) = \prod_{\substack{R_k \in C \\ R_k \neq R_i}} \int_0^{\infty} \frac{\sigma^2_{R_s^{\text{O-DF}},D}}{\sigma^2_{R_s^{\text{O-DF}},D} + \sigma^2_{PT,D}\gamma} \exp(-\frac{N_0\gamma}{\sigma^2_{R_s^{\text{O-DF}},D}}) \times \left[\frac{N_0}{\sigma^2_{R_k,D} + \sigma^2_{PT,D}\gamma} \exp(-\frac{N_0\gamma}{\sigma^2_{R_k,D}}) + \frac{\sigma^2_{R_k,D}\sigma^2_{PT,D}}{(\sigma^2_{R_k,D} + \sigma^2_{PT,D}\gamma)^2} \exp(-\frac{N_0\gamma}{\sigma^2_{R_k,D}}) \right] d\gamma. \quad (34)$$

transmit power of the secondary source is $P_S^{max} = 0.5$ watt. The same value is used for relays, $P_{R_i}^{max} = 0.5$ watt, $\forall R_i \in \mathcal{R}$. We assume that all relays use the same fixed transmit power denoted $\mathcal{P}^{\mathcal{F}}$. For each given primary transmit power, we choose the fixed transmit powers $\mathcal{P}_S$ and $\mathcal{P}^{\mathcal{F}}$ at the beginning of simulations. To do so, we may find numerically the FTP values that minimize the secondary SEP or the ones that maximize the secondary data rate. Without loss of generality, we choose the ones that minimize the secondary SEP assuming that applications require low error rates. The primary transmit power $\mathcal{P}_p$ is set to 0.5 watt. Our simulations are carried out to compare the SEP , the data rate and the power consumption of the investigated relaying scheme using FTP nodes over relaying schemes using ATP nodes. For the direct transmission, the source transmits only when it is able to respect the interference constraint. The value of I_{th} is set to 0.05 watt. In the Figures, we denote by I_p the interference caused by PT.

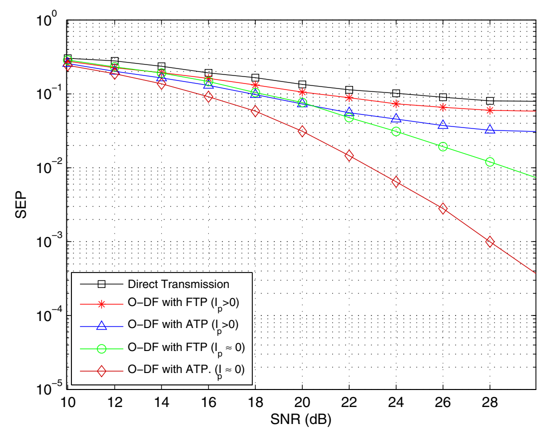
In Fig. 4, Fig.5 and Fig.6, we compare the SEP, the data rate and the power consumed to transmit one symbol of the O-DF with FTP and O-DF with ATP, respectively for a number of relays $M_r = 2$ and $M_r = 4$. In the presence of primary interference, the deterioration of SEP performance due to the use of FTP nodes is by about 0.4×10^{-1} at 30 dB. Moreover, Fig. 6 shows that O-DF with ATP consumes more power than O-DF with FTP. This is because, in O-DF with FTP the cooperation is not always performed and hence the power that may be used by the selected relay is saved.

In the absence of interference, the difference between the SEP of O-DF with FTP and O-DF with ATP becomes more important. In high SNR, O-DF with ATP significantly outperforms the SEP of O-DF with FTP. This is mainly because at high SNR, transmitting with low power is more efficient mainly in the absence of primary interference. Besides, in O-DF with FTP, cooperation is not performed when relays disrespect the primary interference constraint while in O-DF with ATP, the cooperation is always performed. Hence, the SEP of O-DF with ATP is significantly better than that of O-DF with FTP. We observe that the presence of primary interference largely deteriorates the SEP performances of the secondary network. For the same consumed power, the performance of O-DF with FTP are deteriorated by about 0.5×10^{-1} at 20 dB.

In terms of data rate, Fig. 5 shows that O-DF with FTP slightly outperforms O-DF with ATP. This is due to the fact that in O-DF with FTP, the cooperation is not always performed. We observe that when the number of relays increases the SEP performances of the secondary systems improve. This is because, when the number of relays increases, the central schedular S may have better choices to select the best relay.



(a)



(b)

Fig. 4. SEP comparison of O-DF with FTP and O-DF with ATP (a) M_r=4 relays, (b) M_r=2 relays.

Moreover, when the number of relays increases the probability that all the relay do not respect the interference constraint decrease and hence cooperation will often be performed. In terms of data rate, the performances decreases when the number of relay increases. This is because, as explained earlier when the number of relay increases, the cooperation is often performed which deteriorates the data rate. Obviously, when the cooperation is always performed, the secondary system will dispense more power (power allocated for the relay). Finally, we observe that analytical and simulation curves are in perfect accordance which validates the presented performances analysis.

In Fig. 7, Fig. 8 and Fig. 9, we compare the SEP, the data rate and the power consumed to transmit one symbol of the O-AF with FTP and O-AF with ATP, respectively for a number

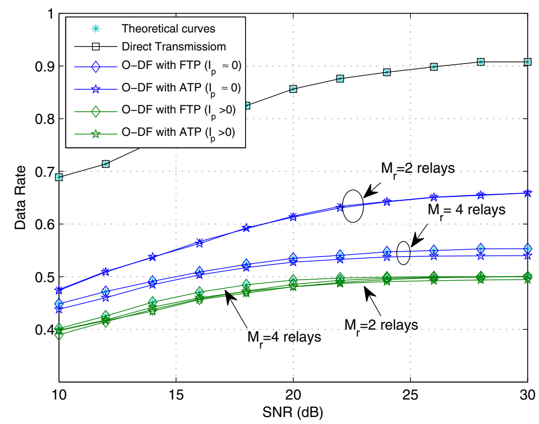


Fig. 5. Data rate comparison of O-DF with FTP and O-DF with ATP for M_r=4 relays and M_r=2 relays.

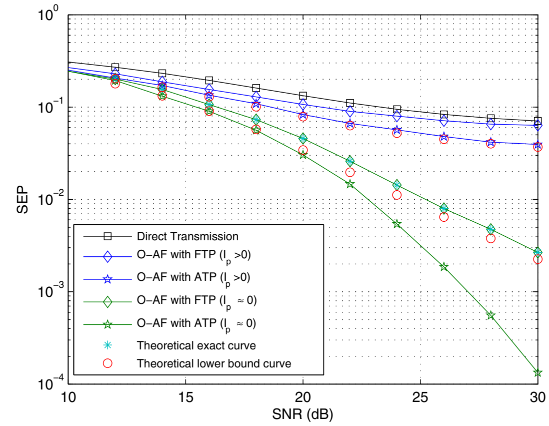


Fig. 7. SEP comparison of O-AF with FTP and O-AF with ATP for M_r=4 relays.

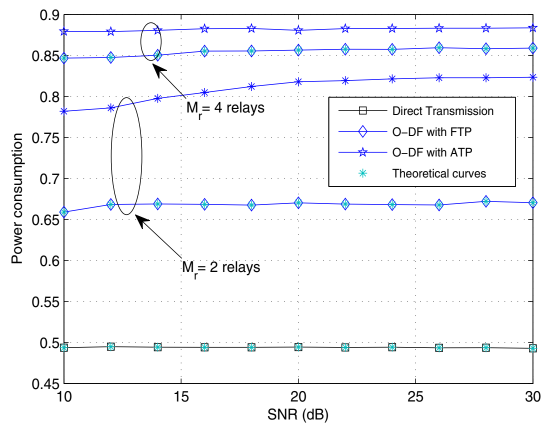


Fig. 6. Power consumption comparison of O-DF with FTP and O-DF with ATP for M_r=4 relays and M_r=2 relays.

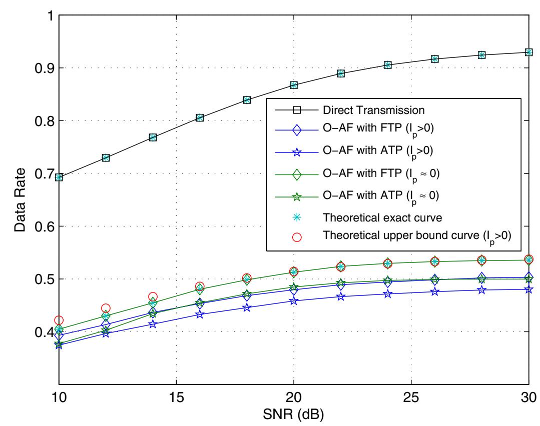


Fig. 8. Data rate comparison of O-AF with FTP and O-AF with ATP for M_r=4 relays.

of relays $M_r = 4$. In the presence of primary interference, we observe that the deterioration in SEP of O-AF with FTP compared to O-AF with ATP is not significant. Fig. 9 indicates that O-AF with ATP requires more power than O-AF with FTP. In the absence of interference, the deterioration in performance

becomes a little important that in the presence of primary interference. This is expected since the primary interference has a great impact on the SEP performances of the secondary network. For data rate performance, Fig. 8 shows that O-AF with FTP slightly outperforms O-AF with ATP. This is because in O-AF with FTP, the cooperation is not always performed contrarily to O-AF with ATP where cooperation is always performed. Form Fig.7-Fig.9, we conclude that O-AF with FTP requires less power than O-AF with ATP while preserving close SEP performance to this latter and so, in this case it is more interesting for practical implementation than O-AF with ATP. The theoretical curves in Fig. 7-Fig. 9 match well with the simulation curves. Moreover, the lower bound curves are very close to the exact curves.

In Fig .10, Fig .11 and Fig. 12, we compare the SEP, data rate and the average power consumed to transmit one symbol of the PR with FTP and the PR with ATP, respectively for a number of relays $M_r = 4$. Like other schemes, we note that the SEP performances of both PR with FTP and PR with ATP are close. Meanwhile, a difference in power consumption is observed in Fig. 12. In the absence of interference, the deterioration in SEP performance of PR with FTP compared to PR with ATP is more important due to the improvement of the channels qualities. In terms of data rate, Fig. 10 shows that the data rate of PR with FTP is a little higher than that of PR with ATP. The data rate of both schemes remain close in the absence of interference. We observe that the exact curves matches well with the simulation ones. Moreover, the provided lower bound curves are close to the exact ones.

We conclude that in the presence of interference, which is a practical case, the deterioration in performances due to the use of FTP nodes is slight. These results can be exploited to have insights in designing simple and efficient cognitive radio networks. Also, for O-DF relaying, Figures show that the deterioration of SEP performance compared to O-DF with ATP is more important than O-AF with FTP and PR with FTP relaying. This is due to the efficiency of cooperation in DF relaying compared to AF relaying. Since in FTP the cooperation is not always performed, this influences the SEP performance when using DF relaying more that AF relaying.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

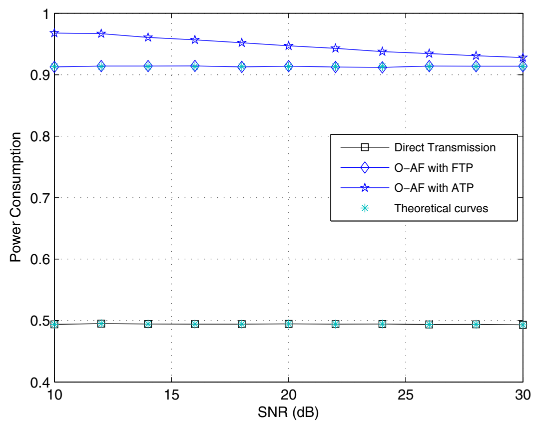


Fig. 9. Power consumption comparison of O-AF with FTP and O-AF with ATP for M_r=4 relays.

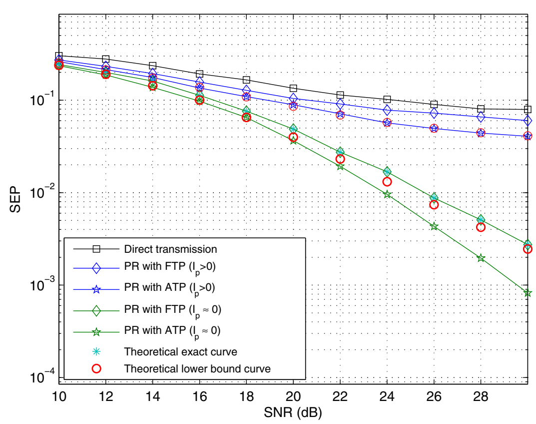


Fig. 10. SEP comparison of PR with FTP and PR with ATP for M_r ==4 relays.

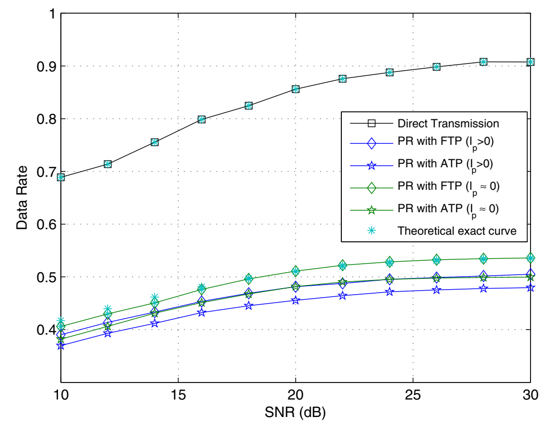


Fig. 11. Data rate comparison of PR with FTP and PR with ATP for M_r =4 relays.

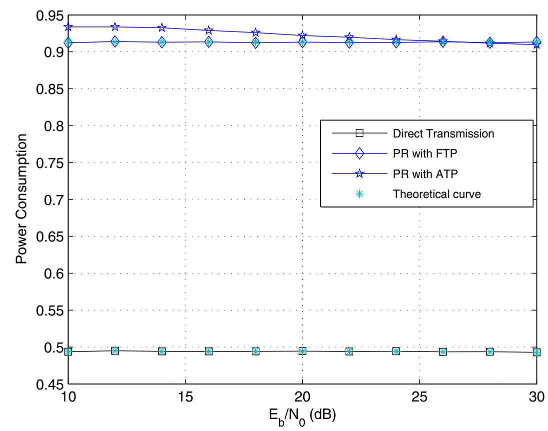


Fig. 12. Power consumption comparison of PR with FTP and PR with ATP for M_r =4 relays.

VII. Conclusion

In this paper, we have showed that FTP needs less signaling than the ATP and we have evaluated the performance degradation incurred by the FTP nodes compared to the ATP. We have investigated three relaying schemes using FTP for an underlay radio cognitive network operating near a primary receiver: O-DF with FTP, O-AF with FTP and PR with FTP. Our proposed relaying schemes work by selecting a relay that is able to satisfy the interference constraint imposed by primary receiver. The corresponding relaying schemes with ATP are also presented in order to compare the performances of relaying schemes with FTP: O-DF with ATP, O-AF with ATP and PR with ATP. In these schemes, relays adjust their transmit power in order to respect the primary interference constraint. Exact form expressions in the absence and presence of primary interference of the SEP, the data rate and power consumption of O-DF are presented in order to validate simulation results. For simplification reasons, exact form expressions for the SEP, the data rate and the power consumption of O-AF with FTP and PR with FTP are provided in the absence of primary interference. Bounds of the performances of O-AF with FTP and PR with FTP are given in both the absence and the presence of primary interference. We proved that the use of O-AF with FTP and PR with FTP consumes less power than O-AF with ATP and PR with ATP, respectively. But, O-AF with FTP and PR with FTP incurs a slight deterioration in SEP performances compared to O-AF with FTP and PR with ATP. For O-DF with FTP relaying, we found that the deterioration of SEP performance compared to O-DF with ATP is more important than O-AF with FTP and PR with FTP relaying.

Appendix A
Expression of $M_{\Gamma_{S,D}}(s)$ and $M_{\Gamma_{R_s^{\text{O-DF}}D}}(s)$ in the Presence of Primary Interference

To derive the expression of $M_{\Gamma_{SD}}(s)$, we need to derive the PDF and CDF of Γ_{SD}.

We have $\Gamma_{SD} = \frac{\mathcal{P}_S|h_{S,D}|^2}{\mathcal{P}_p|h_{PT,Y}|^2+N_0}$. Let $Z = P_S|h_{S,D}|^2$ and $Y = N_0 + P_p|h_{PT,D}|^2$. $|h_{S,D}|^2$ and $|h_{PT,D}|^2$ are two exponential random variable with means $\frac{1}{d_{S,D}^{\alpha}}$ and $\frac{1}{d_{PT,D}^{\alpha}}$, respectively. The CDF of $\Gamma_{SD} = \frac{Z}{Y}$ is given by

$$F_{\Gamma_{SD}}(\gamma) = \int_{N_0}^{\infty}\left(1-\exp(-\frac{z}{\sigma_{S,D}^2})\frac{1}{\sigma_{PT,D}^2\gamma}\right) \times \exp(-\frac{t-N_0}{\sigma_{PT,D}^2\gamma})dt, \text{ for } \gamma \geq 0, \quad (37)$$

where $\sigma^2_{X,Y} = \frac{P_X}{d^\alpha_{X,Y}}$ and $\sigma^2_{PT,Y} = \frac{P_p}{d^\alpha_{PT,Y}}$. Solving this integral yields to the following expression

$$F_{\Gamma_{S,D}}(\gamma) = 1 - \frac{\sigma^2_{S,D}}{\sigma^2_{S,D} + \sigma^2_{PT,D}\gamma} \exp(-\frac{N_0\gamma}{\sigma^2_{S,D}}).$$

The PDF of $\Gamma_{S,D}$ can be obtained by making the derivative of this expression with respect to γ. The obtained expression is given by

$$f_{\Gamma_{S,D}}(\gamma) = \frac{N_0}{\sigma^2_{S,D} + \sigma^2_{PT,D}\gamma} \exp(-\frac{N_0\gamma}{\sigma^2_{S,D}}) + \frac{\sigma^2_{S,D}\sigma^2_{PT,D}}{(\sigma^2_{S,D} + \sigma^2_{PT,D}\gamma)^2} \exp(-\frac{N_0\gamma}{\sigma^2_{S,D}}), \text{ for } \gamma \geq 0$$

The expression of $M_{\Gamma_{S,D}}(s)$ can be obtained by using the expression of $f_{\Gamma_{S,D}}(\gamma)$ as in (7). For the derivation of $M_{\Gamma_{R_s^{\text{Q-DF}}D}}(s)$, we need the PDF of $\Gamma_{R_s^{\text{Q-DF}}D}$. This is can be determined as follows

$$f_{\Gamma_{R_s^{\text{Q-DF}}D}}(\gamma) = \sum_{i \in U} f_{\Gamma_{i,D}}(\gamma) \prod_{k \in U, k \neq i} F_{\Gamma_{i,D}}(\gamma).$$

This can be yet expressed as (38) [19], where $\{l_{R_i,k}\}_{k=1}^{|C|-1}$ is the set of relays indices in $C\backslash\{R_i\}$, $[\xi_p(1), \ldots, \xi_p(|C|-1)]$ is the binary representation of $0 \leq p \leq 2^{|C|-1} - 1$, $\xi(p) = \sum_{k=1}^{|C|-1} \xi_p(k)$ and

$$\Lambda_1(\gamma) = \frac{N_0}{\sigma^2_{R_i,D} + \sigma^2_{PT,D}\gamma} \text{ and}$$

$$\Lambda_2(\gamma) = \frac{\sigma^2_{R_i,D}\sigma^2_{PT,D}}{(\sigma^2_{R_i,D} + \sigma^2_{PT,D}\gamma)^2}. \quad (39)$$

Finally, the expression of $M_{\Gamma_{R_s^{\text{Q-DF}}D}}(s)$ can be obtained by using the expression of $f_{\Gamma_{R_s^{\text{Q-DF}}D}}(\gamma)$ as in (7).

Appendix B
Expression of $M_{\Gamma_{R_s^{\text{Q-DF}}D}}(s)$ in the Absence of Primary Interference

If we ignore the interference from PT, then the PDF of $\Gamma_{R_s^{\text{Q-DF}}D}$ when $C \neq \emptyset$ is given by [19]

$$p_{\Gamma_{R_s^{\text{Q-DF}}D}}(\gamma) = \sum_{R_i \in C} \sum_{p=0}^{2^{|C|-1}-1} \frac{(-1)^{\xi(p)}}{\lambda^2_{R_iD}} \times \exp\left(-\gamma\left(\frac{1}{\lambda^2_{R_iD}} + \sum_{k=1}^{|C|-1} \frac{\xi_p(k)}{\lambda^2_{R_{l_{R_i,k}}D}}\right)\right), \quad (40)$$

where $\{l_{R_i,k}\}_{k=1}^{|C|-1}$ is the set of relays indices in $C\backslash\{R_i\}$, $[\xi_p(1), \ldots, \xi_p(|C|-1)]$ is the binary representation of $0 \leq p \leq 2^{|C|-1} - 1$ and $\xi(p) = \sum_{n=1}^{|C|-1} \xi_p(n)$.

Using the PDF of $\Gamma_{R_s^{\text{Q-DF}}D}$ in (38), we can deduce its MGF,

$$M_{\Gamma_{R_s^{\text{Q-DF}}D}}(s) = \sum_{R_i \in C} \sum_{p=0}^{2^{|C|-1}-1} \frac{(-1)^{\xi(p)}}{\lambda^2_{R_iD}s + 1 + \sum_{k=1}^{|C|-1} \frac{\lambda^2_{R_iD}\xi_p(k)}{\lambda^2_{R_{l_{R_i,k}}D}}}. \quad (41)$$

Appendix C
Expression of $M_{\gamma_{SR_s^{\text{PR with FTP}}D}}(s)$

The expression of $M_{\Gamma_{SR_s^{\text{PR with FTP}}D}}(s)$ can be written as

$$M_{\Gamma_{SR_s^{\text{PR with FTP}}D}}(s) = \sum_{R_i \in U} M_{\Gamma_{SR_s^{\text{PR with FTP}}D}|R_s^{\text{PR with FTP}}=R_i}(s) \times \mathbb{P}(R_s^{\text{PR with FTP}} = R_i). \quad (43)$$

The probability $\mathbb{P}(R_s^{\text{PR with FTP}} = R_i)$ is given by [20]

$$\mathbb{P}(R_s^{\text{PR with FTP}} = R_i) = \sum_{\substack{R_k \in U \\ R_k \neq R_i}} \sum_{p=0}^{2^{|U|-2}-1} \frac{(-1)^{\xi(p)}}{1 + \frac{\lambda^2_{SR_k}}{\lambda^2_{SR_i}} + \lambda^2_{SR_k} \sum_{n=1}^{|U|-2} \frac{\xi_p(n)}{\lambda^2_{SR_{l_{R_i,R_k,n}}}}}, \quad (44)$$

where $\{l_{R_i,R_k,n}\}_{n=1}^{|U|-2} = U\backslash\{R_i, R_k\}$ is the set of relays indices except R_i and R_k.

The conditional MGF $M_{D|R_s^{\text{PR with FTP}}=R_i} = M_{\Gamma_{S,D}}(s) M_{\Gamma_{SR_iD}}(s)$, where, the expression of $M_{\Gamma_{SR_iD}}(s)$ is given by (42) [18], where $\Psi(a,b;z)$ is the Tricomi's confluent hypergeometric function [21] and

$$\varphi^{\pm}_{\nu,\mu}(s) \triangleq \frac{1}{2}[s + \nu + \mu \pm \sqrt{(s + \nu + \mu)^2 - 4\nu\mu}].$$

Using (43) and (44), we obtain the MGF of $M_{\gamma_{SR_s^{\text{PR with FTP}}D}}(s)$ when $U \neq \emptyset$.

References

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[2] A. Goldsmith, S. Jafar, I. Maric, and S. Srinivasa, "Breaking spectrum gridlock with cognitive radios: an information theoretic perspective," *Proc. IEEE*, vol. 97, no. 5, pp. 894–914, May 2009.

[3] Y. Zou, J. Zhu, B. Zheng, and Y. Yao, "An adaptive cooperation diversity scheme with best-relay selection in cognitive radio networks," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5438–5445, Oct. 2010.

[4] D. Chen, H. Ji, and X. Li, "Optimal distributed relay selection in underlay cognitive radio networks: an energy-efficient design approach," in *Proc. 2011 IEEE Wireless Commun. Networking Conf.*, pp. 1203–1207.

[5] ——, "Distributed best-relay node selection in underlay cognitive radio networks: A restless bandits approach," in *Proc. 2011 IEEE Wireless Commun. Networking Conf.*, pp. 1208–1212.

[6] C. Luo, F. Yu, H. Ji, and V. Leung, "Distributed relay selection and power control in cognitive radio networks with cooperative transmission," in *Proc. 2010 IEEE Int. Conf. Commun.*, pp. 1–5.

[7] R. Krishna, K. Cumanan, Z. Xiong, and S. Lambotharan, "Cooperative relays for an underlay cognitive radio network," in *Proc. 2009 IEEE Int. Conf. Wireless Commun. Signal Process.*, pp. 1–4.

[8] P. Lin, S. Su *et al.*, "A low-interference relay selection for decode-and-forward cooperative network in underlay cognitive radio," in *Proc. 2011 IEEE Int. Conf. Cognitive Radio Oriented Wireless Netw. Commun.*, pp. 306–310.

[9] M. Seyfi, S. Muhaidat, and J. Liang, "Relay selection in underlay cognitive radio networks," in *Proc. 2012 IEEE Wireless Commun. Networking Conf.*, pp. 283–288.

[10] S. Hussain, M. Abdallah, M. Alouini, M. Hasna, and K. Qaraqe, "Performance analysis of selective cooperation in underlay cognitive networks over rayleigh channels," in *Proc. 2011 IEEE Int. Workshop Signal Process. Advances Wireless Commun.*, pp. 116–120.

[11] S. Hussain, M. Alouini, M. Hasna, and K. Qaraqe, "Partial relay selection in underlay cognitive networks with fixed gain relays," in *Proc. 2012 IEEE Veh. Technol. Conf. – Spring*, pp. 1–5.

[12] S. Hussain, M. Abdallah, M. Alouini, M. Hasna, and K. Qaraqe, "Best relay selection using SNR and interference quotient for underlay cognitive networks," in *Proc. 2012 IEEE Int. Conf. Commun.*, pp. 5713–5715.

$$f_{\Gamma_{R_s^{\text{O-DF}}D}}(\gamma) = \sum_{R_i\in C}\sum_{n=1}^{2}\Lambda_n(\gamma)\sum_{p=0}^{2^{|C|-1}-1}(-1)^{\xi(p)}\prod_{k=1}^{|C|-1}\left[\frac{\sigma^2_{R_{l_{R_i,k}}}}{\sigma^2_{R_{l_{R_i,k}}}+\sigma^2_{PT,D}\gamma}\right]^{\xi_p(k)}\exp\left(-\gamma\left(\frac{N_0}{\sigma^2_{R_iD}}+\sum_{k=1}^{|C|-1}\frac{N_0\xi_p(k)}{\sigma^2_{R_{l_{R_i,k}},D}}\right)\right). \tag{38}$$

$$\begin{aligned} M_{\Gamma_{SR_iD}}(s) = {} & \frac{\nu_{R_i}+\mu_{R_i}}{\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)-\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)}[\Psi(1,0;\varphi^-_{\nu_{R_i},\mu_{R_i}}(s))-\Psi(1,0;\varphi^+_{\nu_{R_i},\mu_{R_i}}(s))] \\ & \times\left(1+\frac{\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)+\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)}{[\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)-\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)]^2}\right)+\frac{\nu_{R_i}\mu_{R_i}}{\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)-\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)}\Big[\Psi(1,1;\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)) \\ & -\Psi(1,1;\varphi^+_{\nu_{R_i},\mu_{R_i}}(s))\Big]\left(1+\frac{\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)+\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)}{\frac{1}{2}[\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)-\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)]^2}\right)-\frac{\nu_{R_i}+\mu_{R_i}}{[\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)-\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)]^2} \\ & \times\left[\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)\Psi(2,1;\varphi^-_{\nu_{R_i},\mu_{R_i}}(s))+\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)\Psi(2,1;\varphi^+_{\nu_{R_i},\mu_{R_i}}(s))\right]-\frac{2\nu_{R_i}\mu_{R_i}}{[\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)-\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)]^2} \\ & \times\left[\varphi^-_{\nu_{R_i},\mu_{R_i}}(s)\Psi(2,2;\varphi^-_{\nu_{R_i},\mu_{R_i}}(s))+\varphi^+_{\nu_{R_i},\mu_{R_i}}(s)\Psi(2,2;\varphi^+_{\nu_{R_i},\mu_{R_i}}(s))\right]. \end{aligned} \tag{42}$$

[13] S. Hussain, M. Alouini, K. Qaraqe, and M. Hasna, "Reactive relay selection in underlay cognitive networks with fixed gain relays," in *Proc. 2012 IEEE Int. Conf. Commun.*, pp. 1809–1813.

[14] A. S. Ibrahim, A. K. Sadek, W. Su, and K. R. Liu, "Cooperative communications with relay-selection: when to cooperate and whom to cooperate with?" *IEEE Trans. Wireless Commun.*, vol. 7, no. 7, pp. 2814–2827, 2008.

[15] I. Krikidis, J. Thompson, S. McLaughlin, and N. Goertz, "Amplify-and-forward with partial relay selection," *IEEE Commun. Lett.*, vol. 12, no. 4, pp. 235–237, Apr. 2008.

[16] M. Alouini and M. Simon, "An MQF-based performance analysis of generalized selection combining over Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 48, no. 3, pp. 401–415, Mar. 2000.

[17] N. Kong and L. Milstein, "Average SNR of a generalized diversity selection combining scheme," *IEEE Commun. Lett.*, vol. 3, no. 3, pp. 57–59, Mar. 1999.

[18] B. Barua, H. Ngo, and H. Shin, "On the SEP of cooperative diversity with opportunistic relaying," *IEEE Commun. Lett.*, vol. 12, no. 10, pp. 727–729, Oct. 2008.

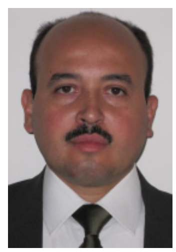
[19] H. Boujemâa, "Exact and asymptotic NEP of cooperative DS-CDMA systems using decode and forward relaying in the presence of multipath propagation," *IEEE Trans. Wireless Commun.*, vol. 8, no. 9, pp. 4464–4469, Sept. 2009.

[20] ——, "Exact symbol error probability of cooperative systems with partial relay selection," *European Trans. Telecommun.*, vol. 21, no. 1, pp. 79–85, Jan. 2010.

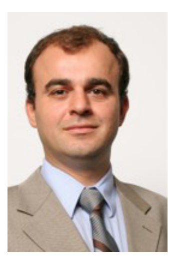
[21] I. Gradshteyen, I. Ryzhik, and A. Jeffrey, *Table of Integrals, Series and Products*. Academic Press, 2000.

Hela Hakim (S'10) was born in Sfax, Tunisia in 1985. She received the Diplôme d'ingénieur and the Master degree in telecommunications (both with honors) from the higher school of communication of Tunis (Sup'Com) in 2009 and 2010, respectively. Since September 2010, she has been a Ph.D. student in information and communication technologies at the higher school of communication of Tunis.

She received several Tunisian Government fellowships for her academic excellence during her MSc and Ph.D. studies. She is also a winner of the Travel Grant of IEEE WiMob Conference 2013 and is preselected by the École polytechnique de Montréal as a candidate for the 2014-2015 competition of the prestigious Merit Scholarship program for Foreign Student offered by the Ministère de l'Éducation, du Loisir et du Sport de Québec. Hela Hakim's main research focus on the cooperative communication, performance analysis of wireless systems and the spectrum sharing in cognitive radio systems. She acts as a reviewer for the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY journal.



Hatem Boujemaa (M'09) was born in Tunisia in 1974. He received the Engineering degree from Ecole Polytechnique, Tunis, Tunisia, in 1997 and the M.Sc. and Ph.D. degrees in electronics and communications from Ecole Nationale Supérieure des Télécommunications, Paris (Telecom Paris Tech), in 1998 and 2001, respectively. From October 1998 to September 2001, he prepared the Ph.D. degree at France Télécom R&D (Orange Labs). He participated in the National Network for Telecommunications Research (RNRT) project New Baseband UMTS Architectures (AUBE). Between 2001 and 2002, he was with Ecole Superieure dÉlectricite (SUPELEC), Gif-sur-Yvette Cedex, France, where he worked on mobile localization for the RNRT project emergency localization using cellular phone (LUTECE). Since September 2002, he has been with the Higher School of Communications of Tunis, Ariana, Tunisia, where he is currently a Professor. His research activities include the field of digital communications, with special emphasis on localization, direct-sequence code division multiple access (CDMA), multi-carrier CDMA, hybrid automatic repeat request protocols, cognitive radio networks and cooperative communications.



Wessam Ajib (M'05) received the Engineer Diploma degree in physical instruments from the Institute National Polytechnique de Grenoble, Grenoble, France, in 1996 and the Diplome dEtudes Approfondies degree in digital communication systems and the Ph.D. degree in computer sciences and computer networks from the cole Nationale Suprieure des Tlcommunication, Paris, France, in 1997 and 2000, respectively. From October 2000 to June 2004, he was an Architect and a Radio Network Designer with Nortel Networks, Ottawa, ON, Canada, where he had conducted many projects and introduced different innovative solutions for the third generation of wireless cellular networks. From June 2004 to June 2005, he was a Postdoctoral Fellow with the Department of Electrical Engineering, Ecole Polytechnique de Montral, Montreal, QC, Canada. Since June 2005, he has been with the Department of Computer Science, University of Quebec at Montreal, Montreal, where he is currently an Assistant Professor of computer networks. He is the author or coauthor of many journal and conference papers. His research interests include wireless communications and wireless networks, multipleand medium-access control design, traffic scheduling, multiple-inputmultipleoutput systems, and cooperative communications.