Performance Analysis of Cognitive Femtocell Network with Ambient RF Energy Harvesting

Jerzy Martyna(✉)

Institute of Computer Science, Faculty of Mathematics and Computer Science, Jagiellonian University, ul. Prof. S. Lojasiewicza 6, 30-348 Cracow, Poland
martyna@ii.uj.edu.pl

Abstract. Radio frequency (RF) energy harvesting is a promising technique to collect energy from the concurrent downlink transmissions. This energy after converting it into DC power can power up such devices as cell phones, Wi-Fi networks, etc. In this paper, a model of RF energy harvesting in the cognitive femtocell is presented. Additionally, an algorithm to maximise the average throughput of the secondary system over a given slot time is given. Increased throughput allows to improve the energy harvesting in the femtocell. Moreover, the effect of varying the different parameters such as the spatial density of BSs, significantly affects the values of energy harvesting in cognitive femtocell network. The obtained results of simulation tests confirm the obtained theoretical results of energy harvesting in cognitive femtocell networks.

Keywords: Cognitive radio · Femtocell network
RF energy harvesting · Spectrum sharing · Power control

1 Introduction

Recently, a radio frequency (RF) energy harvesting technique is emerging as an attractive solution to power low-energy wireless communicatiuon devices [4,11]. Such a technique allows to improve spectrum utilisation and convert electromagnetic waves from ambient RF sources (cellular base stations, PU base stations, etc.) into energy which can be used as to power up many devices such as cell phones, sensors, etc. This has been confirmed by numerous experiments and reports, a.o. results given by Ostaffe [10], which has been shown that with the transmit power of 0.5 W by a mobile phone, 0.4 mW of power can be harvested at the distance 10 m.

The idea of simultaneously transmitting both energy and information was first proposed by Varshney [19]. Author characterised the fundamental trade-off for capacity-energy function under the assumption of an ideal energy harvesting receiver. The basic relationships between the energy transferred by electromagnetic waves and the information contained in them is presented by Grover and

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Sathai [3]. Two practical approaches for energy harvesting have been proposed in the paper by Zhou *et al.* [21]. The first approach is based on a power-splitting (PS) mechanism, where a PS receiver splits the received signal into two parts, based on the PS ratio. While the first part of the received signal is used for energy harvesting, the second one is used for information processing. The second approach is based on time-switching (TS) technique, where the total time is divided into two intervals: first for data harvesting and second for information processing. Some relaying protocols for wireless energy harvesting have been proposed by Nazir *et al.* [9] that can be implemented in an amplify-and-forward (AP) relay based one-way-communication networks.

Another approach to solving problems of energy harvesting is a concept of a cooperative network of simultaneously data relaying and energy harvesting [7]. An energy harvesting protocol and information processing in two-way multiplicative relay network using power and splitting-based relaying (PSR) protocol was proposed by Shah *et al.* [16]. The impact of the time switched-based relaing protocol at high transmission rates has been studied by Shah *et al.* [17]. On the other hand, a number of works investigated how the location of BS and the hierarchy in cellular networks affect energy harvesting. Among others, a performance evaluation of multi-tier uplink cellular network with RF energy harvesting and flexible cell association was developed by Sakr *et al.* [12]. An analysis of K-tier uplink cellular networks with ambient RF energy harvesting has been presented by the same author [15]. Nevertheless, none of these and other publications have analyzed the performance of harvesting in cognitive femtocell networks.

Cognitive radio network (CRN) is a technology that connects nodes in the form of cognitive radio (CR) systems [8] using network technologies. In general, these nodes are intelligent and have the ability to observe, learn, and optimise their performance. They can cooperate with others, but only then when cooperation can improve theiDow to develop cooperation among selfish nodes. Furthermore, the division of CRN equipments into two sub-networks: primary network (PN), using exclusive licensed band, and secondary network (SN), using both unlicensed bandwidth and unused at the moment, the licensed band, a system was created that allows to increase the efficiency of the use of spectrum resources. The PN network consists of all Primary Users (PUs) who use the licensed band, while the SN network includes secondar users (SUs).

Cognitive radio femtocell networks (CRFN) [13] are recent technology breakthroughs that aim to achieve throughput improvement by means of spectrum management and interference mitigation, respectively. Based on the CR technology, the access control scheme greatly improves the performance of cognitive users near to femtocells. The jointly designed distributed access and power control algorithm can be solved by game theory [14]. Downlink scheduling and power allocation in cognitive femtocell networks are studied a.o. by Elmaghrab [2]. According to the given results, the throughput maximisation of femtocell users allows to share spectrum resources with macrocell base station (MBS) while limiting interference between macrocell and femtocells. Distributed resource allocation with imperfect spectrum sensing information and channel uncertainty in cognitive femtocell networks has been studied by Huang *et al.* [6]. Nevertheless, none of the paper known to the author analyze RF energy harvesting by the cognitive femtocell network.

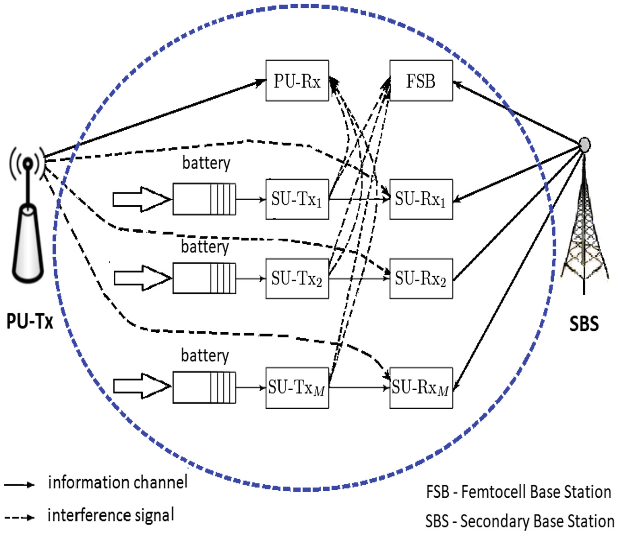

Fig. 1. System model of cognitive femtocell network.

The main purpose of the work is to create a model for acquiring energy transferred by electromagnetic waves in the cognitive femtocell network. Next, the second objective of the work is to formulate the basic dependencies allowing for the calculation of the obtained energy from the basic parameters of this network. Finally, the purpose of the work is to provide an algorithm that maximises bandwith for better performance SUs and guarantee QoS for PUs users.

The rest of the paper is organized as follows. The second section presents the system model. The third section presents the modelling of energy harvesting in the cognitive femtocell network. Section 4 presents the algorithm for obtaining energy from the femtocell network and the algorithm of bandwidth maximisation for better performance of SUs and QoS guarantee for PUs. Section 5 gives the results of simulation studies. The conclusion ends with this paper.

2 System Model

This section presents the model of the cognitive femtocell network.

Let the system model be a single PU receiver (PU-Rx) and M SUs, as shown in Fig. 1. It is assumed that each SU has an energy harvesting (EH) device. It is also assumed that all subcarriers are of the same band. Both PN and SN systems use the OFDMA scheme. In addition, it is assumed that one subcarrier can only be used by one SU at each time slot. The interference between individual SUs is ommitted. Each SU can use multiple subcarriers at each time slot.

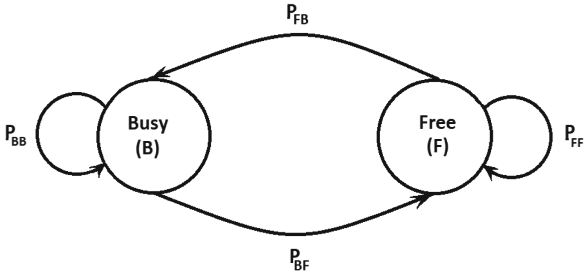

Fig. 2. Markov channel model.

The Rayleigh fading channel will be modelled as a two-state Markov chain (see Fig. 2) [18]. As shown in this figure, state B denotes that PU is inactive, while the state F means that the PU is inactive. For a time slot $k, k \in \{1, \ldots, K\}$ it is possible to define the state of the channel n, namely

$$x_k^n = \begin{cases} 1, & \text{if the channel is in the state } B \\ 0, & \text{if the channel is in the state } F \end{cases} \tag{1}$$

Let N be the number of subcarriers in the femtocell and L be the number of subcarriers occupied by PU receiver. Thus, the number of random subcarrier state can be expressed by

$$I = \binom{N-M}{L} \tag{2}$$

Let Q_k be the set of states of all channels at the k-th time slot. Then states of all channels available in cognitive femtocell at the time slot k can be given by

$$y_k = \{x_k^1, x_k^2, \ldots, x_k^N\}, \quad i \in \{1, 2, \ldots, K\} \tag{3}$$

For the transition matrix of PU receiver is defined the occupation state as $\mathbf{P}^o$. The state transition probability of the n-th channel can be given by

$$P_{BF}^n = \Pr\{x_{k+1}^n = 0 \mid x_k^n = 1\} \tag{4}$$

$$P_{FB}^n = \Pr\{x_{k+1}^n = 1 \mid x_k^n = 0\} \tag{5}$$

The transition probability of $\mathbf{P}^o$ can be described as follows

$$p_{ij}^o = \Pr\{O_{k+1} = y_j \mid O_k = y_i\} \tag{6}$$

After transformation

$$p_{ij}^{o} = \prod_{n=1}^{N} \Pr\{x_{k+1}^{n} \mid x_{k}^{n}\} \tag{7}$$

3 RF Energy-Harvesting Model of Cognitive Femtocell Network

Regarding the RF energy as an energy-harvesting source, the following model is proposed here. First, by expanding the above-mentioned model it is assumed that the femtocell $\mathcal{F}$ is in the radio range of Ω primary transmitters (PUs-Tx). Next, each SU must be equipped with a power conversion circuit that can extract DC power from the received electromagnetic waves [10]. For each SU is defined the harvesting zone, which is a disk with radius r_h centered at each PU-Tx with the radius r_P. The radius r_h is determined by the energy harvesting circuit sensitivity for a given transmission power level of PU-Tx as P_P. It is assumed that given SU within a harvesting zone is entirely inside the femtocell and can receive power larger than the energy harvesting threshold, which is given by $P_P r_h^{\alpha}$, where $\alpha > 2$ is the path-loss exponent. The received power by a SU outside any harvesting zone is too small to activate the energy harvesting circuit, which means it can be omitted.

The probability that a SU lies in femtocell is equal to the probability that there is one PU-Tx inside the disk $\mathrm{SU}(Y, r_h)$, if Y is a coordinate of SU and belongs to the area occupied by femtocell. Let the number of SUs inside $\mathrm{SU}(Y, r_h)$ is denoted by Ω and is a Poisson random variable with mean $\pi r_h^2 \lambda_p$, where $\lambda_p = p\lambda_p'$, p is the probability of accessing PU-Tx at each time slot, λ_p' is the density of PU-Tx.

Thus, the probability mass function (PMF) inside the disk $\mathrm{SU}(Y, r_h)$ is given by

$$\Pr\{\Omega = \omega\} = e^{-\pi r_h^2 \lambda_p} \frac{(\pi r_h^2 \lambda_p)^{\omega}}{\omega!}, \quad \omega = 0, 1, 2, \ldots \tag{8}$$

The probability that the SU lies in femtocell within radio range of PUs-Tx, p_h, is given by

$$p_h = \Pr\{SU \in \mathcal{F}\} \tag{9}$$

$$= \Pr\{\Omega \geq 1\} \tag{10}$$

$$= \sum_{\omega=1}^{\infty} e^{-\pi r_h^2 \lambda_p} \frac{(\pi r_h^2 \lambda_p)^{\omega}}{\omega!} \tag{11}$$

$$= 1 - e^{-\pi r_h^2 \lambda_p} \tag{12}$$

In practice, values λ_p and r_h are both small. Thus, it is assumed that $\pi r_h^2 \lambda_p \ll 1$. This allows approximation of Eq. (12) by ignoring the higher-order terms with $\omega > 1$. It indicates that if SU is inside the harvesting zone of one single PU-Tx most probably most probably, which equivalently means that the harvesting zones of different PUs-Tx do not overlap at most time. Thus, the amount of average power harvested by SU in femtocell in a time slot can be lower-bounded by $\eta p_p R^{-\alpha}$, where $R \leq r_h$ indicates the distance between SU and its nearest PU-Tx, η is the harvesting efficiency.

It is necessary to define the remaining baterry energy for each m-th SU in the k-th time slot. It can be assumed using [18] that the battery energy is available at the next slot $k+1$ in the n-th channel can be defined

$$B_{k+1}^{m} = \min\{B_k^m - p_k^{m,n} T + E_k^m, B_{max}\}, \quad k \in \{1, \ldots, K\}, \ m \in \{1, \ldots, M\} \quad (13)$$

where $p_k^{m,n}$ is the transmission power allocated in the m-th SU in the n-th channel at time slot k, T denotes the duration of one time slot and B_{max} denotes the maximum energy battery capacity.

It is possible to define for a cognitive femtocell signal-to-interference-plus-noise ratio (SINR) $SINR_k^{m,n}$ of the m-th SU in the n-th channel at the time slot k, namely

$$SINR_k^{m,n} = \frac{h_k^{m,n} p_k^{m,n}}{\sum_{\omega=1}^{\Omega} h_k^{\omega,n} p_k^{\omega,n} + \sum_{j=1, j\neq m}^{M} h_k^{j,n} p_k^{j,n} + h_k^{F,n} p_k^{F,n} + \sigma^2}, \\ k \in \{1, \ldots, K\}, \quad j, m \in \{1, \ldots, M\}, \quad n \in \{1, \ldots, N\} \quad (14)$$

where $p_k^{\omega,n}$ and $p_k^{F,n}$ denote the transmission power in the n-th channel of the ω PU-Tr and FSB, respectively, at the time slot k; $h_k^{m,n}$ is the channel coefficient at the m-th SU in the n-th channel, $h_k^{\omega,n}$, $h_k^{F,n}$ are the channel coefficient at the ω-PU-Tr and the FSB, σ^2 is the noise power, respectively.

Then it is possible to define

$$g_k^{m,n} = \frac{h_k^{m,n}}{\sum_{\omega=1}^{\Omega} h_k^{\omega,n} p_k^{\omega,n} + \sum_{j=1, j\neq m}^{M} h_k^{j,n} p_k^{j,n} + h_k^{F,n} p_k^{F,n} + \sigma^2}, \\ k \in \{1, \ldots, K\}, \quad j, m \in \{1, \ldots, M\}, \quad n \in \{1, \ldots, N\} \quad (15)$$

The throughput of the m SU at the time slot k can be presented as follows:

$$R_k^m = \sum_{n=1}^{N} \log_2(1 + g_k^{m,n} \cdot p_k^{m,n}), \quad m \in \{1, \ldots, M\} \quad (16)$$

where $g_k^{m,n}$ means the channel gain distribution of the m-th SU in the subcarrier-occupied state of time slot k in the n-th channel.

The throughput of the m-th SU at the k-th time slot in the n-th channel can be maximised as follows

$$\max_{p_k^{m,n}} E\{\frac{1}{K} \sum_{k=1}^{K-1} \sum_{m=1}^{M} \sum_{n=1}^{N} \log_2(1 + g_k^{m,n} \cdot p_k^{m,n})\} \quad (17)$$

subject to

$$\sum_{k=1}^{K}\left(\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{\omega=1}^{\Omega} h_k^{\omega,n}p_k^{\omega,n} + \sum_{j=1,j\neq m}^{M} h_k^{j,n}p_k^{j,n} + h_k^{F,n}p_k^{F,n}\right) + \sigma^2 \leq I^{TH}, \quad k \in \{0,\ldots,K-1\} \tag{18}$$

$$\sum_{n=1}^{N} p_k^{m,n} \leq \frac{B_k^m}{T}, \quad k \in \{0,\ldots,K-1\} \tag{19}$$

$$p_k^{m,n} \geq 0, \quad m \in \{1,\ldots,M\}, k \in \{0,\ldots,K-1\}, n \in \{1,\ldots,N\} \tag{20}$$

$$R_k^m \geq R_{min}^m, \quad k \in \{0,\ldots,K-1\} \tag{21}$$

The condition defined by Eq. (18) gives the interference power constraint to guarantee the interference to PUs. I^{TH} denotes the interference threshold acceptable for PUs. The condition given by Eq. (19) denotes the maximum transmission power constraint $\frac{B_k^m}{T}$ defines the total transmission power budget for the m-th SU at the time slot k. Equation (20) gives the minimum throughput requirement in cognitive femtocell network. The condition given by Eq. (21) guarantees the transmission power of each SU.

It remains to be defined how specific performance by measures are achieved by the RF-powered device as the expectation of RF energy harvesting rate, including average energy outage probability, and average transmission outage probability. The mathematical quantities of interest are then defined in the following. The expectation of the RF energy harvesting rate can be defined as:

$$E_{P_H} \triangleq E[P_H] \tag{22}$$

where the RF energy harvesting rate (in watts) by the device from the RF transmitter in a fading channel is given [21] by

$$P_H = \frac{\tau\beta P_S g_m}{d_\omega^\alpha} \tag{23}$$

where β is the RF-to-DC power conversion efficiency of the device, P_S is the transmit power of the PU transmitter, α is the path-loss exponent, h_ω is the channel power gain from the transmitter ω to the device, d_ω is the distance from the ω-th PU.

Energy outage occurs when the RF powered device cannot harvest sufficient RF energy from the ambiance to operate the circuit. The energy outage probability is defined as P_{CO}, P $(P_H < P_C)$, where P_H is the RF energy harvesting rate of the SU device, P_C is the circuit power consumption of the RF-powered device. QoS metric can be defined as a transmission outage probability.

Let $\kappa \geq 0$ denote the minimum information throughput requirement. If the RF-powered device fails to obtain enough throughput, it incurs a transmission outage. Thus, the transmission outage probability can be calculated as:

$$P_{TO} \stackrel{\triangle}{=} P\left(P_H < P_C\right) + P(C < \kappa, P_H \geq P_C) \tag{24}$$

which indicates that the transmission outage occurs in two cases, namely when there is an energy outage, and when the decoded information throughput is less than the minimum requirement under the condition that there is enough harvested power.

4 An Algorithm for Energy Harvesting in Cognitive Femtocell Network

This part proposes an algorithm that can be used for RF energy harvesting in cognitive femtocell network.

Obtaining the highest possible amount of energy obtained by SU devices can be possible only when for all SUs are maximized their throughput, while maintaining guaranteed interference from the PU below a certain threshold. Therefore, an algorithm is proposed here that maximises the average throughput of SUs over a finite time interval. This algorithm uses a reward function, which is defined as the maximum of the sum of throughput at the current time slot and the expectected cumulative throughput at the future time slot from the current time system state.

The current reward function at time slot k is a function of the current energy budget B_k^m of each SU and the current system state S_k at time slot k and is given by

$$\begin{aligned} V_k(B_k^1, B_k^2, \ldots, B_k^M; S_k) = \max_{p_k^{m,n}} E\{\sum_{v=k}^{K-1} \sum_{m=1}^{M} \sum_{n=1}^{N} log_2(1 + g_k^{m,n} p_k^{m,n})\} \\ k \in \{1, \ldots, K\} \end{aligned} \tag{25}$$

The steps of throughput maximisation for energy harvesting in cognitive femtocell network are presented in Algorithm 1 (see Fig. 3). The presented algorithm checks the occupancy of all subcarriers available for each SU in cognitive femtocell. Then it maximises sum of the throughput at the current time slot. It uses Bellman's dynamic programming method.

5 Simulation Results

This section will present the results of simulation tests for cognitive femtocell network.

It was assumed that the system is composed of PU-Tx outside the femtocell and a single PU-Rx inside fem-tocell. Inside the femtocell are located four SUs with energy harvesting devices. In addition, the OFDMA scheme is used OFDMA scheme, wherein the available spectrum is sharing into 12 subcarriers (N = 12). The number of subcarrier occupation state is equal to 70. It was assumed that the maximum battery capacity is equal to 6 J. Thus, the energy budget of femtocell is equal to 24 J. It is assumed that the constant depending on the energy budget at current time slot is equal to 0.001 W. In this case, the permissible interference at the PU-Rx is equal to 0.01 W.

Algorithm 1 Power allocation in CRFN system for energy harvesting

procedure PA IN CFN FOR ENERGY HARVESTING
    for $m \leftarrow 1, M$ **do**
        if $\sum_{n=1}^{N}\sum_{m=1}^{M}(a_k^{m,n}p_k^{P,n} + b_k^{m,n}p_k^{F,n}) \leq I^{TH}$ **then**
            while $\sum_{n=1}^{N} p_k^{m,n} \leq \frac{B_k^m}{T}$ **do**
                for $k \leftarrow 0, K-1$ **do**
                    for $k \leftarrow K-1, 0$ **do**
                        $V_k(B_k^1, B_k^2, \ldots, B_k^M; S_k)$
                        $= \max_{p_k^{m,n}} E\{\sum_{v=k}^{K-1}\sum_{n=1}^{N}\sum_{m=1}^{M}\log_2(1 + g_k^{m,n}p_k^{m,n})\}$
                    end for
                end for
                $Energy\ harvesting\ for\ the\ m-th\ SU$
            end while
        end if
        $Energy\ harvesting\ for\ the\ m-th\ SU$
    end for
end procedure

Fig. 3. Algorithm for energy harvesting in cognitive femtocell network.

Figure 4 shows the total throughput versus the number of slots. For comparison, the total throughput for the optimal area has been calculated by use the method proposed by [5]. It is evident that the proposed algorithm gives a minimally smaller values of total throuhput in comparison with the method described in [5].

Figure 5 shows the dependence of total energy budget depending on interference at PU-Rx. In this case, the proposed solution is slightly better than the method used in the paper by [5]. Nevertheless, this indicates the efficiency of the proposed algorithm for energy harvesting. This is due to the more accurate operation of the algorithm based on optimization than the proposed heuristic.

Figure 6 shows the total energy buget depending on the average bandwidth. It can be seen from the figure that the total energy budget is much higher for the optimal algorithm than for the used heuristic.

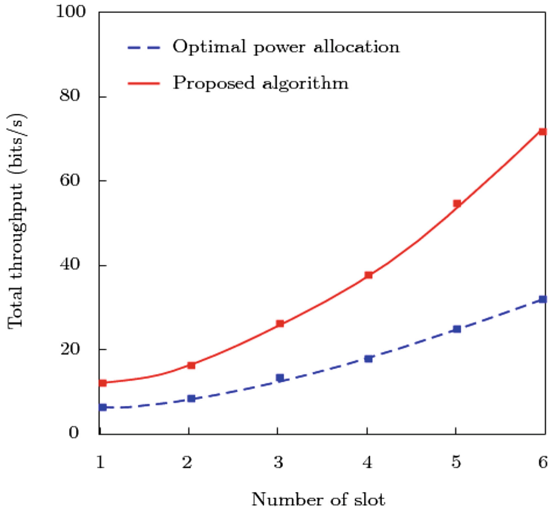

Fig. 4. Total throughput versus the number of slots.

Figure 7 shows P_{TO} as a function of an energy harvesting under different minimum information throughput requirement κ, which is associated with the specified QoS parameters. When the energy harvesting is small, transmission outage is mainly caused by insufficient harvested energy. Growth of energy harvesting causes decreasing value of transmission outage probability.

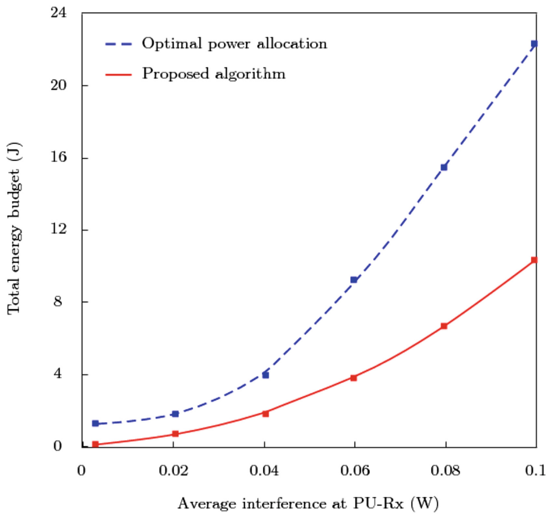

Fig. 5. Total energy budget versus average interference at PU-Rx.

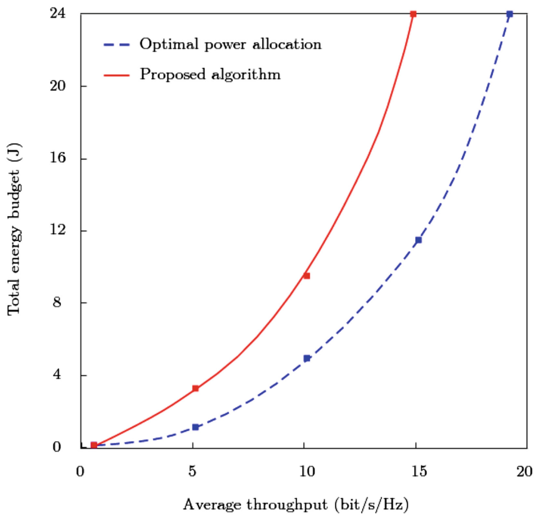

Fig. 6. Total energy budget versus the RF energy harvesting.

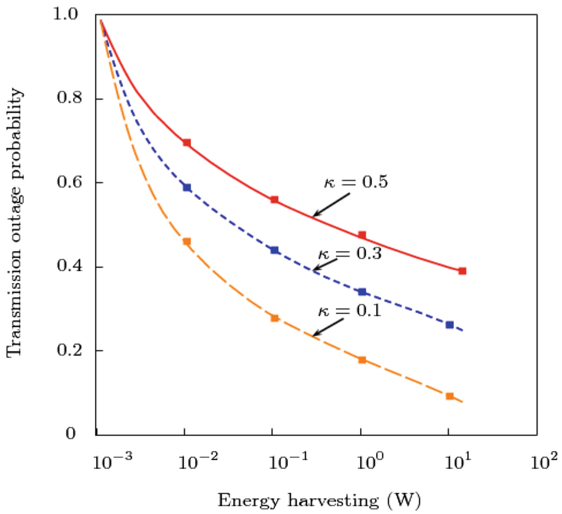

Fig. 7. Transmission outage probability versus RF energy harvesting.

6 Conclusion

This paper presents the model of energy harvesting in cognitive femtocell networks. This allow, among others SUs can generate energy from electromagnetic waves of PUs transmitters, and thus, the lifetime of these devices can be extended. The article presents the basic dependencies, combining SUs density with the value of harvesting energy by SUs. The given procedure shows the maximisation of energy harvesting within the femtocell. The compliance of the mathematical model was confirmed by simulation results, which were presented in the paper.

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