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Stochastic geometry cooperative spectrum sharing scheme between cellular network downlink and mobile ad-hoc network to enhance throughput efficiency using cognitive radio approach

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ABSTRACT

The emerging Cognitive Technology promises to improve the network spectrum-utilization efficiency by allowing cognitive secondary users (SUs) to intelligently sense and opportunistically access those spectrum holes temporarily unused by license-holding primary users (PUs). Cognitive radios hold tremendous promise for increasing spectral efficiency in wireless systems. In this paper, we propose a cooperative spectrum sharing scheme between cellular network downlink and mobile ad-hoc network based on the analysis using stochastic geometry theory. The licensed spectrum belongs to the cellular network and the strong interference at cell-edge becomes a bottleneck to guarantee the quality of service requirement. In this case, the secondary ad-hoc users can assist the transmission between the base station and cell-edge mobile users in exchange for spectrum usage. Through maximizing the transmission capacity of secondary system under the constraint of throughput improvement of primary system, an optimal spectrum allocation can be obtained. Numerical and simulation results are provided to validate the analysis and verify the efficiency of the proposed scheme.

Introduction

The radio spectrum is a scarce resource. It is commonly believed that there is a crisis of spectrum availability at frequencies that can be economically used for wireless communications. In the cooperative spectrum sharing schemes, the secondary users (SUs) can help the primary data transmission in exchange for the channel access in time domain [1], spatial domain [2], or frequency domain [3]. The locations of SUs are usually fixed or restricted into a small area and it is assumed that there is no interference from other concurrent secondary links. It is nontrivial to extend the cooperative spectrum sharing to the mobile ad-hoc networks (MANETs), because the topology changes frequently and the interference suffers from uncertainities, such as random locations of mobile users and fading effects of channels, etc. Non-cooperative spectrum sharing is proposed in the overlaid wireless network through modeling the users as Poisson Point Process (PPP) [4]. The overlay and underlay spectrum sharing are studied for the MANET in [5] and [6], where the primary and secondary systems interfere with each other [7]. It is shown that the interference avoidance overlay scheme outperforms the interference averaging underlay scheme. The stochastic geometry model of three types of cognitive radio networks are proposed in [8], where the single primary link, multi-cast primary system, or primary ad-hoc network coexists with a secondary ad-hoc network shown in Fig-1.

Transmission capacity has often been used as the major performance metric to study MANETs and it is defined as the area throughput under the constraint of outage performance [9]. A slight performance deterioration of primary system can bring a great capacity enhancement of the overlaid wireless network [10]. In terms of transmission capacity, the decode-and-forward based incremental relaying or selection cooperation [11] significantly outperforms the sharing scheme [5], the secondary system accesses the licensed spectrum of primary system without any contribution and the transmission capacity tradeoff is studied considering the mutual interference between two systems.

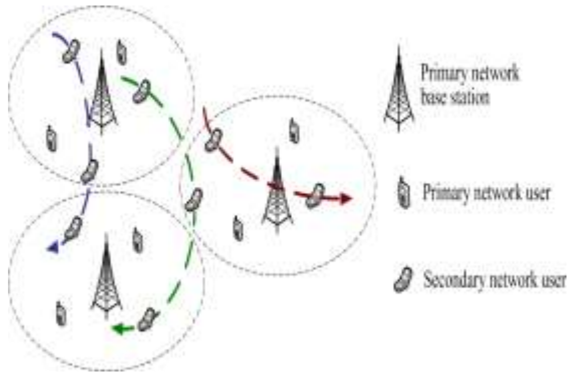

Fig 1. Cellular network overlaid with MANET

In this work, we focus on modeling and analyzing the practical cooperative spectrum sharing scheme between cellular network downlink and MANET. The cellular network is the primary system and it owns the licensed spectrum, while the MANET is the secondary system. As spatial diversity can be

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expected, the cellular net- work needs the assistance of SUs to forward the base station's (BS) data to the cell-edge mobile users (MUs) to combat the strong interference from other cells. Unlike the two-hop relaying in the cellular network [14], where the BSs are located on a regular grid, we model the BSs more flexibly as a PPP. As a reward of the cooperation, a fraction of spectrum is released to the MANET and the remaining disjoint bandwidth is kept by the primary system shown in Fig-2. So, there is no interference between the two systems. Using the stochastic geometry theory, we analyze the transmission capacity of MANET and the throughput of cellular network. The optimal bandwidth allocation is obtained through maximizing the transmission capacity of secondary system under the constraint that throughput of primary sys- tem should be improved. Performance results are provided to verify the efficiency of cooperative spectrum sharing.

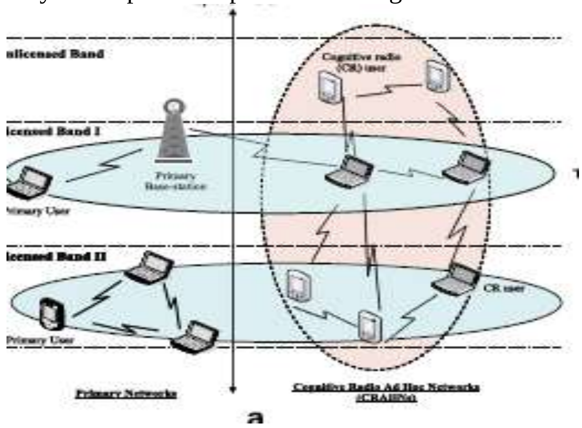

Fig.2. Spectrum sharing between Cellular network and MANET

The licensed spectrum belongs to the cellular network and it is reused by different cells. The locations of BSs are modeled as a homogenous PPP with intensity λb, i.e., Πb={xi, i ∈ Z}. The MUs follow another PPP Πm={yi , i ∈ Z} with intensity λm .

Each MU is served by its nearest BS. As shown in Fig. 3, the cellular network forms a Poisson Tessellation of the plane [5]. Each BS communicates with a randomly selected MU in its cell and the downlink communication is considered. The SUs are distributed in the same geographic region following a PPP with intensity λs, i.e., Πs = {zi, i ∈ Z}. Each SU has a receiver departed d away.The time slotted Aloha protocol is applied in the MANET and each SU independently decides whether to access the channel or not according to the media access probability (MAP).

A fraction of spectrum is released to the MANET in exchange for its cooperative transmission. The normalized bandwidth allocated to the secondary system is β ∈ (0, 1) and the remaining (1−β) spectrum is used by the primary system. The channel between terminal u1 and u2 undergoes small-scale block fading and large-scale path-loss. The small-scale power fading Gu1, u2 is exponentially distributed with unit mean, and it is independent across links. The large-scale path-loss is $1^{-c}_{u1,u2}$, Where $1_{u1,u2}$=|u1 – u2| is the distance and is the path-loss exponent. The symbol u2 in the subscript is omitted for brevity if u2 lies at the origin.

The serving area of each BS is divided into the cell-interior and cell-edge regions.

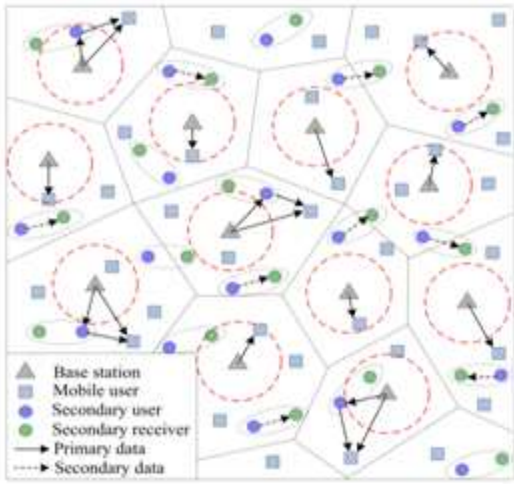

Fig.3.Celluar network overlaid with MANET.

The interior region is defined as a circular area Centered at the BS with radius c0 as shown in Fig-3.For the cell- interior communication, the truncated automatic repeat request (T-ARQ) scheme with one retransmission is adopted. The BS transmits a data packet to its intended cell-interior MU and one of the following two events will occur • E1 : The original transmission succeeds, the acknowledgement (ACK) frame is fed back and the BS continues to transmit a new data packet. • E2: The original transmission fails, the negative acknowledgement (NACK) frame is released and the BS retransmits the data packet. For the cell-edge communication, the cooperative T-ARQ is adopted with the help from a SU. The BS broadcasts a data packet to cell- edge MU and SU, and one of the following three events will occur.

• E1: The cell-edge MU correctly receives the data packet, and the ACK frame is broadcast. The SU flushes its memory and the BS continues to transmit a new data packet.

• E2: The cell-edge MU cannot correctly detect the primary data and the NACK frame is released. The SU fails to receive the data and the BS retransmits its original data packet.

• E3: The primary data is erroneously received by the cell- edge MU and the NACK frame is released. The SU correctly receives the primary data packet and retransmits.

Design objective and performance study

Let the transmission capacity of secondary system be C∈ with ϵ de- noting the target outage probability. To maximize the transmission capacity of secondary system under the performance constraint of primary system, we formulate an optimization problem as follows.

$$\max_{\beta\in(0,1)} \quad C_{\epsilon}\ ,$$
$$s.t.\ \frac{V_c(\beta)-V_d(\beta=0)}{V_d(\beta=0)} \geq \rho\ , \qquad (1)$$

Secondary System: Transmission Capacity C∈

The typical secondary receiver is located at the origin and the achievable rate of the typical link is given as

$$R_s = \beta\, log_2(1 + G_{zo}d^{-\alpha}/I_s), \qquad (2)$$

Where the interference is

$$I_s = \sum_{z\epsilon\Pi_s/\{z_0\}} G_z l_z^{-\alpha}\ . \qquad (3)$$

All the active SUs except the typical one contribute to the aggregate Interference in (3). The transmitting SUs form the PPP **Π**s, which is an independent thinning of **Π**s with intensity ξλs, where ξ is the MAP of the Aloha protocol. The interference-limited environment is considered and the noise effect is negligible. The outage probability is derived as [4],

$$P_{out}^{s} = \Pr\{R_s < T_1\}$$
$$= 1 - \exp\left(-\xi\lambda_s \pi d^2 \tau_1^{2/\propto} \frac{2\pi/\alpha}{\sin(\frac{2\pi}{\alpha})}\right), \quad (4)$$

Where $\tau 1 = 2^{T1/\beta} - 1$ with T_1 denoting the target rate of SUs. The target outage performance of secondary system is ϵ, and the maximum node density λ_ϵ^s that can protect the outage performance is obtained through $P_{out}^{s} = \varepsilon$.Then, the transmission capacity [9] of the secondary system is derived as

$$C_\epsilon = \xi\lambda_\epsilon^s T_1 (1-\varepsilon) = -\frac{l_n(1-\epsilon)}{\pi d^{2\tau_1^{2/\propto}}} \frac{\sin\left(\frac{2\pi}{\alpha}\right)}{\frac{2\pi}{\alpha}} T_1(1-\epsilon). \quad (5)$$

The increase of β leads to the decrease of τ_1. With the decrease of τ_1, the transmission capacity of secondary system gets larger.

Primary System: Throughput $V_c(\beta)$ **and** $V_d(\beta)$

One typical MU is located at the origin and it is served by the nearest BS x_O. The distance between them is r_o and it is a realization of random variable R, which is defined as the (random) distance between a randomly selected MU and its nearest BS. The complement cumulative density function (CCDF) is [15],

$P_r\{R>r_0\} = \Pr\{$No BS closer than $r_0\} = \exp(-\lambda\pi r_0^2)$.

Then, the CDF is obtained as $F_R(r_0)$ = 1- exp(- λbπr02). The probability density function (PDF) is given by

$$f_R(ro) = \frac{dF_R(ro)}{dro} = 2\pi\lambda_b ro\exp(-\lambda_b \pi r_0^2). \quad (6)$$

For each BS $x \boldsymbol{\epsilon} \boldsymbol{\Pi_b}$, a mark r_x is applied to denote the distance of its intended MU. The intended MU is an interior user with $r_{x \leq} c_0$. Otherwise, it is a cell-edge user.

With cooperative spectrum sharing, the throughput of primary system is derived as follows by averaging over random variable R.

$$V_c(\beta) = \int_0^{co} T_0\left[P_{in1}(ro) + \frac{1}{2}P_{in2}(ro)\right] f_R(ro)dro \quad (7)$$
$$+ \int_{co}^{\infty} T_0\left[P_{ed1}(ro) + \frac{1}{2}P_{ed2}(ro) | \frac{1}{2}P_{ed3}(ro)\right] f_R(ro)dro,$$

Where the first and second integrals are applied corresponding to the cell-interior and cell-edge communications, respectively.

The transmission rate (target rate) of primary system is denoted as T_0. The pre-factor 1/2 before some success probabilities is adopted due to the retransmission. For the cell-interior communication, $P_{in1}(ro)$and $P_{in2}(ro)$ represent the conditional success probability of events E_{in}^1andE_{in}^2, respectively. For the cell edge communication, $P_{ed1}(ro), P_{ed2}(ro)$, and $P_{ed3}(ro)$represent the conditional success probability of eventsE_{ed}^1, E_{ed}^2, and E_{ed}^3, respectively. Next, we analyze the conditional success probabilities to obtain Vc (β).

For the typical MU, no matter whether it lies in the cell-interior or cell-edge region, the interference is modeled as

$$I_p \approx \sum_{x\epsilon\Pi_b\setminus\{x_0\}} P_x G_x l_x^{-\propto}, \quad (8)$$

Where $P_x = 1(r_x \leq c_0) + 1(r_x > c_0)\eta$. The indicator random variable denotes whether the BS x communicates to a cell-interior MU with unit power or communicates to a cell-edge MU with power η. The approximation is given because the position of cooperative SU is not the same as its serving BS when it performs the possible retransmission towards the cell-edge MU.

Cell-Interior Communication

Conditioned on R = r_0, the achievable rate of primary link in the original phase is given as

$$R_{in}(r_0)=(1-\beta)\log_2(1+G_{x0r0}^{-\alpha}/I_p). \quad (9)$$

The conditional success probability of original data transmission for the cell-interior MU is

$$P_{in1}(r_0)=\Pr\{R_{in}(r_0)\geq \tau_0\}=\exp[-(a_1+\hat{a}_1)r_0^2], \quad (10)$$

Where

$$a_1 = \frac{2\pi\lambda_b d_1 \tau_0^{2/\propto}}{\propto} \int_0^\infty g^{2/\propto}\left[\Gamma\left(-\frac{2}{\propto}, \tau_0 g\right) - \Gamma\left(-\frac{2}{\propto}\right)\right] \times \exp(-g)\, dg - \pi\lambda_b d_1, \quad (11)$$

$$\hat{a}_1 = \frac{2\pi\lambda_b d_{2(\eta}\tau_{0)}^{2/\propto}}{\propto} \int_0^\infty g^{2/\propto}\left[\Gamma\left(-\frac{2}{\propto}, \eta\tau_0 g\right) - \Gamma\left(-\frac{2}{\propto}\right)\right] \times \exp(-g)\, dg - \pi\lambda_b d_2 \quad (12)$$

With $d_1 = 1-\exp(-\lambda_b\pi c_o^2)$,

$d_2 = \exp(-\lambda_b\pi c_o^2)$, and $T_0=2^{To/1-\beta} - 1$.

The Gamma function is$\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt$ and the incomplete Gamma function is

$\Gamma(\mu, x) = \int_x^\infty t^{u-1}e^{-t}\,dt$. In the derivation of (10), The Laplace transform of interference is derived similarly to [15] and the proof is omitted here. When the original transmission fails, the transmission is performed by the typical BS with the following achievable rate

$$\check{R}_{in}(r_0) = \frac{1-\beta}{2}\log_2(1+2G_{xo}r_0^{-\propto}/I_P), \quad (13)$$

Where the pre-factor ½, and the double SIR is applied due to the retransmission and MRC. The conditional success probability is

$P_{in2}(r_0)=\Pr\{\check{R}_{in}(r_0)<T_0, \check{R}_{in}(r_0)\geq T_0/2\}$

=exp[-(a1+â1)r0],-exp[-$(a_1+\hat{a}_1)r_0$], (14)

Where $\grave{a}_1$ and $\hat{\grave{a}}_1$ can be replacing τ_0 of a_1 and $\hat{a}_1$ in (11) and (12) as $\tau_0/2$, respectively.

Cell-Edge Communication

Conditioned on distance r_0 between BS and its intended cell-edge MU, the achievable rate of primary link in the original phase is

$$R_{ed}(r_0)=(1-\beta)\log_2(1+\eta G_{x0}r_0^{-\alpha}/I_P). \quad (15)$$

Similar to (10), the conditional success probability is derived as

$$P_{ed1}(r_0)=\Pr\{R_{ed}(r_0)\geq T_0\}=\exp[-(a_2+\hat{a}_2)r_0^2], \quad (16)$$

where

$$\boldsymbol{a_2} = \frac{2\pi\lambda_b d_2 \tau_0^{2/\propto}}{\propto} \int_0^\infty g^{2/\propto}\left[\Gamma\left(-\frac{2}{\propto}, \tau_0 g\right) - \Gamma(-2/\propto)\right] \times \exp(-g)\, dg - \pi\lambda_b d_2, \quad (17)$$

$$\hat{a}_2 = \frac{2\pi\lambda_b d_1\left(\frac{\tau_0}{\eta}\right)^{\frac{2}{\propto}}}{\propto} \int_0^\infty g^{\frac{2}{\propto}}\left[\Gamma\left(-\frac{2}{\propto}, \left(\frac{\tau_0}{\eta}\right)g\right) - \left(-\frac{2}{\propto}\right)\right] \times \exp(-g)\, \boldsymbol{d_g - \pi\lambda_b d_1}. \quad (18)$$

When the original transmission fails at both MU and SU, the success probability of source retransmission is derived as

$P_{ed2}(r_0)=\mathbb{P}\{\frac{To}{2}\leq \gamma_{x0} < \tau 0, \tilde{\gamma}x0 < \tau 0\}$

$= \exp[-(\acute{a}_2 + \acute{a}_2 r_0^2)r_0^2] - \exp[-(\acute{a}_2 + \acute{a}_2)r_0^2]$

$$- \exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 r_0^{-\alpha}}{\eta}, \frac{\tau_0 r_0^{\alpha}}{2\eta}\right)\right] + \exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 \tau r_0^{-\alpha}}{\eta}, \frac{\tau_0 r_0^{\alpha}}{\eta}\right)\right] \quad (19)$$

Where $\gamma_{xo} = \eta G_{xo} r_o^{-\alpha} / I_p$ and $\tilde{y}_{xo} = \eta \breve{G}_{xo} \acute{r}_o^{-\alpha} / _p$ are the SIRs at MU and SU, respectively. The distance between BS and its cooperative SU is denoted as r~0 = ζr0 (0 < ζ < 1). The parameters a′2 and a^′2 are obtained by replacing τ0 of a2 and a^2 in (17) and (18) as τ0/2, respectively. The function g(s1, s2) is given by

$$g(s_1, s_2) = \int_{ro}^{\infty} [1 - \frac{d_1}{(1+s_1 l^{-\alpha})(1+s_2 l^{-\alpha})} \frac{d_2}{(1+s_1 \eta l^{-\alpha})(1+s_2 \eta l^{-\alpha})}] l \, dl. \quad (20)$$

The joint Laplace transform of location-dependent interferences is derived similarly to [16] and the proof is omitted here. When the original transmission fails at MU and succeeds at the SU, then the SU retransmits the primary data to the cell-edge MU[17]. Conditioned on the distance r_0, we have the success probability as

$$P_{ed3}(r_0) = \mathbb{p}\{\gamma_{xo} < \tau_0, \gamma_{xo} \geq \tau_0, \gamma_{xo} + \gamma_{zo} \geq \tau_0\}$$

$$\frac{r_0^{\alpha}}{r_0^{\alpha} - \acute{r}_0^{\alpha}}\left\{\exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 r_0^{\alpha}}{\eta}, \frac{\tau_0 \acute{r}_0^{\alpha}}{\eta}\right)\right] - \exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 r_0^{\alpha}}{\eta}, \frac{\tau_0 \check{r}_0^{\alpha}}{\eta}\right)\right]\right\} \quad (21)$$

Where $\gamma_{zo} = \eta G_{zo} \check{r}_0 / I_p$ is the SIR between SU and MU. The distance between SU and MU is r^0 = r0 r~0 = (1 ζ)r0. The function (s1, s2) is given by (20).

So far, we have derived all the related conditional success probabilities. Then, the throughput of primary system with cooperative

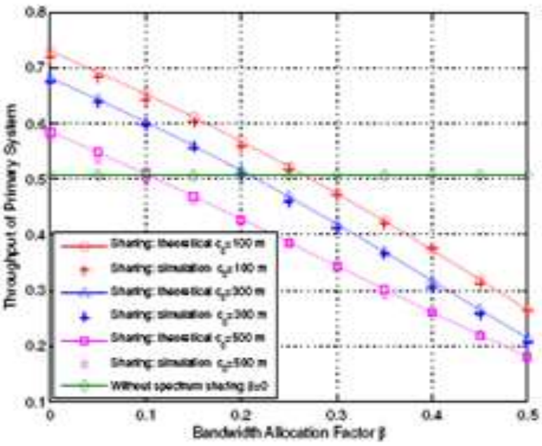

Fig. 4. Throughput of primary system with spectrum sharing.

Sys- tem settings are λb = 10−6, λm = 10−5, T0 = 2 bps, and ζ = 0.5.

Spectrum sharing, i.e., Eq. (7), is further derived as

$$V_c(\beta) = V_d(\beta) + \frac{T_0}{2}\int_{co}^{\infty}\left\{\frac{r_0^{\alpha}}{r_0^{\alpha} - \check{r}_0^{\alpha}} \exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 r_0^{\alpha}}{\eta}, \frac{\tau_0 r_0^{\alpha}}{\eta}\right)\right]\right.$$

$$\frac{r_0^{\alpha}}{r_0^{\alpha} - \acute{r}_0^{\alpha}}\left\{\exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 r_0^{\alpha}}{\eta}, \frac{\tau_0 \acute{r}_0^{\alpha}}{\eta}\right)\right] - \exp\left[-2\pi\lambda_b g\left(\frac{\tau_0 r_0^{\alpha}}{\eta}, \frac{\tau_0 \check{r}_0^{\alpha}}{\eta}\right)\right]\right\} \quad (22)$$

Where

$$V_d(\beta) = \frac{T_0 \lambda_b \pi}{2(\lambda_b \pi + a_1 + \hat{a}_1)}\{|1 - \exp[-(\lambda_b \pi + a_1 + \hat{a}_1) c_0^2]\}$$

$$\frac{T_0 \lambda_b \pi}{2(\lambda_b \pi + a`_1 + \hat{a}`_1)}\{1 - \exp[-(\lambda_b \pi + a`_1 + \hat{a}`_1) c_0^2]\}$$

$$+ \frac{T_0 \lambda_b \pi}{2(\lambda_b \pi + a_2 + \hat{a}`_2)}\{\exp[-(\lambda_b \pi + a`_2 + \hat{a}`_2) c_0^2]\}$$

$$+ \frac{T_0 \lambda_b \pi}{2(\lambda_b \pi + a_2 + \hat{a}`_2)}\{\exp[-(\lambda_b \pi + a`_2 + \hat{a}`_2) c_0^2]\}$$

…………….. (23)

Represents the throughput of primary system without cooperation from SUs. The possible retransmission is performed by the BS no matter whether it communicates with a cell-interior or cell-edge MU. In the derivation of $V_d(\beta)$, the bandwidth used by the primary sys- tem is (1 β). Particularly, when β = 0, we can obtain the through- put of the cellular network operating over the whole bandwidth.

For the cooperative spectrum sharing, the larger the through- put improvement requirement of primary system, the smaller the bandwidth allocation factor β for the secondary system. The larger the bandwidth allocation factor β, the more transmission capacity is achieved for the secondary system, the fewer throughputs is obtained for the primary system. Therefore, the released bandwidth satisfying the optimization problem (1) is derived through setting Vc(β) = (1 + ρ)V_d(β = 0).

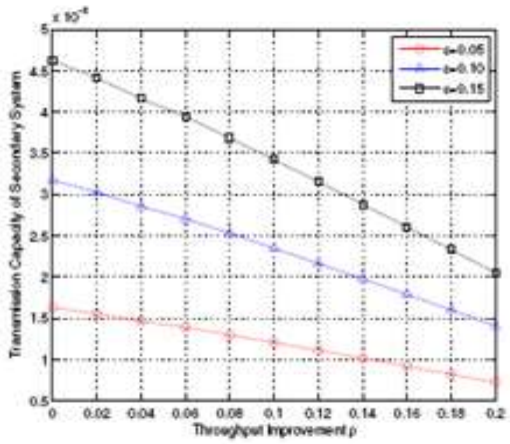

Fig.5. Transmission capacity of MANET.

Parameters: λb = 10−6,T0 = 2 bps, T1 = 0.5 bps, c0 = 100 m, d = 10 m, and ζ = 0.5.

Numerical and simulation results

In the simulations, the power ratio η* between cell-edge and cell- interior transmissions is obtained through maximizing the through- put of stand-alone cellular network without spectrum sharing, i.e., η* = arg maxη V_d(β = 0). For the cooperative spectrum sharing, we also use this optimal power ratio η*.

Fig.4 shows the throughput of cellular network with cooperative spectrum sharing. The theoretical results agree well with the simulation results, which can verify our analysis in Section 3. The throughput of primary system gets smaller when the cell-interior region is enlarged, because the opportunity of cooperation for the cell- edge communication is reduced. The performance deteriorates with the increase of bandwidth allocation β, as it becomes more difficult to support the target rate with the remaining narrower bandwidth. When β = 0, no spectrum is allocated to the secondary system, but the primary transmission is helped by SUs, so the throughput greatly outperforms its counterpart without cooperative spectrum sharing. Only the curve of cooperative spectrum sharing is above the straight line of non-sharing could the factor β be used to realize the secondary transmission and improve the primary performance [18].

Fig. 5 shows the transmission capacity of secondary system. When the outage probability ϵ gets larger, it becomes easier to meet the target rate T_1, so the transmission capacity gets larger. With the increase of performance improvement ratio ρ, less bandwidth is allocated to the MANET, and the transmission capacity of secondary system turns smaller.

Conclusions:

CR networks are envisaged to solve the problem of spectrum scarcity by making efficient and opportunistic use of frequencies reserved for the use of licensed users of the bands. To realize the goals of truly ubiquitous spectrum-aware communication, the CR devices need to incorporate the spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility functionalities. The main challenge in CRAHNs is to integrate these functions in the layers of the protocol stack, so that the CR users can communicate reliably in a distributed manner, over a multi-hop/multi-spectrum environment, without any infrastructure support.

The discussions provided in this survey strongly advocate cooperative spectrum-aware communication protocols that consider the spectrum management functionalities. This cross-layer design requirement necessitates a rethinking of the existing solutions developed for classical wireless networks. Many researchers are currently engaged in developing the communication technologies and protocols required for CRAHNs. However, to ensure efficient spectrum-aware communication, more research is needed along the lines introduced in this paper.

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