COOPERATIVE SPECTRUM SHARING IN WIRELESS AD-HOC NETWORKS

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ABSTRACT

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.

***Index Terms*—** Cognitive radio, cooperative diversity, spectrum sharing, transmission capacity, stochastic geometry.

1. INTRODUCTION

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 uncertainties, 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.

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 non-cooperative system [12] [13]. For the non-cooperative spectrum 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.

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 expected, the cellular network 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. 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 system should be improved. Performance results are provided to verify the efficiency of cooperative spectrum sharing.

2. SYSTEM MODEL

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 λ_{b}, i.e., $\Pi_{\mathrm{b}} = \{x_i, i \in \mathbb{Z}\}$. The MUs follow another PPP $\Pi_{\mathrm{m}} = \{y_i, i \in \mathbb{Z}\}$ with intensity λ_{m}. Each MU is served by its nearest BS. As shown in Fig. 1, 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 λ_{s}, i.e., $\Pi_{\mathrm{s}} = \{z_i, i \in \mathbb{Z}\}$. 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 $\beta \in (0, 1)$ and the remaining $(1-\beta)$ spectrum is used by the primary system. The channel between terminals u_1 and u_2 undergoes small-scale block fading and large-scale path-loss. The small-scale power fading G_{u_1,u_2} is exponentially distributed with unit mean, and it is independent across links. The large-scale path-loss is $\ell_{u_1,u_2}^{-\alpha}$, where $\ell_{u_1,u_2} = |u_1 - u_2|$ is the distance and α is the path-loss exponent. The symbol u_2 in the subscript is omitted for brevity if u_2 lies at the origin.

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

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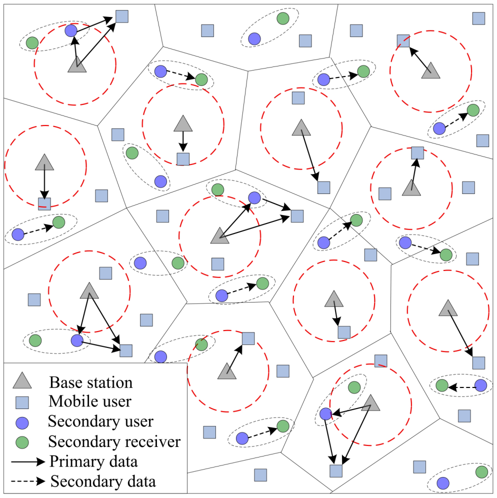

Fig. 1. Cellular network overlaid with MANET.

cell-edge regions. The interior region is defined as a circular area centered at the BS with radius c_0 as shown in Fig. 1. 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.

- E^1_{in}: The original transmission succeeds, the acknowledgement (ACK) frame is fed back and the BS continues to transmit a new data packet.
- E^2_{in}: 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.

- E^1_{ed}: 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.
- E^2_{ed}: 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.
- E^3_{ed}: 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.

The received signals in both the original and retransmission phases are maximal ratio combined (MRC) by the MU for detection.

3. DESIGN OBJECTIVE AND PERFORMANCE STUDY

Let the transmission capacity of secondary system be C_ϵ with ϵ denoting 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.

$$\begin{aligned} \max_{\beta\in(0,1)} \quad & C_\epsilon\,, \\ \text{s. t.} \quad & \frac{V_c(\beta)-V_d(\beta=0)}{V_d(\beta=0)} \ge \rho\,, \end{aligned} \tag{1}$$

where the throughput of primary system with and without spectrum sharing are denoted as $V_{\text{c}}(\beta)$ and $V_{\text{d}}(\beta=0)$, respectively. The parameter $\rho \ge 0$ is the required performance improvement (a pre-defined value) of primary system with cooperative spectrum sharing.

3.1. Secondary System: Transmission Capacity C_ϵ

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

$$R_{\text{s}} = \beta \log_2\left(1 + G_{z_0} d^{-\alpha}/\mathcal{I}_{\text{s}}\right), \tag{2}$$

where the interference is

$$\mathcal{I}_{\text{s}} = \sum_{z\in\tilde{\Pi}_{\text{s}}/\{z_0\}} G_z \ell_z^{-\alpha}. \tag{3}$$

All the active SUs except the typical one contribute to the aggregate interference in (3). The transmitting SUs form the PPP $\tilde{\Pi}_{\text{s}}$, which is an independent thinning of Π_{s} with intensity $\xi\lambda_{\text{s}}$, 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],

$$\begin{aligned} P^{\text{s}}_{\text{out}} &= \Pr\left\{R_{\text{s}} < T_1\right\} \\ &= 1 - \exp\left(-\xi\lambda_{\text{s}}\pi d^2 \tau_1^{\frac{2}{\alpha}} \frac{2\pi/\alpha}{\sin(2\pi/\alpha)}\right), \end{aligned} \tag{4}$$

where $\tau_1 = 2^{T_1/\beta} - 1$ with T_1 denoting the target rate of SUs.

The target outage performance of secondary system is ϵ, and the maximum node density $\lambda^{\text{s}}_\epsilon$ that can protect the outage performance is obtained through $P^{\text{s}}_{\text{out}} = \epsilon$. Then, the transmission capacity [9] of the secondary system is derived as

$$C_\epsilon = \xi\lambda^{\text{s}}_\epsilon T_1(1-\epsilon) = -\frac{\ln(1-\epsilon)}{\pi d^2 \tau_1^{\frac{2}{\alpha}}} \frac{\sin(2\pi/\alpha)}{2\pi/\alpha} T_1(1-\epsilon). \tag{5}$$

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.

3.2. 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_0. The distance between them is r_0 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],

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

Then, the CDF is obtained as $F_R(r_0) = 1 - \exp(-\lambda_{\text{b}}\pi r_0^2)$. The probability density function (PDF) is given by

$$f_R(r_0) = \frac{\mathrm{d}F_R(r_0)}{\mathrm{d}r_0} = 2\pi\lambda_{\text{b}} r_0 \exp(-\lambda_{\text{b}}\pi r_0^2). \tag{6}$$

For each BS $x \in \Pi_b$, a mark r_x is applied to denote the distance of its intended MU. The intended MU is an interior user with $r_x \le c_0$. 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.

$$\begin{aligned} V_{\text{c}}(\beta) = &\int_0^{c_0} T_0\left[P_{\text{in1}}(r_0) + \frac{1}{2}P_{\text{in2}}(r_0)\right] f_{\text{R}}(r_0)\,\mathrm{d}r_0 \\ &+ \int_{c_0}^{\infty} T_0\left[P_{\text{ed1}}(r_0) + \frac{1}{2}P_{\text{ed2}}(r_0) + \frac{1}{2}P_{\text{ed3}}(r_0)\right] f_{\text{R}}(r_0)\,\mathrm{d}r_0, \end{aligned} \tag{7}$$

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, $P_{\rm in1}(r_0)$ and $P_{\rm in2}(r_0)$ represent the conditional success probability of events $E_{\rm in}^1$ and $E_{\rm in}^2$, respectively. For the cell-edge communication, $P_{\rm ed1}(r_0)$, $P_{\rm ed2}(r_0)$, and $P_{\rm ed3}(r_0)$ represent the conditional success probability of events $E_{\rm ed}^1$, $E_{\rm ed}^2$, and $E_{\rm ed}^3$, respectively. Next, we analyze the conditional success probabilities to obtain $V_{\rm c}(\beta)$.

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

$$\mathcal{I}_{\rm p} \approx \sum_{x\in\Pi_{\rm b}\setminus\{x_0\}} P_x G_x \ell_x^{-\alpha}, \tag{8}$$

where $P_x = \mathbf{1}(r_x \leq c_0) + \mathbf{1}(r_x > c_0)\eta$. 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.

3.2.1. Cell-Interior Communication

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

$$R_{\rm in}(r_0) = (1-\beta)\log_2\Big(1 + G_{x_0} r_0^{-\alpha}/\mathcal{I}_{\rm p}\Big). \tag{9}$$

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

$$P_{\rm in1}(r_0) = \Pr\left\{R_{\rm in}(r_0) \geq T_0\right\} = \exp\left[-(a_1+\hat{a}_1)r_0^2\right], \tag{10}$$

where

$$a_1 = \frac{2\pi\lambda_{\rm b} d_1 \tau_0^{\frac{2}{\alpha}}}{\alpha}\int_0^\infty g^{\frac{2}{\alpha}}\left[\Gamma(-2/\alpha, \tau_0 g) - \Gamma(-2/\alpha)\right] \times \exp(-g)\,{\rm d}g - \pi\lambda_{\rm b} d_1, \tag{11}$$

$$\hat{a}_1 = \frac{2\pi\lambda_{\rm b} d_2 (\eta\tau_0)^{\frac{2}{\alpha}}}{\alpha}\int_0^\infty g^{\frac{2}{\alpha}}\left[\Gamma(-2/\alpha, \eta\tau_0 g) - \Gamma(-2/\alpha)\right] \times \exp(-g)\,{\rm d}g - \pi\lambda_{\rm b} d_2, \tag{12}$$

with $d_1 = 1 - \exp(-\lambda_{\rm b}\pi c_0^2)$, $d_2 = \exp(-\lambda_{\rm b}\pi c_0^2)$, and $\tau_0 = 2^{\frac{T_0}{1-\beta}} - 1$. The Gamma function is $\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}\,{\rm d}t$ and the incomplete Gamma function is $\Gamma(\mu, x) = \int_x^\infty t^{\mu-1}e^{-t}\,{\rm d}t$. 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 retransmission is performed by the typical BS with the following achievable rate

$$\hat{R}_{\rm in}(r_0) = \frac{1-\beta}{2}\log_2\Big(1 + 2G_{x_0} r_0^{-\alpha}/\mathcal{I}_{\rm p}\Big), \tag{13}$$

where the pre-factor $1/2$ and the double SIR is applied due to the retransmission and MRC. The conditional success probability is

$$\begin{aligned} P_{\rm in2}(r_0) &= \Pr\left\{R_{\rm in}(r_0) < T_0, \hat{R}_{\rm in}(r_0) \geq T_0/2\right\} \\ &= \exp\left[-(a_1'+\hat{a}_1')r_0^2\right] - \exp\left[-(a_1+\hat{a}_1)r_0^2\right], \end{aligned} \tag{14}$$

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

3.2.2. 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

$$R_{\rm ed}(r_0) = (1-\beta)\log_2\Big(1 + \eta G_{x_0} r_0^{-\alpha}/\mathcal{I}_{\rm p}\Big). \tag{15}$$

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

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

where

$$a_2 = \frac{2\pi\lambda_{\rm b} d_2 \tau_0^{\frac{2}{\alpha}}}{\alpha}\int_0^\infty g^{\frac{2}{\alpha}}\left[\Gamma(-2/\alpha, \tau_0 g) - \Gamma(-2/\alpha)\right] \times \exp(-g)\,{\rm d}g - \pi\lambda_{\rm b} d_2, \tag{17}$$

$$\hat{a}_2 = \frac{2\pi\lambda_{\rm b} d_1 (\tau_0/\eta)^{\frac{2}{\alpha}}}{\alpha}\int_0^\infty g^{\frac{2}{\alpha}}\left[\Gamma(-2/\alpha, (\tau_0/\eta) g) - \Gamma(-2/\alpha)\right] \times \exp(-g)\,{\rm d}g - \pi\lambda_{\rm b} d_1. \tag{18}$$

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

$$\begin{aligned} P_{\rm ed2}(r_0) &= \mathbb{P}\Big\{\frac{\tau_0}{2} \leq \gamma_{x_0} < \tau_0, \tilde{\gamma}_{x_0} < \tau_0\Big\} \\ &= \exp\left[-(a_2'+\hat{a}_2')r_0^2\right] - \exp\left[-(a_2+\hat{a}_2)r_0^2\right] \\ &\quad - \exp\left[-2\pi\lambda_{\rm b} g\left(\frac{\tau_0\tilde{r}_0^\alpha}{\eta}, \frac{\tau_0 r_0^\alpha}{2\eta}\right)\right] \\ &\quad + \exp\left[-2\pi\lambda_{\rm b} g\left(\frac{\tau_0\tilde{r}_0^\alpha}{\eta}, \frac{\tau_0 r_0^\alpha}{\eta}\right)\right], \end{aligned} \tag{19}$$

where $\gamma_{x_0} = \eta G_{x_0} r_0^{-\alpha}/\mathcal{I}_{\rm p}$ and $\tilde{\gamma}_{x_0} = \eta\tilde{G}_{x_0}\tilde{r}_0^{-\alpha}/\tilde{\mathcal{I}}_{\rm p}$ are the SIRs at MU and SU, respectively. The distance between BS and its cooperative SU is denoted as $\tilde{r}_0 = \zeta r_0$ $(0 < \zeta < 1)$. The parameters a_2' and $\hat{a}_2'$ are obtained by replacing τ_0 of a_2 and $\hat{a}_2$ in (17) and (18) as $\tau_0/2$, respectively. The function $g(s_1, s_2)$ is given by

$$g(s_1, s_2) = \int_{r_0}^\infty \Big[1 - \frac{d_1}{(1+s_1\ell^{-\alpha})(1+s_2\ell^{-\alpha})} - \frac{d_2}{(1+s_1\eta\ell^{-\alpha})(1+s_2\eta\ell^{-\alpha})}\Big]\ell\,{\rm d}\ell. \tag{20}$$

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. Conditioned on the distance r_0, we have the success probability as

$$\begin{aligned} P_{\rm ed3}(r_0) &= \mathbb{P}\left\{\gamma_{x_0} < \tau_0, \tilde{\gamma}_{x_0} \geq \tau_0, \gamma_{x_0} + \gamma_{z_0} \geq \tau_0\right\} \\ &= \frac{r_0^\alpha}{r_0^\alpha - \hat{r}_0^\alpha}\Big\{\exp\Big[-2\pi\lambda_{\rm b} g\left(\frac{\tau_0\tilde{r}_0^\alpha}{\eta}, \frac{\tau_0\hat{r}_0^\alpha}{\eta}\right)\Big] \\ &\quad - \exp\Big[-2\pi\lambda_{\rm b} g\left(\frac{\tau_0\tilde{r}_0^\alpha}{\eta}, \frac{\tau_0 r_0^\alpha}{\eta}\right)\Big]\Big\}, \end{aligned} \tag{21}$$

where $\gamma_{z_0} = \eta G_{z_0}\hat{r}_0/\mathcal{I}_{\rm p}$ is the SIR between SU and MU. The distance between SU and MU is $\hat{r}_0 = r_0 - \tilde{r}_0 = (1-\zeta)r_0$. The function $g(s_1, s_2)$ is given by (20).

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

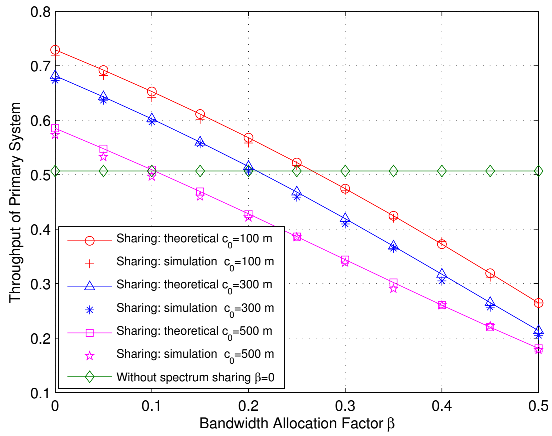

Fig. 2. Throughput of primary system with spectrum sharing. System settings are $\lambda_{\mathrm{b}} = 10^{-6}$, $\lambda_{\mathrm{m}} = 10^{-5}$, $T_0 = 2$ bps, and $\zeta = 0.5$.

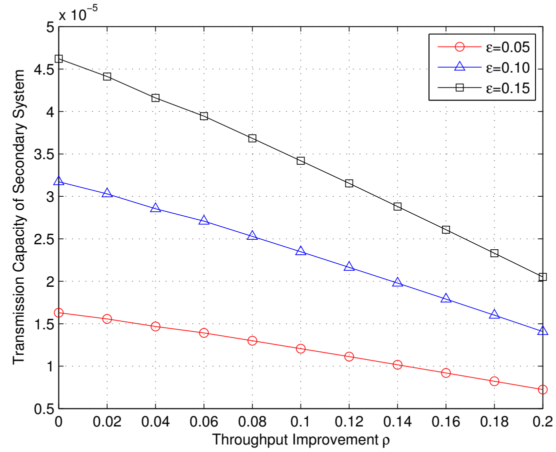

Fig. 3. Transmission capacity of MANET. Parameters: $\lambda_{\mathrm{b}} = 10^{-6}$, $T_0 = 2$ bps, $T_1 = 0.5$ bps, $c_0 = 100$ m, $d = 10$ m, and $\zeta = 0.5$.

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

$$\begin{aligned} V_{\mathrm{c}}(\beta) &= V_d(\beta) \\ &+ \frac{T_0}{2}\int_{c_0}^{\infty}\left\{\frac{r_0^{\alpha}}{r_0^{\alpha}-\hat{r}_0^{\alpha}}\exp\left[-2\pi\lambda_{\mathrm{b}} g\Big(\frac{\tau_0\tilde{r}_0^{\alpha}}{\eta},\frac{\tau_0\hat{r}_0^{\alpha}}{\eta}\Big)\right]\right. \\ &\quad - \frac{\hat{r}_0^{\alpha}}{r_0^{\alpha}-\hat{r}_0^{\alpha}}\exp\left[-2\pi\lambda_{\mathrm{b}} g\Big(\frac{\tau_0\tilde{r}_0^{\alpha}}{\eta},\frac{\tau_0 r_0^{\alpha}}{\eta}\Big)\right] \\ &\quad \left. - \exp\left[-2\pi\lambda_{\mathrm{b}} g\Big(\frac{\tau_0\tilde{r}_0^{\alpha}}{\eta},\frac{\tau_0 r_0^{\alpha}}{2\eta}\Big)\right]\right\} f_R(r_0)\,\mathrm{d}r_0, \end{aligned} \tag{22}$$

where

$$\begin{aligned} V_d(\beta) &= \frac{T_0\lambda_{\mathrm{b}}\pi}{2(\lambda_{\mathrm{b}}\pi + a_1 + \hat{a}_1)}\left\{1-\exp\left[-(\lambda_{\mathrm{b}}\pi + a_1 + \hat{a}_1)c_0^2\right]\right\} \\ &+ \frac{T_0\lambda_{\mathrm{b}}\pi}{2(\lambda_{\mathrm{b}}\pi + a_1' + \hat{a}_1')}\left\{1-\exp\left[-(\lambda_{\mathrm{b}}\pi + a_1' + \hat{a}_1')c_0^2\right]\right\} \\ &+ \frac{T_0\lambda_{\mathrm{b}}\pi}{2(\lambda_{\mathrm{b}}\pi + a_2 + \hat{a}_2)}\exp\left[-(\lambda_{\mathrm{b}}\pi + a_2 + \hat{a}_2)c_0^2\right] \\ &+ \frac{T_0\lambda_{\mathrm{b}}\pi}{2(\lambda_{\mathrm{b}}\pi + a_2' + \hat{a}_2')}\exp\left[-(\lambda_{\mathrm{b}}\pi + a_2' + \hat{a}_2')c_0^2\right], \end{aligned} \tag{23}$$

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 system is $(1-\beta)$. Particulary, when $\beta = 0$, we can obtain the throughput of the cellular network operating over the whole bandwidth.

For the cooperative spectrum sharing, the larger the throughput 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 less throughput is obtained for the primary system. Therefore, the released bandwidth satisfying the optimization problem (1) is derived through setting $V_{\mathrm{c}}(\beta) = (1+\rho)V_d(\beta = 0)$.

4. NUMERICAL AND SIMULATION RESULTS

In the simulations, the power ratio η^* between cell-edge and cell-interior transmissions is obtained through maximizing the throughput of stand-alone cellular network without spectrum sharing, i.e., $\eta^* = \arg\max_{\eta} V_d(\beta = 0)$. For the cooperative spectrum sharing, we also use this optimal power ratio η^*.

Fig. 2 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 $\beta = 0$, 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 when 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.

Fig. 3 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.

5. CONCLUSION

In this paper, we propose a cooperative spectrum sharing scheme between cellular network downlink and MANET. The transmission capacity of secondary system and the throughput of primary system are analyzed using the stochastic geometry theory. The optimal bandwidth release is used to maximize the transmission capacity of secondary system while satisfying the performance improvement requirement of primary system. As observed by the numerical results, this cooperative spectrum sharing can enhance the primary throughput and satisfy the secondary transmission requirement.

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