The Capacity of Cognitive Ad-Hoc Networks with Carrier Sensing Errors

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***Abstract*—We analyze the capacity of cognitive ad-hoc networks under the effects of sensing errors: false alarm and missed detection. We present an ad-hoc network model overlaid on a primary system from which a cognitive node exploits spectrum holes for retransmissions. We derive per-link capacity, the indicator of the network's capacity, by considering statistics of the primary users' (PUs) channel occupancy and sensing errors. Our analysis shows that the capacity scaling law is kept unchanged, $O(1/\sqrt{\log n})$ by the number of nodes n, even after sensing errors are introduced. It also shows how the capacity depends on the PUs' channel occupancy and sensing errors.**

keywords–Ad-hoc, sensing errors, capacity.

I. Introduction

One of the most important discussions on wireless ad-hoc networks has been the consistent finding that the capacity of the networks is fundamentally constrained by the load of relaying burden at each node. It has provoked a number of remarkable studies [2]-[5]. In [2], a model for studying the capacity of random networks was provided and the result showed that the capacity is $O(1/\sqrt{n \log n})$ according to the number of nodes n. In [3], Hwang and Kim reviewed the model of [2] and proved that the capacity is still $O(1/\sqrt{n \log n})$ even after MAC, link adaptation and ARQ are considered. In [4], under IEEE 802.11n standard MAC, the capacity is enhanced to $O(1/\sqrt{n})$, but they assumed an extended network where the node density is kept constant as the number of nodes grows, which makes interference less severe. In [5], the authors showed that multiuser diversity, achieved by mobility of nodes, asymptotically leads the capacity to $\Theta(1)$[1]. However, there are a lot of cases that mobility cannot be practically realized, e.g., a large scale ubiquitous sensor network (USN) established at an automated place such as a smart-energy applied building.

Therefore, as a solution for ad-hoc networks' capacity constraint, we examined the feasibility of deploying *cognitive radio (CR)* to static ad-hoc networks [1]. Especially, we consider an ad-hoc network that is overlaid on another network from where it seeks spectrum holes to use [6], [7]. In [6], the authors identified a critical region in which the overlaying cognitive ad-hoc users and the primary user (PU) can concurrently transmit data without interference. They suggested that the solution for this problem can be the location information of each other. In [7], lower and upper bounds for the capacity of an ad-hoc network comprised of cognitive nodes overlaid on a cellular network are studied. Each node exploits opportunities for transmission from the cellular band. However, these works limited their applicability by assuming perfect carrier sensing although sensing errors inevitably occur in practical environment. Considering sensing errors, it is obvious that the capacity is worsened due to a lesser number of available spectrum holes. Nevertheless, it is worthwhile to discuss the significance of the impacts of sensing errors on the capacity of ad-hoc networks and to provide an analytic guideline for cognitive ad-hoc networks under sensing errors.

In this context, the main purpose of this paper is to analyze the capacity of cognitive ad-hoc networks with the effects of imperfect carrier sensing. For this, we provide an ad-hoc network model where a node exploits spectrum holes for retransmissions and derive the capacity of the network. Our analysis suggests that the capacity scaling law is remained unchanged even though sensing errors are considered.

II. Network Model

Consider a wireless ad-hoc network with homogeneous fixed nodes, overlaid on the primary system. Fig. 1 describes this network architecture.

A. Assumptions

Throughout this paper, $\mathbf{X_{ij}}$ represents the location of a node at the jth depth in the ith route (it denotes the node itself, too); a *route* is defined as a series of a number of links; a *link*–replaceable with *hop*–indicates a pair of two adjacent nodes, one for the *sender* and the other for the *receiver*; *depth* refers to a relative position of a node in a route. Note from Fig. 1 that routes are lined up in rows, while levels of depth are arrayed in columns. A *frame* which is composed of a certain number of packets is to be relayed through a route. Again, a *packet* is made of a certain number of symbols. Frames being transferred are different from a route to another.

The architecture of the network is a lattice and a square where all columns and rows are equally spaced. This can be rewritten by, for $i, j = 1, 2, \cdots, \sqrt{n}$ and $\|\cdot\|$ representing the Euclidean length, $\left\|\mathbf{X_{i(j-1)}} - \mathbf{X_{ij}}\right\| = \left\|\mathbf{X_{ij}} - \mathbf{X_{i(j+1)}}\right\| = \left\|\mathbf{X_{(i-1)j}} - \mathbf{X_{ij}}\right\| = \left\|\mathbf{X_{ij}} - \mathbf{X_{(i+1)j}}\right\|$. Further, both the width and the height of the whole network are 1 and the number of columns and rows are equally $\sqrt{n}$. This is given by $(\sqrt{n}-1)\left\|\mathbf{X_{(i-1)j}} - \mathbf{X_{ij}}\right\| = (\sqrt{n}-1)\left\|\mathbf{X_{i(j-1)}} - \mathbf{X_{ij}}\right\| = 1$, for $i, j = 1, 2, \cdots, \sqrt{n}$. We do not care of routing in this paper, assuming that all routes have been already discovered and they are maintained unchanged until transmission of a frame in all routes are completed.

[1]We recall Knuth's notation for capacity bounds with real numbers k_0, k_1, k_2, and z. For some $k_0, k_1, k_2 > 0$, as $z \to \infty$, $f(z) \in O(g(z))$ if and only if $|f(z)| \le k_0 \cdot g(z)$, $f(z) \in \Omega(g(z))$ if and only if $|f(z)| \ge k_0 \cdot g(z)$, and $f(z) \in \Theta(g(z))$ if and only if $k_1 \cdot g(z) \le |f(z)| \le k_2 \cdot g(z)$.

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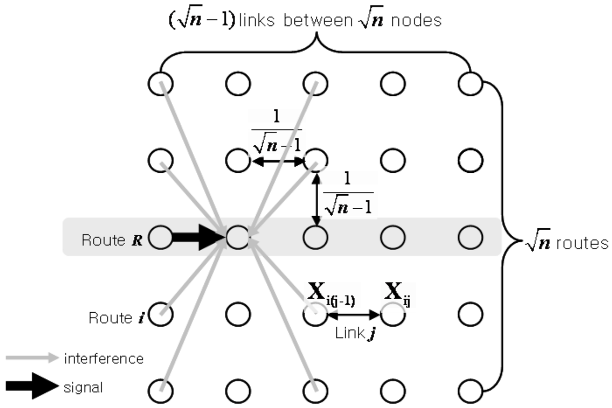

Fig. 1. An architecture of a cognitive ad-hoc network model

B. Retransmission protocol

We consider a *slotted* system where a packet is transmitted through a link in a time slot. In a time slot, a node can be either in Tx or Rx phase. *Half duplex* is assumed: if the sender node is in the Tx phase to send a packet, the receiver must be in the Rx phase to receive it. After that, the sender turns into the Rx phase to receive feedback from the receiver. As a dense network, it is assumed that packet transmission of a link is interfered by all other links that are currently in transmission; for example, given a receiver node located at $(i,j)=(i',j')$, transmission of all other links, $i \neq i'$ and $j \in J$ where J is the set of all sender nodes in a route, become interference.

All nodes are equipped with two transceiver modules for *Band I* and *Band II*: Band I refers to spectral resource that all nodes mainly use for transmission, while Band II is spectrum of the primary system, which is exploited by CR and dedicated for retransmission. Based on the *automatic retransmission request (ARQ)* protocol, the receiver on a link feeds an indicator back to the sender whether the transmission was successful or not. If the signal-to-interference ratio (SIR) at the receiver node is greater than the outage threshold, $\gamma > \eta_{out}$, it generates an ACK signal. Otherwise, in case of *outage*, it transmits the ID of a primary channel as a NACK signal and waits for retransmission over the channel. The sender receiving NACK retransmits the same packet via a designated channel in Band II in the following Tx phase. In contrast, if the sender receives ACK, the packet is relayed to the next hop and the next packet is to be transmitted through the current link.

Initially, all $\sqrt{n}$ nodes at the first hop commence their transmission over Band I. Due to retransmissions, however, the progress of packet transfer differs from a route to another. Here we assume that our analysis is based on the ath (a>1) packet. Based on this, whichever time slot we observe, all $\sqrt{n}$ sender nodes of any hop are in transmission: some transmit on-time packets over Band I and the others are in retransmission over Band II. Given that all $\sqrt{n}$ nodes at a depth are in transmission, they partly interfere with each other: some at Band I and the others at Band II. Further, in Band II, if an outage occurs again or no spectrum hole is found, the packet shall be discarded–no capacity shall be achieved–and the node at the first depth shall send the same packet again.

III. Carrier Sensing Strategy and Statistics

A. Carrier sensing strategy

In Band II, a node attempts to scan the spectrum at the beginning of every slot. It is assumed that a node can use both Band I and II at a time, which leads that detection of spectrum holes can be performed regardless of operations of Band I. Moreover, since all nodes are in the area of only one primary system's influence, the exploited spectrum holes are all the same for one node and another.

Suppose there are N_{II} (>1) channels in total at Band II while there is only one channel at Band I. Spectrum holes are found among these N_{II} channels and a node randomly chooses only one for its retransmission in a time slot; the choice is independent from each other. It leads the number of interfering nodes at Band II to be determined stochastically, and this will be explained in Section IV-B in more detail.

B. Statistics for sensing errors and the primary channels

As in [8], we assume both signal and noise are white Gaussian random processes and define the following hypotheses:

$$H_0 : Y \sim \mathcal{N}(0, \sigma_0^2) \tag{1}$$

$$H_1 : Y \sim \mathcal{N}(0, \sigma_0^2 + \sigma_1^2) \tag{2}$$

where

Y : an observation sample,
σ_0^2 : the thermal noise power,
σ_1^2 : the received signal power from a PU.

Based on the Neyman-Pearson detection theory, the probability of false alarm P_{fa} and missed detection P_m are defined by

$$P_{fa} \triangleq \Pr(H_1|H_0) = 1 - \Gamma\left(\frac{1}{2}, \frac{\eta_{se}}{2\sigma_0^2}\right) \tag{3}$$

$$P_m \triangleq \Pr(H_0|H_1) = 1 - \Gamma\left(\frac{1}{2}, \frac{\eta_{se}}{2\left(\sigma_0^2 + \sigma_1^2\right)}\right) \tag{4}$$

where η_{se} denotes the sensing error threshold and the incomplete gamma function is given by

$$\Gamma(t,z) = \frac{1}{\Gamma(t)} \int_0^z t^{t-1} e^{-x} dx. \tag{5}$$

A PU's channel occupancy is assumed to be a Poisson random process. Thus, in Band II, if a primary channel is occupied by only one PU and this occupancy is independent of other PUs' channel usages, time fraction of a PU's channel use T_{on} is an *i.i.d.* exponential random variable of which the probability density function (PDF) is given by

$$f_T(t) = \overline{T}_{on} \exp\left(-\overline{T}_{on} t\right), \ t \geq 0 \tag{6}$$

where $\overline{T}_{on}$ denotes the expected channel occupation time of a PU. We define the expected channel occupancy rate of a PU in a primary channel as

$$\beta \triangleq \mathbb{E}[\beta_j] = \overline{T}_{on} (T_s)^{-1} \tag{7}$$

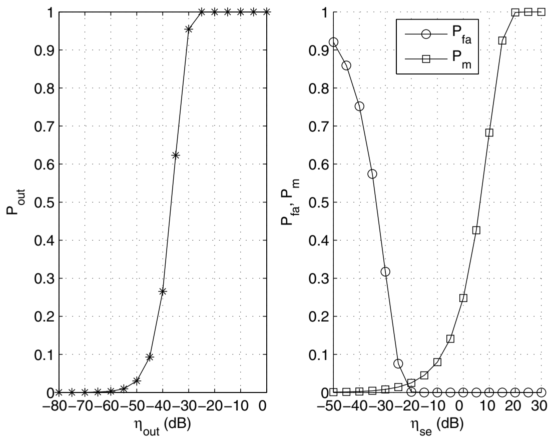

Fig. 2. The probability of outage versus the outage threshold and the probability of false alarm and missed detection versus the sensing error threshold ($n = 25, \sigma_0^2 = -30\mathrm{dB}, \sigma_1^2 = 10\mathrm{dB}, l = 4$)

where T_s denotes the length of a time slot. Note β is static during transmission of a given packet through a route.

The average number of spectrum holes for a link can be finally developed as

$$H = \sum_{k=0}^{N_{II}} k \begin{pmatrix} N_{II} \\ k \end{pmatrix} (1-\beta)^k \beta^{(N_{II}-k)} = N_{II}(1-\beta). \tag{8}$$

Considering sensing errors, we assume that a channel of Band II found by missed detection is abandoned. It is true, by definition, that a missed detection presents an unexpected opportunity of channel usage to a cognitive node, by wrongly declaring an actually occupied channel to be unoccupied. However, we should note, in a CR system, it is inviolable that operations of cognitive nodes must be transparent to PUs. In addition, even if a cognitive node achieves data rate, it would be severely interfered by the corresponding PU, thus ignorable. Hence, the expected number of spectrum holes that can actually be utilized is given by

$$H' = H(1 - P_{fa} - P_m). \tag{9}$$

IV. Analysis of The Capacity

A. Channel model

We define a received symbol for a given time slot by

$$y = \sqrt{\lambda_{ij}} h_{ij} x_{ij} + \mathbf{I}\mathbf{x} \tag{10}$$

where

- λ_{ij} : the received power varying with long-term fading,
- h_{ij} : a short-term fading of the jth link in the ith route,
- x_{ij} : the transmitted symbol from the sender node to the receiver node in the jth hop of the ith route.

As a dense network, time variation of the channel occurs only with short-term fading, so the long-term fading gain is not a random variable. Moreover, since it is assumed to be interference-limited, the effects of the thermal noise can be neglected. Notice that h_{ij} is a complex Gaussian random variable $\sim\mathcal{CN}(0,1)$. The fading channel is static during a time slot duration. Further, $\mathbb{E}[|x_{ij}^2|] = 1$ is the normalized transmit power of a node, thus λ_{ij} directly comes to represent the received signal power.

Considering interference, suppose that all sender nodes in the network interfere with each other: some at Band I and the others at Band II. Note that vectors $\mathbf{x}$ and $\mathbf{I}$ represent the interference signal and gain, respectively. For example, if we consider a receiver node which is placed at the j'th link of the i'th route, the interference signal vector is given by $\mathbf{x} = \left[x_{11}\ x_{12}\ \cdots\ \mathrm{x}_{\sqrt{\mathrm{n}}\sqrt{\mathrm{n}}}\right]^T$ and the interference gain vector from all other nodes in the same depth of other routes $\mathbf{I} = \left[\sqrt{\lambda_{11}}h_{11}\ \sqrt{\lambda_{12}}h_{12}\ \cdots\ \sqrt{\lambda_{\sqrt{n}\sqrt{n}}}h_{\sqrt{n}\sqrt{n}}\right]$ respectively, for $i \neq i'$ and $j \in J$ where J represents the set of all sender nodes in a route.

B. Received SIR and link failure

We assume that a packet is being transmitted at the j'th link of the i'th route. Note that even if we take this case as an example, it can be generally applied to any further case with different values of i and j. Hence, $i = i'$ and $j = j'$ from now. Based on (10), we obtain the instantaneous SIR achieved by the receiver node of the j' link in the i'th route by

$$\gamma^{(i',j')} \triangleq \frac{1}{\sigma_z^2}\lambda_{i'j'}\left|h_{i'j'}\right|^2 \left\|\mathbf{X_{i'(j'-1)}} - \mathbf{X_{i'j'}}\right\|^{-l}. \tag{11}$$

where l denotes the path-loss exponent. Based on an assumption that the number of interfering nodes is large enough and they are independent of each other, based on the Central Limit Theorem, the interference can be a complex Gaussian random variable z of which variance is given by

$$\sigma_z^2 = \sum_{i\neq i', j\in J, j\neq j'} \lambda_{ij}\left\|\mathbf{X_{i(j-1)}} - \mathbf{X_{ij}}\right\|^{-l}. \tag{12}$$

From (11) and (12), the expected SIR over short-term fading is given by

$$\overline{\gamma} \triangleq \mathbb{E}\left[\gamma^{(i',j')}\right] = \frac{1}{\sigma_z^2}\lambda_{i'j'}\left\|\mathbf{X_{i'(j'-1)}} - \mathbf{X_{i'j'}}\right\|^{-l}. \tag{13}$$

Considering $h_{i'j'}$ is a complex normal random variable, $\gamma^{(i',j')}$ is an exponential random variable. We can find the PDF and the cumulative distribution function (CDF) of $\gamma^{(i',j')}$ as

$$f_\gamma\left(\gamma^{(i',j')}\right) = (\overline{\gamma})^{-1}\exp\left(-\gamma^{(i',j')}(\overline{\gamma})^{-1}\right) \quad \text{and} \tag{14}$$

$$F_\gamma\left(\gamma^{(i',j')}\right) = 1 - \exp\left(-\gamma^{(i',j')}(\overline{\gamma})^{-1}\right), \tag{15}$$

respectively.

We define a link failure as a link with a lower SIR level than the outage threshold η_{out}. Given this, we can express the probability of link failure as

$$\begin{aligned} P_{out} \triangleq \Pr\left[\gamma^{(i',j')} \leq \eta_{out}\right] &= F_\gamma(\eta_{out}) \\ &= 1 - \exp\left(-\eta_{out}(\overline{\gamma})^{-1}\right). \end{aligned} \tag{16}$$

In Fig. 2, we plot P_{out} with the outage threshold η_{out}, along with P_{fa} and P_m according to the sensing error threshold η_{se}.

With (16), we can quantify the average number of failed links in the i'th route as

$$\begin{aligned}\omega &= \sum_{j=0}^{\sqrt{n}-1} j \begin{pmatrix} \sqrt{n}-1 \\ j \end{pmatrix} (P_{out})^j (1-P_{out})^{\sqrt{n}-1-j} \\ &= \left(\sqrt{n}-1\right) P_{out}. \end{aligned} \tag{17}$$

Similar to (17), in a link, let M ($>\overline{H}$) denote the average number of nodes moving to Band II due to outages among $(\sqrt{n}-1)$ neighboring nodes. It is also given by

$$M = \left(\sqrt{n}-1\right) P_{out}. \tag{18}$$

Notice, however, not all M nodes in Band II compete with each other since each node randomly chooses a channel from H' available spectrum holes. The expected number of interfering nodes in Band II among M nodes is given by

$$M' = M/H' = M/(H \cdot (1-P_{fa}-P_m)). \tag{19}$$

C. Per-link capacity

The expected received power from an interfering node can be given by

$$I_{node} \triangleq \frac{2}{n} \sum_{i'=1}^{\sqrt{n}} \sum_{j' \in J} \sum_{i \neq i'} \sum_{j \neq j'} \|\mathbf{X_{i'j'}} - \mathbf{X_{ij}}\|^{-l} \tag{20}$$

where $\sqrt{n}$ (>1) is an odd number, $\sqrt{n} = 3, 5, 7, \cdots$. Then the average interference power of Band I and II are given by

$$I_I \triangleq I_{node}\left(\sqrt{n}-M-1\right)\lfloor\sqrt{n}/2\rfloor \quad \text{and} \tag{21}$$

$$I_{II} \triangleq I_{node} M' \lfloor\sqrt{n}/2\rfloor = \frac{I_{node} M \lfloor\sqrt{n}/2\rfloor}{H\left(1-P_{fa}-P_m\right)}, \tag{22}$$

respectively. From (21) and (22), the expected SIR of Band I and II are given by

$$\overline{\gamma_I} = \frac{(\sqrt{n}-1)^l}{I_{node}\left(\sqrt{n}-M-1\right)\lfloor\sqrt{n}/2\rfloor} \quad \text{and} \tag{23}$$

$$\overline{\gamma_{II}} = \frac{(\sqrt{n}-1)^l H\left(1-P_{fa}-P_m\right)}{I_{node} M \lfloor\sqrt{n}/2\rfloor}, \tag{24}$$

respectively. With an assumption that the channel is ergodic, the channel capacity of a given link can be formulated as

$$\begin{aligned} C_{erg} &= \int_0^{\infty} \log_2\left(1+\gamma^{(i',j')}\right)(\overline{\gamma})^{-1} \exp\left(-\gamma^{(i',j')}(\overline{\gamma})^{-1}\right) d\gamma \\ &= (\ln 2)^{-1} \exp\left((\overline{\gamma})^{-1}\right) E_1\left((\overline{\gamma})^{-1}\right). \end{aligned} \tag{25}$$

Now, we define per-link capacity by taking an average over the capacities achieved by all $(\sqrt{n}-1)$ links in the i'th route, considering that the amount of interference is differentiated by the type of spectrum: Band I or II. This is given by

$$\begin{aligned} C_{l,cr} &= \frac{1}{(\sqrt{n}-1+\omega)\ln 2\sqrt{\ln n}} \\ &\times \left[\left(\sqrt{n}-1-\omega\right) C_{erg}\left((\overline{\gamma}_I)^{-1}\right) + \omega C_{erg}\left((\overline{\gamma}_{II})^{-1}\right)\right] \end{aligned} \tag{26}$$

where $\left\lfloor 1\big/\sqrt{\ln n}\right\rfloor$ is introduced to represent decrement of the capacity caused by the prolonged traverse time fraction of a given packet by scaling the network [2], [3]. In the numerators, C_{erg} is linearly combined according to the type of spectrum they are served: $(\sqrt{n}-1)$ links by Band I and ω by Band II. The expectation is taken over $(\sqrt{n}-1+\omega)$ links considering wasted time slots at failed links.

For a comparison with the capacity of cognitive ad-hoc networks derived in (26), we define that of a conventional ad-hoc network where ARQ is adopted just as the proposed cognitive ad-hoc network, but nodes are not equipped with spectrum agility. In other words, it is assumed that a Tx attempts a retransmission–via Band I–when a packet transmission fails. The capacity of this network is formulated by

$$C_{l,conv} = C_{erg}\left((\overline{\gamma}_I)^{-1}\right)\left[\ln 2\sqrt{\ln n}\right]^{-1}. \tag{27}$$

where the aggregation of the ergodic capacities is averaged over $(\sqrt{n}-1)$ links. Note that $C_{l,conv} = 0$ when $P_{out} = 1$, which means all $(\sqrt{n}-1)$ links of the i'th route are failed.

D. Discussions

In Fig. 3 and Fig. 4, we investigate the capacity law of the cognitive ad-hoc networks. We plot the analytical expression (26) along with (27) according to the number of nodes n. Fig. 4 shows that the term C_{erg} in (26) can be asymptotically bounded on $O(1)$ for both $\overline{\gamma_I}$ and $\overline{\gamma_{II}}$. Since both $(\sqrt{n}-1+\omega)$ and ω are $\Theta(\sqrt{n})$, the numerator goes to $O(\sqrt{n})$. The denominator which is composed of $(\sqrt{n}-1+\omega) = \Theta(\sqrt{n})$ and $\sqrt{\log n} = \Theta(\sqrt{\log n})$ grow like $\Theta(\sqrt{n \log n})$. Therefore, $C_{l,cr}$ is $O(1/\sqrt{\log n})$. Similarly, $C_{l,conv}$ also scales with $O(1/\sqrt{\log n})$. It is confirmed in Fig. 3 that the capacity scaling law is kept unchanged even though sensing errors are considered. Furthermore, even with sensing errors, $C_{l,cr}$ decays lesser rapidly than $C_{l,conv}$ because the cognitive ad-hoc network generates lower interference by balancing the number of nodes between Band I and II based on CR technique.

In Fig. 5 and 6, we analytically plot the capacity of cognitive ad-hoc networks $C_{l,cr}$ according to β, and P_{fa} and P_m. In Fig. 5, we plot how $C_{l,cr}$ is affected by the expected channel occupancy rate of a PU β. From (8) and (9), the number of available spectrum holes H' gets smaller as β increases. It makes the number of interfering nodes in Band II M' greater, which leads to a higher interference in Band II. As a result, $C_{l,cr}$ decreases as β increases.

In Fig. 6, we plot $C_{l,cr}$ versus the probabilities P_{fa} and P_m. From (9), it is straightforward that $C_{l,cr}$ drops with greater P_{fa} and P_m. However, it is worth to note that these probabilities show the opposite tendency with η_{se} as described in Fig. 2: P_{fa} falls, while P_m increases, as η_{se} gets greater. It makes $C_{l,cr}$ to be optimized by η_{se}, which will be discussed in the future work.

V. Conclusions

In this paper, we analyzed the capacity of cognitive ad-hoc networks with carrier sensing errors. For this, we propose

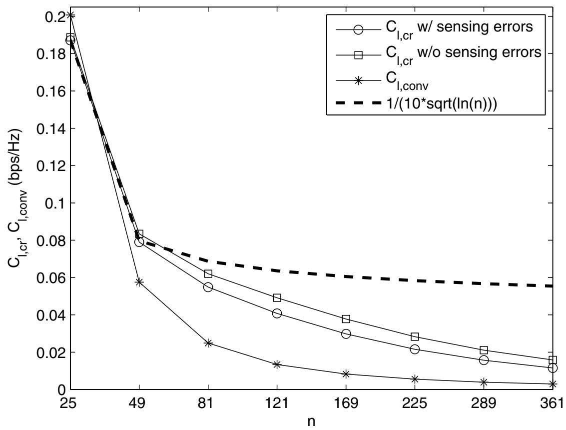

Fig. 3. Per-link capacity versus the number of nodes ($\beta = 0.1, N_{II} = 10, \eta_{out} = \eta_{se} = -30\text{dB}, \sigma_0^2 = -30\text{dB}, \sigma_1^2 = 10\text{dB}, l = 4$)

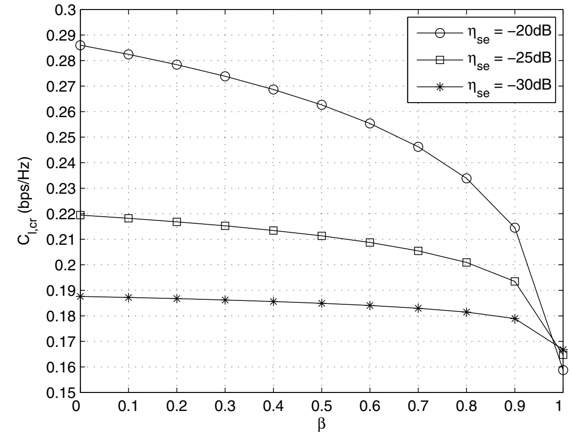

Fig. 5. Per-link capacity versus the expected channel occupancy rate of a PU ($n = 25, N_{II} = 10, \eta_{out} = -30\text{dB}, \sigma_0^2 = -30\text{dB}, \sigma_1^2 = 10\text{dB}, l = 4$)

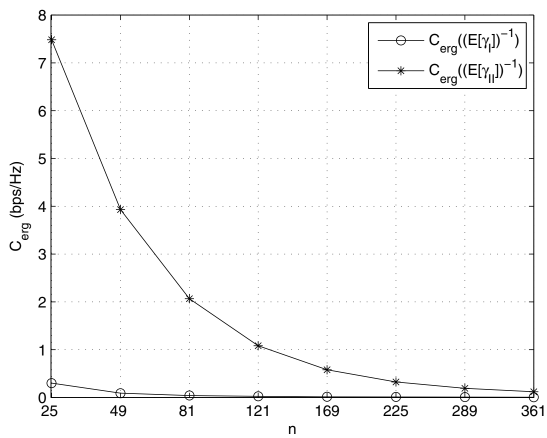

Fig. 4. Ergodic capacity versus the number of nodes ($\beta = 0.1, N_{II} = 10, \eta_{out} = \eta_{se} = -30\text{dB}, \sigma_0^2 = -30\text{dB}, \sigma_1^2 = 10\text{dB}, l = 4$)

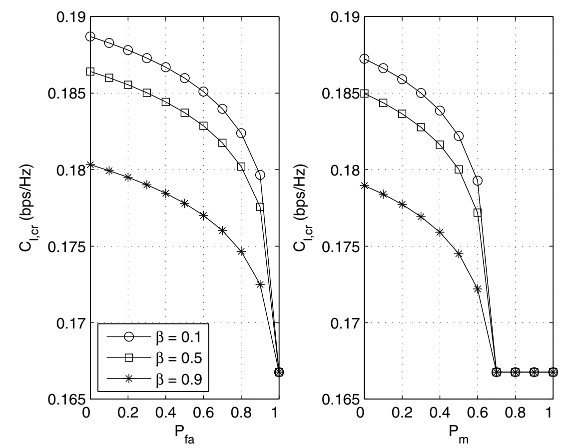

Fig. 6. Per-link capacity versus the probability of false alarm and missed detection ($n = 25, N_{II} = 10, \eta_{out} = -30\text{dB}, l = 4$)

a generic ad-hoc network with fixed nodes equipped with spectrum agility for reducing the load of retransmissions. In addition, we defined per-link capacity as a performance metric, taking into account the PUs' stochastic channel usage pattern. Our analysis proved that the capacity of the network composed of n fixed nodes is $O(1/\sqrt{\log n})$. Furthermore, it guidelines the dependency of the capacity on the PUs' channel occupancy rate and sensing errors.

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