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Dynamic Spectrum Leasing for Bi-Directional Communication: Impact of Selfishness

Maryam Hafeez & J. M. H. Elmirghani.
School of Electronic and Electrical Engineering, University of Leeds, U.K.
email:{elmh, j.m.h.elmirghani}@leeds.ac.uk.

***Abstract*—In this paper, we propose a beamforming based dynamic spectrum leasing (DSL) technique to improve the spectral utility of bi-directional communication of the legacy/primary spectrum users through the help of co-located secondary users. The secondary users help for a time interval to relay the data between two primary terminals using physical layer network coding and beamforming to attain bi-directional communication with high spectral utility. As a reimbursement, the secondary users, cognitive radios (CRs) in our case, get exclusive access to the primary spectrum for a certain duration. We use Nash Bargaining to determine the optimal division of temporal resources between relaying and reimbursement. Moreover, we consider that a fraction of secondary nodes can act selfishly by not helping the primary yet enjoy the reimbursement time. We measure the utility of the DSL scheme in terms of a metric called time-bandwidth product (TBP) ratio quantifying the number of bits transmitted in direct communication vs. DSL. We show that if all secondary nodes act honestly, more than 17 folds increase in the TBP ratio is observed for a sparse CR network (CRN). However, in such a network, selfish behavior of CR nodes can reduce the gain by more than a factor of 2.**

I. Introduction

Wireless spectrum sharing has been acknowledged as a future direction to face the challenge of meeting the growing capacity requirements. Sharing the spectrum of a legacy user with other secondary users under regulatory constraints can help to expand the overall spectral utility while meeting the QoS requirements of the legacy network [1]. Spectrum sharing/leasing with QoS guarantees finds its direct application in the evolving frameworks of device to device (D2D) and small cells empowered HetNet deployments [2]. Taxonomically, spectrum leasing can be casted under the *proprietary rights* model of spectrum sharing where spectrum owner/primary user holds exclusive rights to use/lease the spectrum to a secondary network [3]. Practically, spectrum leasing is lucrative for the owner of the spectrum only if by doing so, either it gets a monetary benefit or its own spectral utility is improved while its stringent QoS requirements are met [4].

Performance improvements offered by bi-directional communication are of special importance in the era of intolerable spectrum demand. Various cooperative relaying schemes have been devised to enhanced two-way communication throughput [5], [6]. However, bi-directional communication protocols based on spectrum leasing have not gained much attention in the literature. Specifically, DSL with performance enhancement and QoS guarantees for both primary and secondary networks via bi-directional communication has not been studied before.

a) Proposed DSL Scheme: In this paper, we present a stochastic geometry based mathematical model for DSL in which the primary network leases the spectrum to the CRs when they agree to perform two-way relaying between a pair of primary nodes communicating with each other. The primary network wants to improve its bi-directional communication performance by getting the relaying services from geographically close CRs. For such relaying services, the primary network is willing to lease its spectrum to the CRs for a duration of time in which the cooperating/relaying CRs have exclusive right to transmit their data to their respective receivers. This exclusive spectrum access opportunity is the incentive for the CRs to help the primary by relaying its data. In this paper, we characterize the QoS of both networks with and without spectrum leasing in terms of the data rate they can achieve. In order to cooperate with the primary, the CRs exploit physical layer network coding (PNC) [6] to combine the data from two primary nodes and beamform it towards the intended primary destination. Each primary node is then able to extract the data intended for it from the PNC packet relayed by the CRs. Once the CRs have cooperated with the primary network, they can enjoy the exclusive spectrum access during their reimbursement time.

b) Challenges and Solution: The cooperation and the reimbursement to the CRs takes place within a fixed time T_L. The longer the CRs cooperate with the primary, the better the primary throughput is. Similarly, the longer the duration of reimbursement, greater is the utility of the CRs. It is very crucial to divide this time between cooperation and reimbursement phase so that a stable operation point is attained at which both the primary and the CRs benefit from leasing by maximizing their individual utilities. In this paper, we caste this problem in terms of a *Nash bargaining* game between two network players, i.e., primary network and CR network. The secondaries bargain over a reimbursement proportional to the cost incurred for their cooperation. The primary in turn bargains to maximize the cooperation time to increase its data rate via relaying as much as possible. Spectrum leasing requires mutual agreement and adherence to the terms and conditions of the leasing agreement by both the primary network and the CRN. in this way, it ensures a particular QoS for both parties. Any selfish behavior from the CRs can seriously damage the performance of spectrum leasing.

In reality, there is always a finite probability that some selfish CRs also exist in the network [7]. The presence of these selfish nodes can deteriorate the performance of all entities in the network. These CRs enter the leasing agreement giving the impression that they will first cooperate with the primary by relaying their data and then enjoy a proportional reimbursement time. However, while other honest CRs actually adhere to the terms of leasing, these selfish CRs not only enjoy the reimbursement time but also communicate with their respective receivers while they were supposed to cooperate by first listening and then relaying the primary data. In this way they enjoy the cooperation time along with the reimbursement time for their own activity. As a result of this selfish behavior, the primary endures a two-fold loss;

1) Its performance is deteriorated since the selfish CRs interfere with the relayed primary communication.
2) It reimburses the CRs more in terms of time allocated for CR activity.

c) Main Results: Our analysis and results show that DSL for bi-directional communication using PNC and distributed beamforming by the CRs can serve as a useful alternative to direct communication between primary nodes when the CRs act honestly and their density is low. It can increase the primary's throughput up to 17 times as compared to direct communication. This increase is measured in terms of a metric called *time bandwidth product (TBP) ratio* denoted by β. The TBP ratio quantifies the number of bits that can be effectively transmitted between the pair of primary nodes through direct vs. DSL communication These high gains can be realized due to; i) appropriate selection of relays (i.e., harnessing the diversity gain); ii) exploiting PNC for distributed beamforming based relaying of CRs; and iii) the effective division of leasing time between the primary and secondary activities. Not only the primary network, but the CR network also procures a considerable duration of exclusive spectrum access in DSL mode for a relatively sparse deployment. It is also shown that the presence of a few selfish CRs can reduce the utility of the primary network by more than 50%.

II. Previous Work and Our Contribution

Dynamic spectrum leasing for CR networks has only recently attracted a number of contributions [8], [9], [10], [11]. In [8], authors present a spectrum leasing model for the secondary nodes where the division of leasing time follows a leader-follower approach. The authors in [9] present an incentive based DSL scheme where both time and revenue based rewards are considered. In both [8] and [9], mutual agreement is not modeled for the division of time and the spatial locations of the nodes in the network are also ignored. In an earlier work [12], we provided a mathematical model of a two way relaying scheme considering the geometry of the network. The work in [12] assumes full decoding, applying network coding and forwarding scheme at the CRs which takes three time slots. However in this paper, we remove the overhead of complete decoding at the CRs and exploit the natural network coding taking place in the air [6] via PNC. Following this, the exchange of data between the primary nodes only takes two time slots. Also, unlike [12], in this paper we consider denoising and distributed beamforming at the relays. It removes the need for the primary network to be aware of the channel statistics between them and the CR network while decoding the relayed data. An overview of various PNC and denoise and forward techniques can be found in [6] and [5] respectively. In [13], the authors study the two way relaying based on PNC. They study an optimal beamforming design to increase the achievable capacity. In [14], authors investigate a time sharing based resource sharing scheme using PNC and beamforming. However, none of these papers consider a complete geometric modeling of the locations of the nodes. Also a mutual agreement based division of leasing time has not been considered. [15] suggested the use of multiple antenna at the CRs for two way relaying for the primary network. In [16], physical layer network coding with power splitting in the relaying phase is suggested to attain two way communication of the primary network. [17] studied spectrum leasing with PNC and beamforming employing power optimization. However, there is no guarantee of performance enhancement of the primary network and there is no provision of negotiation between the primary and the secondary networks over the leasing terms.

According to the best of the authors' knowledge, the most important novelty of this work is the comprehensive modeling and analysis of DSL for bi-directional communication using PNC and beamforming. None of the studies in past have presented a DSL scheme using these techniques to enhance the performance of the primary network and the secondary network under QoS guarantees. We have shown that our proposed scheme can lead to $17\times$ performance gain for the primary network as compared to conventional direct communication. This significant improvement can be attributed to the efficient spectral utility by saving a time slot using PNC. Also, the MRT beamforming used improves the channel gain at the receiver thereby improving the overall performance of DSL. The proposed scheme also considers the presence of selfish CRs in the network and quantifies the loss incurred by the primary network in its performance due to the presence of these nodes. Bi directional communication under DSL with the presence of selfish nodes has not been studied before. In our work, the entire scheme has been modeled for composite shadow-faded channel conditions which makes the model applicable to a vast range of signal propagation environments. Moreover, there is a provision of negotiation between both primary and secondary networks over the leasing terms via a game theoretic Nash bargaining model. In practical networks, any leasing/sharing of spectrum is bound to take place after certain arbitration/negotiation between the spectrum owner and the lessee. The entire model of proposed DSL scheme considers the underlying geometry of the nodes present in the network which is also a crucial aspect in the practical operation of the scheme. The authors strongly believe that the above mentioned aspects have not been studied previously under the considered setup.

III. System Model

A. Network Model

A well accepted spatial model for CR nodes in a wireless ad hoc network is the homogeneous *Poisson Point Process* (PPP) [18]. We assume that two primary transmitters P_1, P_2, separated by a distance r_p communicate with each other in the presence of a Poisson distributed network of CR nodes in an infinite field. From the theory of PPP, the probability of finding k CRs in an area $A \in \mathbb{R}^2$ is given as

$$\Pr\left\{k\,\text{nodes in}\,A\right\} = \frac{\left(\lambda\left|A\right|\right)^k}{k!}\exp\left(-\lambda A\right), \quad (1)$$

where $|A| = \int_A \mathrm{dx}$ is the area of A and λ is the intensity of the Poisson process defined by the number of CR nodes per unit area. These secondary transmitters S_{tx} are seeking to exploit possible transmission opportunities in the frequencies owned by the primary network to communicate with their receivers S_{rx}. The CR receivers are located at a fixed distance r_0 from the CR transmitters. We assume this well known 'bi polar' model for CR transmitter-receiver pairs for the sake of simplicity. During spectrum leasing, nodes lying within a sector sec(r_p, θ) of radius r_P and angle θ are offered the spectrum in return to their relaying services. Nodes lying within $A_c \subset A$ s.t. $\left\{A_c = \frac{\theta}{2}\left((r_P - \epsilon)^2 - \epsilon^2\right)\right\}$ where $\theta \in [0, \pi]\,; \epsilon \geq 1$ participate in relaying and enjoy the reimbursement in terms of using the primary spectrum. The constraint that $\epsilon \geq 1$ assures that the distance r between any primary node and a relay is ≥ 1 so that the path loss $l\left(r\right) = \frac{1}{r^{\alpha}}$ is always < 1. In brief, it is to avoid the singularity of power-law path-loss function at zero and amplification of power for distances <1. The selected relays also form a homogeneous PPP $\Phi_c \subset \Phi$ with a total number of nodes $k = \lambda\left|A_c\right|$. The PPP Φ_c can further be subdivided into sets of honest CR relays Φ_h and selfish relays Φ_s s.t. $\{\Phi_h, \Phi_s \subset \Phi_c\}$ and $\{\Phi_h \cup \Phi_s = \Phi_c\}$. If φ s.t. $\{0 \leq \varphi \leq 1\}$ is the fraction of the density of selfish users in the network, the intensity of the honest nodes in the network is $\lambda_h = (1-\varphi)\lambda$ and that of the selfish nodes is $\lambda_s = \varphi\lambda$. When there are no selfish nodes in the network, i.e., $\varphi = 0$, the point process takes the form $\left\{\Phi_s = \emptyset, \Phi_h = \Phi_c\right\}$.

B. Signal Propagation Model

The wireless signal propagation and its received quality is mainly dependent upon 1) the number of different paths from which the signal arrives at the destination (fading), 2) multiple scattering of the signal that leads to variations in the local mean signal levels (shadowing), 3) distance dependent path loss. The Nakagami-m distribution provides a comprehensive modeling of the fading conditions in the channel through different values of the fading parameter m_m whereas, shadowing is known to follow the Lognormal distribution. In recent studies [19], [20] however, Gamma distribution has been shown as a good fit to the experimental composite fading data. In this paper, we use the Gamma distribution of order m_s and mean power Ω_0 to model the small scale fading and shadowing. The channel is considered to be slow faded with a flat response across a contiguous band of frequencies. Taking this into account, the signal-to-noise-ratio (SNR) η at an arbitrary receiver located at a distance r from another node transmitting with a power p_t is given as

$$\eta = \frac{aHl(r)p_t}{\sigma^2}, \quad (2)$$

where σ^2 is the power of the additive white Gaussian noise (AWGN) at the receiver front-end and H is the channel coefficient between the transmitter and the receiver. In the above equation, the distance dependent path loss $l(r) = \min\left(1, r^{-\alpha}\right)$ is upper bounded by unity for the case when the transmitter receiver separation distance is less than one. $\alpha \geq 2$ is the environment dependent path loss exponent and a stands for a frequency dependent constant, the value of which is commonly considered to be unity in literature [21]. It effectively absorbs antenna gain etc. which indeed is frequency dependent. We can say that for sake of generality a is assumed to be as unity. Here H follows the Gamma distribution

$$f_{\mathcal{H}}(H) = \frac{1}{\Gamma\left(k\right)\left(\theta_0\right)^k}H^{(k-1)}\exp\left(-\frac{H}{\theta_0}\right), \quad (3)$$

where $k = m_s$ and $\theta_0 = {}^{\Omega_0}\!/_{m_s}$ with moments $\mathbb{E}\left[H\right] = k\theta_0 = \Omega_0$, and var$\left[H\right] = \frac{(m_m+1)(m_s+1)}{m_m m_s}\Omega_0^2$ .The value of m_m is the Nakagami-m multipath fading parameter that determines the severity of fading for $\frac{1}{2} < m_m < \infty$. Lower values of m_m correspond to worse channel conditions. Similarly the order of Gamma function m_s allows varying the probability density function (PDF) of shadowing from lognormal to Gaussian allowing flexibility. Hence, the Gamma distribution can be used to model different cases of multipath fading and shadowing by using the corresponding values of m_m and m_s respectively. In eq.3, $H > 0, m_s > 0, m_m > 0$ and $\Omega_0 = 1$. Following is a table of the most important symbols used in the paper.

IV. Proposed Beamforming-DSL based MAC and PHY

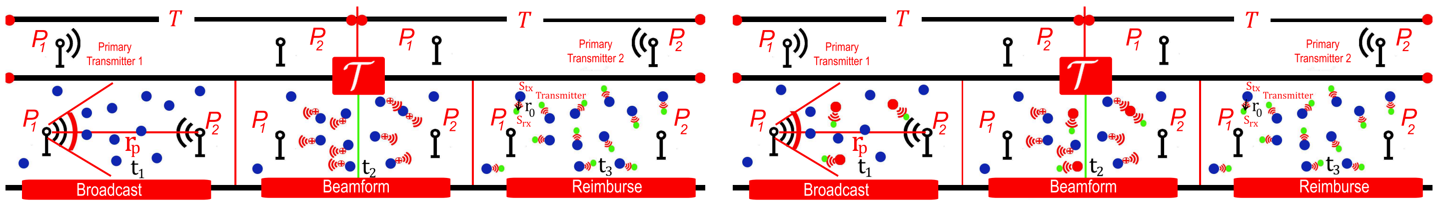
In conventional direct communication between P_1 and P_2, each transmitter uses a power p_t to communicate with the receiver for a duration T achieving a data transmission rate C_P. In the direct transmission mode, the CRs have no access to the spectrum for their communication. The total duration of operation of the direct communication for bi-directional communication is $\mathcal{T} = 2T$.

A. Beamforming-DSL with Honest CRs

Beamforming-DSL mode of communication is operational for a duration T_L . This time is further divided into three phases; a) **Broadcast and PNC** phase for time t_1 during which both P_1 and P_2 simultaneously transmit their data to the CR relays at a rate C_{BD}, b) **Denoise and Beamform** phase for time t_2 during which the secondary relays divide themselves into two groups each of which denoises and beamforms the coded data towards its nearest primary receiver (P_1 or P_2) at a rate C_{BF}, c) **Reimburse** phase for a duration t_3 where the spectrum is freely available to the CR relays to carry out their transmissions to their respective receivers at a rate C_{RI}. Fig. 1a shows the honest operation of DSL.

p_t	Transmit Power of the primary	p_s	Transmit Power of the secondary
r_p	Distance between two primary users	Φ	Point process of the secondary users
$\mathcal{T} = 2T$	Total time for primary communication	θ	Angle of cooperation
λ	Density of secondary users	ϵ	Protective disk radius
A_c	Area of cooperation	H	Channel coefficient
r_0	Distance between two secondary users	α	Path loss coefficient
σ^2	Power of AWGN at receiver front	φ	Fraction of the density of selfish CRs in the network
T_L	Total spectrum leasing duration	t_1	Time reserved for primary to secondary communication
t_3	Time reserved for secondary to secondary communication	t_2	Time reserved for secondary to primary communication

Table I
SYMBOLS USED



(a) DSL with honest CRs

(b) DSL with selfish CRs

Figure 1. DSL operation in three phases.

The overall transmission rate achieved in the DSL operational mode depends upon the capacity of each phase I and II. For two phase DSL based primary communication, the effective average DSL capacity C_{DSL} is then given as

$$C_{DSL} = \min(C_{BD}, C_{BF}) \tag{4}$$

Both primary users and CRs are only interested in participating in spectrum leasing if their respective utilities are increased as compared to what they can achieve without DSL. The utilities of the primary and the secondary network strictly depend on the division of time between t_1, t_2 and t_3. At the MAC layer, we find out the optimal time shares t_1, t_2 and t_3 for a successful Nash bargaining based division. Since the primary and secondary nodes are two physically and logically distinct entities, we present a Nash bargaining solution for a two player game where the primary network is termed as player 1 and the secondary network is player 2. The goal of the primary node is to ensure that its throughput is enhanced by maximizing the time t_1 and t_2 for which the primary sources transmit the data to be relayed to the cooperating secondary nodes and the time for which the CRs relay the data to the primary nodes after denoising respectively. The goal of the secondary nodes is to maximize their share in time so that they get reimbursed for their cooperative relaying services by getting maximum time t_3 to communicate with S_{rx} at a target rate C_{RI}[1]. During the second sub-interval, a secondary node must have enough time to at least overcome its cooperation cost $c\lambda p_s$ given its average transmission rate C_{RI} i.e., $t_3 \geq {}^{cp_s}/_{C_{RI}}$ where p_s is the transmit power of a CR. Here c measures the bits transmitted per unit of power consumed. We define the utility of the primary $U_P(t)$ and the secondary node $U_{CR}(t)$ in terms of the product of the capacity attained in a particular phase and the duration of that phase as follows,

$$U_P(t) = \begin{cases} C_{BD}t_1 & \text{Phase 1} \\ C_{BF}t_2 & \text{Phase 2} \end{cases} \quad U_{CR}(t) = C_{RI}t_3 - c\lambda p_s \ \text{Phase 3}. \tag{5}$$

respectively, where $t_1 + t_2 + t_3 = T_L$.

The simultaneous transmission by P_1 and P_2 during the time t_1 allows a natural mixing of the data of both primaries in the air at the receiving CR relays. This phenomenon is called physical layer network coding (PNC). In contrast to the conventional approaches of avoiding collision and interference, PNC exploits these phenomena to naturally combine packets from multiple sources to maximize the information flow across the network. Algebraic techniques are used to separate the combined data into the intended information at the receivers. The received signal at the CRs takes the following form:

$$y_i = \sqrt{p_t l(r_{1i}) H_{1i}} s_1 + \sqrt{p_t l(r_{2i}) H_{2i}} s_2 + n_i, \tag{6}$$

where $\sqrt{H_{xi}}$ and $l(r_{xi})$ are the Gamma distributed channel and path gain from a primary transmitter P_x to CR receiver i where $x \in \{1, 2\}$ and $i \in \Phi_c$. Also, s_x are the transmitted symbols (s_1 and s_2) from P_x and n_i is AWGN at the CR receiver.

During t_2, a group of CR nodes lying within a radius r_p cooperate with the primary network and help to relay its data. The relays only attempt to remove the noise from the combined received signal by mapping the received signal to a denoise symbol d

$$d \rightleftharpoons f_D(s_1, s_2), \tag{7}$$

where $f_D(s_1, s_2)$ is the specific denoising function used (see Sec. V-B). In order to relay this information, the honest CRs divide into two groups forming a distributed multi antenna array while they forward the denoised data d to the closest of the two primary users. Here we exploit the channel knowledge

[1]CRs form a homogeneous network in terms of the hardware platform and leasing time demand.

present at the CR relays[2] and propose Maximum Ratio Transmission (MRT) based beamforming at the secondary users.

The process of leasing is initiated by the primary network and the CRs are notified of the leasing decision and parameters over a control channel [3]. The CR network in response bargains over the fraction of reimbursement time it gets in return to its cooperative relaying services to the primary network. The primary assumes that all CRs are honest. The CRs demand a reimbursement based on the assumption that all CRs will first honestly help the primary in relaying its data. The primary network in turn weighs and bargains over the time reserved for CR based relaying of primary data since a longer cooperative time is directly proportional to greater throughput of the primary network (eq. 5). These negotiations continue until either a mutual agreement is reached (successful game) or the players end up in disagreement with each other (game ends and the spectrum is not leased).

B. Selfish CRs

As stated, both the primary and the CR network inherently assume that all nodes are truthful and honest. However, in reality, some selfish nodes might want to increase their utility by not cooperating with the primary during the second DSL phase of denoising and beamforming. Instead, while the honest CRs relay the primary data in the second phase, the selfish nodes carry out their own communication with their respective receivers during the entire duration of t_2.

1) Identifying selfish nodes: There can be a number of ways to identify which nodes act selfishly and cause damage to the primary nodes. One possible way is to enforce that every CR participating in the leasing process has to send an identification beacon to the primary in a mandated format. While decoding the message from CRs in the second DSL phase, the primary only needs to see the identities of the interfering nodes to find out the culprits. Another way to identify the selfish nodes is to use the RF fingerprints [22] of individual devices. This avoids the overhead of a mandated identification beacon. The concept of using taboo codes has been suggested in [23] claiming it to be highly efficient. For our study, the process of exchange of terms before a DSL agreement is reached makes it easy to use any of the above mentioned approaches to identify the selfish nodes.

2) Utility Function of Selfish Nodes: Due to selfish behavior, the selfish CRs enjoy transmission during t_2 for their own communication at a rate C_S and in doing so they cause harmful interference to the cooperating honest CRs. Moreover, as per the DSL agreement, these nodes also enjoy transmission during the reimbursement time. So the total utility of a selfish CR becomes

$$U_S(t) = t_2 C_S + t_3 C_{RI}. \tag{8}$$

It is clearly evident that $U_S(t) > U_{CR}(t)$ for any positive value to t_2. Hence, selfish behavior can be expected to emerge as a result of a successful bargaining agreement between the primary and CR network.

V. Analytic Modeling of Beamforming-DSL

In order to compare the proposed spectrum leasing scheme with conventional communication performance, it is important to revisit the direct two-way communication between P_1 and P_2. The information theoretic data transmission rate C when P_1 sends its message to P_2 is given by

$$C \quad = \quad \log_2\left(1+\gamma\right) \quad \text{(bits/sec/Hz)}, \tag{9}$$

where $\gamma = \frac{p_t H_p l(r_p)}{\sigma^2}$. Here, H_p is the channel power gain between the P_1 and P_2, p_t is the transmit power and $l\left(r_p\right)$ is the distance dependent path loss[4] between the nodes. As the distance between the two nodes is fixed and the channel is reciprocal, it is safely assumed that the communication rate from P_1 to P_2 is the same as the transmission rate from P_2 to P_1. In practical networks, the primary maintains a certain QoS for its communication. Here we define this QoS ρ-outage rate, C_D, as the largest rate of transmission C such that the outage probability p_{out} on this link is less than ρ. Using the Gamma distribution of the channel power gain, the ρ-outage probability can be given as

$$p_{\text{out}} \quad = \quad \Pr\left\{\gamma < \gamma^{th}\right\} < \rho, \tag{10}$$

where γ^{th} is that threshold SNR above which ρ is less that p_{out}. Using the cumulative density function (CDF) of Gamma distribution, the success probability can be written as.

$$\frac{Q\left(k, \frac{\gamma^{th}\sigma^2}{l(r_p)p_t}\theta_0^{-1}\right)}{\Gamma(k)} = \rho, \tag{11}$$

where $\frac{Q\left(k, \frac{x}{\theta_0}\right)}{\Gamma(k)}$ is the lower incomplete Gamma function. Using the inverse Gamma function $\Gamma^{-1}\left(\rho, k, \theta_0\right)$ which can be calculated using standard mathematical analytical tools like MATLAB, the outage capacity C_D can be stated as

$$C_D \quad = \log_2 \quad \left(1 + \frac{p_t l(r_p)}{\sigma^2}\Gamma^{-1}\left(\rho, k, \theta_0\right)\right) \ , \tag{12}$$

which is the least outage capacity that can be attained during direct communication.

A. Broadcast and PNC

As explained earlier, in this phase both primary nodes simultaneously transmit their data to the cooperating CRs. The coded received signal at the CRs is given as in eq. 6. The outage rate C_{BD} at which this broadcast is received at the CRs is important since the effective data rate of CR cooperation is dependent upon the rate in both phases

[2]CRs generally listen to the primary network in order to capitalize on any transmission opportunity. This listening over the control channel enables them to gather the knowledge of the channel coefficients and time synchronization in transmission between them and the primary transmitters. It is assumed that the CRs are aware of their respective distances from the primary nodes.

[3]A particular CR can be selected as a representative for the bargaining negotiations. A separate CR controlling station can also be assumed that carries out the negotiations with the primary network. Moreover, a network wide controlling station can also assumed to be present which controls the operations of all phases and regulates its implementation.

[4]Due to the assumption that there is no transmitter within $\epsilon \geq 1$ distance from both P_{tx} and P_{rx}, $l\left(\|r_P\|\right)$ is assumed to be $\frac{1}{r_P^{\alpha}}$ unless stated otherwise.

(i.e. $C_{DSL} = \min(C_{BD}, C_{BF})$, eq.4). Also, the CRs get a better reimbursement if their offered cooperative rate to the primary network is high. Different C_{BD} are experienced at individual cooperating relays due to their different and independent geographical locations and channel conditions. Since the minimum of these observed individual C_{BD} dictates the overall DSL performance, we only attempt to find the worst case C_{BD} of all the relays during this phase.

Assuming that C_{BD} at any relay is strongly distance dependent, we extend our analysis for the weakest P_x-CR relay link which is the link between any primary transmitter and the relay at the farthest distance r_n with a channel gain H_n from the primary in the cooperation region A_c. Hence the outage capacity of the worst link in phase-I can be written as

$$p_{\text{out}} = \Pr\left\{\frac{H_n p_t r_n^{-\alpha}}{\sigma^2} < \gamma^{th}\right\}. \tag{13}$$

The above probability conditioned on the knowledge of the channel gain can be written as

$$\rho \quad > \mathbb{E}_H \quad \left[\Pr\left\{r_n > \left(\frac{H_n P_t}{\gamma^{th}\sigma^2}\right)^{\frac{1}{\alpha}} \mid H_n\right\}\right] \quad . \tag{14}$$

The distance between the primary transmitter and its farthest relay in the sector is the Complementary Cumulative Distribution Function (CCDF) of finding at least one relay at a distance $r_n < R < r_p - \epsilon$. It is given in [24] as,

$$\Pr\{R > r_n\} = \frac{1 - \exp\left(-\lambda_h \frac{\theta}{2}\left((r_p - \epsilon)^2 - r_n^2\right)\right)}{1 - \exp\left(-\lambda \frac{\theta}{2}(r_p - \epsilon)^2\right)}, \tag{15}$$

where λ_h is the density of honestly cooperating CRs. From the above distribution, the outage probability becomes

$$\rho > \mathbb{E}_H\left[\frac{1 - \exp\left(-\lambda_h \frac{\theta}{2}\left((r_p - \epsilon)^2 - \left(\frac{H_n p_t}{\gamma^{th}\sigma^2}\right)^{\frac{2}{\alpha}}\right)\right)}{1 - \exp\left(-\lambda \frac{\theta}{2}(r_p - \epsilon)^2\right)}\right]. \tag{16}$$

Further, the above expression can be simplified to find out the outage threshold SNR by using the Jensen's inequality and the moment defined in sec. III. From the above expression, the lower bound on the final outage capacity is given as follows

$$C_{BD} \quad \geq \quad \log_2\left(1 + \frac{p_t}{\sigma^2}\left(\left(\frac{\eta}{\lambda_h\theta/2}\right) + (r_p - \epsilon)^2\right)^{\frac{\alpha}{2}}\right) \quad , \tag{17}$$

where $\eta = \ln\left(1 - \rho\left(1 - \exp\left(-\lambda \frac{\theta}{2}(r_p - \epsilon)^2\right)\right)\right)$. It is notable that C_{BD} is the lower bound and other relays can achieve an average outage rate better than this.

B. Denoise and Beamform

1) Outage Capacity : In this phase, the honest relays only attempt to remove the noise from the combined received signal by mapping the received signal to a denoise symbol d as shown in eq. 7. The output d belongs to a codebook of denoise symbols available at the relays and the primary network. If, for example, the fading and the path loss are ignored and BPSK modulation $\{-1, 1\}$ is considered, then there are four possible pairs $\{(-1,-1),(1,-1),(-1,1),(1,1)\}$ of transmitted primary data symbols that can be received at the relays. In the absence of fading and path loss, the combined signal would yield the possible outcomes: $\{-2, 0, 2\}$. The denoise symbols corresponding to these outcomes can be $f_D(-1,-1) = f_D(1,1) = 1$ and $f_D(-1,1) = f_D(1,-1) = -1$. Upon receiving d, the primary source is able to deduce the information coming from the other primary transmitter knowing what it transmitted earlier. For the case of path loss and uncorrelated channel gains $\sqrt{H_{xr_i}}$ with channel estimate at the relays, the relays make a decision about the value of d for each combined outcome o_i. It is such that on the reception of d at say primary node P_1, the receiver can deduce the information sent by P_2 to be $s_2 = d \oplus s_1$.

For the scenario where a composite channel is considered, the received signal at a relay i follows eq. 6 with H_{xi} being the fading coefficient. At the relays, a maximum likelihood operation is done to map the received signal to a denoise symbol as follows

$$f_D(s_1, s_2) = \text{argmin}\left\|y_i - \sqrt{p_t l(r_{1i}) H_{1i}}s_1' - \sqrt{p_t l(r_{2i}) H_{2i}}s_2'\right\|^2,$$

. where $d \rightleftharpoons f_D(s_1, s_2)$ given s_1' and s_2' are the codebook symbols at the relay. A discussion on methods relying on reducing the pairwise error probability of the symbols can be found in [25].

After denoising, all the honest secondary nodes have the same information to transmit. In order to relay this information, the CRs divide into two groups forming a distributed multi antenna array while they forward the denoised data to the closest of the two primary users. Here we exploit the channel knowledge present at the CR relays and propose Maximum Ratio Transmission (MRT) at the secondary users. Assuming that the CRs are aware of the channel gains of the CR network to the primary nodes, each secondary i relay precodes its data according to the channel state information between itself and the closest primary transmitter as

$$o_p = \frac{d\sqrt{H_{xi}^*}}{\sqrt{\sum_{y \in \Phi_{hx}} \mathcal{X}}}, \tag{18}$$

where $\mathcal{X} = |H_{xy}|\, l(r_{xy})$, Φ_{hx} consists of the set of honest nodes with intensity $\lambda_h = (1 - \varphi)\lambda$, precoding that data for its closest primary P_x s.t. $\{x \in (1,2)\}$. The selfish CRs act greedily and instead of denoising and beamforming the primary data, they simply start communicating with their own receivers. By doing so, they reduce the number of CR cooperators for the primary network and also cause harmful interference I_g to the beamformed signal transmitted to the primary by the cooperating CRs. From the reciprocity of the channel gain on the reverse link, the received signal at P_x is given as

$$y_{Px} = \sqrt{p_s}\sqrt{\sum_{y \in \Phi_{hx}} \mathcal{X}}d + n_{Px} + I_g. \tag{19}$$

In this scenario, the outage beamforming rate C_{BF} is half of the conventional rate i.e., $C_{BF} = \frac{1}{2}\log_2\left(1 + \gamma^{th}\right)$ since we assume that the two groups of CRs transmit simultaneously on two disjoint frequency bands. The outage capacity in this phase in the presence of selfish CRs can be worked out by considering the interference $I_g = \mathbb{E}\left[\sum_{y\in\Phi_{gx}} \mathcal{X}\right]$ caused by these selfish users where Φ_{gx} consists of the set of selfish nodes with intensity $\lambda_g = \varphi\lambda$. We define outage as probability $p_{\text{out}} < \rho$ as

$$p_{\text{out}} = \Pr\left\{\frac{\sum_{y\in\Phi_{hx}} \mathcal{X}}{\sigma^2+I_g} p_s < \gamma^{th}\right\} . \quad (20)$$

For the sake of simplicity, we again apply Chebyshev's inequality as in eq. 11 to upper bound the outage probability to

$$1-\rho \geq \frac{\text{var}\left[\sum_{y\in\Phi_{hx}} \mathcal{X}\right]}{\left(\frac{\gamma^{th}(\sigma^2+I_g)}{p_s} - \mathbb{E}\left[\sum_{y\in\Phi_{hx}} \mathcal{X}\right]\right)^2} . \quad (21)$$

Probability generating functional (PGFL) of the point process [18] is an important tool that helps to determine the statistical averages of functions of point processes. Here, we need to determine the average $\mathcal{Z} = \mathbb{E}\left[\sum_{y\in\Phi_{hx}} \mathcal{X}\right]$. Taking the Laplace transform of the of the expectation over both point process and shadow fading gives

$$\mathbb{E}\left[\exp^{-s\sum_{y\in\Phi_{hx}} \mathcal{X}}\right] = \mathbb{E}_\Phi\left[\prod_{j\in\Phi_{hx}} \mathbb{E}_H\left[\exp^{(-s\mathcal{X})}\right]\right] \quad (22)$$

From the definition of PGFL,

$$\mathbb{E}\left[\exp^{-s\sum_{y\in\Phi_{hx}} \mathcal{X}}\right] = \exp^{\left(-\mathbb{E}_H\left[\int_{\mathbb{R}^d}\left(1-\exp^{(-s\mathcal{X})}\right)\lambda \text{dx}\right]\right)} \quad (23)$$

Cumulants of a probability distribution can be defined in terms of the moment generation function (MGF)

$$\kappa_n = \frac{d^n}{ds^n} \ln\left(\mathbb{E}\left[\exp^{s\mathcal{Z}}\right]\right)|_{s=0} . \quad (24)$$

We use eq. 23 and the definition in eq. 24 to find the cumulants of interference for 2-dimensional network

$$\kappa_n = -\frac{\lambda}{2}\mathbb{E}_H\left[H_{xy}^n \int_{\mathcal{A}} r^{-\alpha n} \exp^{\left(sH_{xy}r^{-\alpha}\right)} dr^{d-1} \text{drd}\theta\right], \quad (25)$$

where $\mathcal{A} = \mathbb{R}^2 \cap \sec(\theta, r_p - \epsilon)$ and κ_1 is the average of the aggregate composite channel gain and path loss and $\mathcal{X} = |H_{xy}|\, l\,(r_{xy})$.

$$\mathbb{E}\left[\sum_{y\in\Phi_{hx}} \mathcal{X}\right] = \kappa_1 = \left(\frac{\lambda\theta}{2}\right)\left(\frac{(r_p-\epsilon)^{2-\alpha} - \epsilon^{2-\alpha}}{2-\alpha}\right). \quad (26)$$

The average interference $\mathbb{E}[I_g] = \mathbb{E}\left[\sum_{y\in\Phi_{hx}} \mathcal{X}\right]$ follows from κ_1. Similarly κ_2 is the variance of this aggregate signal

$$\text{var}\left[\sum_{y\in\Phi_{hx}} \mathcal{X}\right] = \kappa_2 = \left(\frac{\lambda\theta}{2}\right)\left(\frac{(r_p-\epsilon)^{2-2\alpha} - \epsilon^{2-2\alpha}}{2-2\alpha}\right) \text{var}[H], \quad (27)$$

where $\text{var}[H] = \frac{(m_m+1)(m_s+1)}{m_m m_s}\Omega_0^2$ as defined in Sec. III-B. From eq. 26 and 27, the probability of outage in equation 21 can be completely characterized and the outage capacity C_{BF} takes the following form

$$C_{BF} = \frac{1}{2}\log_2\left(1 + p_s\left(\sigma^2 + \left(\frac{\lambda_s\theta}{2}\right)\mathcal{R}\right)^{-1}\mathcal{K}\right), \quad (28)$$

where $\mathcal{R} = \left(\frac{(r_p-\epsilon)^{2-\alpha}-\epsilon^{2-\alpha}}{2-\alpha}\right)$ $\mathcal{K} = \left(\sqrt{\frac{\kappa_2}{1-\rho}} + \kappa_1\right)$. C_{BF} is the achievable rate by the beamforming CRs under the outage constraint of ρ[5]. It can be clearly seen that the capacity in this phase with selfish CRs i.e., when $\varphi \neq 0 \rightleftharpoons \lambda_s \neq 0$, is lower compared to the the capacity when all CRs are honest. This is because of the interference they cause when the honest CRs beamform towards their respective primary node.

C. Reimburse

During this phase, the secondary network enjoys an exclusive access to the spectrum for its own activity. As a reimbursement to the cooperation of the CRs, the primary remains inactive during this time and allows the CR network to use the spectrum. Since all the CR nodes simultaneously transmit in this phase, each node experiences a certain interference coming from other communicating CRs. The SINR experienced at any CR receiver z is given as

$$1-\rho = \Pr\left\{\frac{p_s H_{z0} l(r_0)}{\sum_{y\in\Phi_c} H_{zy} l(r_{zy}) + \sigma_z^2} > \gamma^{th}\right\} \quad (29)$$

We adopt the same approach as in eq. 12 to find out the outage capacity C_{RI}. By using the definition of PGFL and some mathematical simplifications, it comes out to be

$$C_{RI} = \log_2\left(1 + p_s\left(\sigma^2 + \left(\frac{\lambda\theta}{2}\right)\mathcal{R}\right)^{-1}\mathcal{N}\right), \quad (30)$$

where $\mathcal{N} = \Gamma^{-1}(\rho, k, \theta_0)\, r_0^{-\alpha}$. It is readily evident that C_{RI} tends to get limited by the interference caused by concurrent transmission of all CR relays.

1) Outage capacity of Selfish CRs : In order to quantify the utility of the selfish nodes, it is important to analyze the capacity C_S achieved by the selfish CRs in phase II. In terms of the SINR experienced at any CR receiver z, the probability of successful communication is given as,

$$1-\rho = \Pr\left\{\frac{p_s H_{z0} l(r_0)}{\sum_{y\in\Phi_c} H_{zy} l(r_{zy}) + \sigma_z^2} > \gamma^{th}\right\}. \quad (31)$$

From eq. 25, the outage capacity can be expressed as

$$C_S = \log_2\left(1 + p_s\left(\sigma^2 + \left(\frac{\lambda\theta}{2}\right)\mathcal{R}\right)^{-1}\mathcal{N}\right). \quad (32)$$

Remarks: It is important to note that the capacities C_{BF} and C_S strongly depend on the density of CR nodes. The aggregate interference experienced with increasing the value of φ resulting in lesser C_{BF}. The outage capacity of selfish CRs in phase II ,C_S, is dependent on the entire CR density λ since all nodes interfere with a selfishly operating node during the second phase of DSL.

[5]Notice that eq. 28 follows from the Silvnyak's theorem which states that adding a point to the HPPP does not change the law. The interested readers are referred to [18] for further details.

D. Game theoretic leasing time division

The important question that still remains unanswered relates to the duration of time of the three phases (t_1, t_2, t_3). As discussed earlier, for every primary and CR node, time division is crucial since a greater share in time leads to a greater throughput. It is important to mention that the game is played assuming that all players are honest and once an agreement is reached, all players abide by it i.e., $\varphi = 0$.

The Nash bargaining framework is employed to model this situation in which the players negotiate for their agreement on a particular point out of a set of joint feasible payoffs $\mathcal{G}$. In a two player Nash Bargaining game, $\mathcal{G} \equiv \{g = (g_1, g_2) : g_i = f_i(\mathbf{S}),\ i = 1, 2;\ \mathbf{S} \in S1 \times S2\}$, where the functions $f_i(.)$ represent the individual utilities of the two players and $\mathbf{S}$ is the strategy of the i^{th} player from the strategy profile S_i. In Nash Bargaining, in case the negotiations render unsuccessful, if the outcome of the game becomes $\mathcal{G} = (g_{01}, g_{02})$. It is a fixed vector known as the disagreement vector. The whole bargaining problem can be described conveniently by the pair $(\mathcal{G}, g_0)$ [26].

Maximizing the amount of time to maximize the capacity of any phase is the most simple way to increase the performance and hence the utilities $U_P(t)$ and $U_{CR}(t)$ of the primary and the CRs. For this reason, we formulate a bargaining game over the durations t_1, t_2 and t_3. The time demand of each player i.e,. t_1 and t_2 for the primary node and t_3 for the secondary node are the strategies chosen from their respective strategy profiles. In this case, the fraction of leased time should be large enough to ensure that the time-rate product of broadcast phase $t_1 C_{BD}$ and the cooperation phase $t_2 C_{BF}$ is greater than the direct communication time $\mathcal{T}$ and rate C_D product. During the second sub-interval, a secondary node must have enough time to at least overcome its cooperation cost $c\lambda p_s$ given its average transmission rate C_{RI}. Here c measures the bits transmitted per unit of power consumed. Mathematically, the conditions $t_1 > {}^{\mathcal{T}C_D}/_{C_{BD}}$, $t_2 > {}^{\mathcal{T}C_D}/_{C_{BF}}$ and $t_3 > {}^{c\lambda p_s}/_{C_{RI}}$ are ensured in a successful time division decision. An agreement is not reached if the players are not satisfied by the outcome of the negotiations. Hence, the disagreement vector of our Nash Bargaining game becomes $t_{01} = {}^{\mathcal{T}C_D}/_{C_{BD}}$, $t_{02} = {}^{\mathcal{T}C_D}/_{C_{BF}}$ and $t_{03} = {}^{c\lambda p_s}/_{C_{RI}}$. A triplet of payoffs (t_1^*, t_2^*, t_3^*) is a Nash Bargaining solution if it solves the following optimization problem

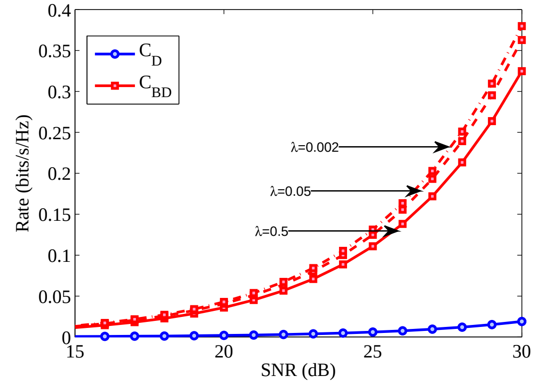
$$\max \left(\log\left(t_1 - t_{01}\right) + \log\left(t_2 - t_{02}\right) + \log\left(t_3 - t_{03}\right)\right), \quad (33)$$

$$\text{subject to} \quad \begin{array}{rcl} t_1 C_{BD} & = & t_2 C_{BF} \\ T_L & = & t_1 + t_2 + t_3 \end{array}.$$

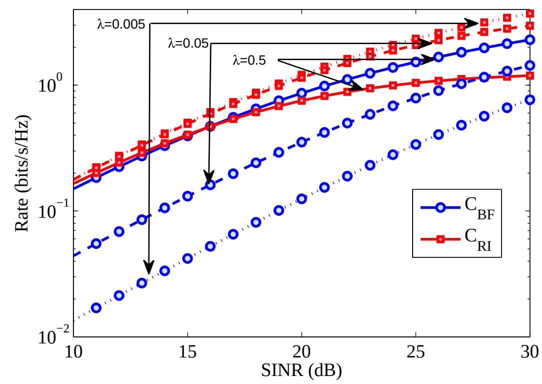
If the set $\mathcal{G}$ is compact and convex, and there exists at least one $g \in \mathcal{G}$ such that $g > g_0$, then the unique solution to the bargaining problem $(\mathcal{G}, g_0)$ corresponds to the unique solution of the optimization problem [27], [26]. Using the Lagrangian dual of the above optimization problem, the time t_2 is the solution of the following quadratic equation;

$$t_2 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \quad (34)$$

where $a = \delta + 2\Upsilon_1$, $b = \Upsilon_1\left(2\Upsilon_3 - t_{02} - \Upsilon_1 t_{01}\right) - \delta\left(t_{02} + t_{01}\right)$ and $c = \delta\Upsilon_1 t_{01} t_{02} - \Upsilon_1\Upsilon_3 t_{02} - \Upsilon_1^2\Upsilon_3 t_{02}$ with



(a) Data rate of the primary transmissions in direct communication and DSL phase I.



(b) Data rate of the CR transmissions in DSL phase II and III, $\lambda = 0.5$.

Figure 2. Performance of direct communication and three DSL phases for various densities of the CR network. $p_t = 1$, $p_s = 0.1$,$\rho = 0.1$, $r_p = 10$,$\epsilon = 1$.

$\Upsilon_1 = {}^{\bar{C}_{BD}}/_{\bar{C}_{BF}}$, $\Upsilon_2 = (\Upsilon_1^{-1} + 1)^{-1}$, $\Upsilon_3 = \Upsilon_2\left(t_{03} - T_L\right)$ and $\delta = \Upsilon_2\left(\Upsilon_1 + 1\right)$. Also t_1 and t_3 can be found out using the constraints in eq. (33).

VI. Discussion and Results in the Absence of Selfish CRs

In this section, we study the behavior of conventional bi-directional communication vs. our proposed beamforming based DSL. We begin by analyzing the capacity achieved while the primary nodes transmit i.e., C_D and C_{BD} in fig. 2. From fig. 2a it can be seen that for a given link distance, the direct communication rate C_D is significantly lower than C_{BD}. As mentioned before, this phenomenon is a consequence of the fact that transmission in the DSL phase I encounters reduced path loss due the reduced link distance between the primary nodes and the relays. The capacity of the primary to secondary communication in the broadcast phase is strongly dependent upon the number of secondary nodes present in the area of cooperation. In fig. 2a, the rate from one primary source to the farthest CR node is shown. For a very low secondary density, e.g., $\lambda \lll 0.002$, the probability of finding a neighbor in the region of cooperation is extremely low. *For this reason, the capacity analysis for very sparse secondary network is not possible since the transmission rates from* $P_{1,2}$

to the CRs are nearly zero. For higher λ, it can be seen from fig. 2a that the average transmission rate C_{BD} is greater than that of the direct communication. This is a consequence of such cooperation region selection where the relays are located in a close proximity to both P_1 and P_2. However, if the number of secondary users increases in the cooperation region, the average distance between the transmitter $P_{1,2}$ and the farthest node increases which follows from the average distance quantification in eq. 17. Hence C_{BD} decreases when λ increases. Also, both C_D and C_{BD} increase with improving channel conditions.

We study the CRs transmission in phase II and III i.e., C_{BF} and C_{RI} respectively in fig. 2b. It can be seen that C_{BF} increases with increasing density of the CRs. This happens because of the increase in the diversity due to multiple relays beamforming towards the primary nodes. C_{RI} on the other hand decreases as expected with increasing CR density. As discussed earlier, the aggregate interference due to multiple concurrent transmission poses a bottleneck and even improving channel conditions fail to improve C_{RI} proportionally. C_{RI} is interference limited in higher SNR regions.

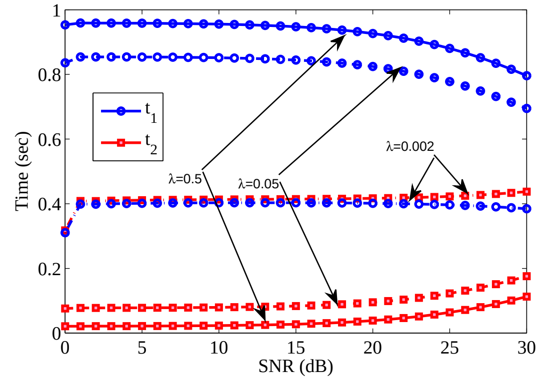
In fig. 3a we show the amount of time reserved for DSL phase I and II. It can be seen that at low values of λ, more time t_2 is reserved for phase II to increase the rate C_{BF}. At lower CR densities, the time required by the CRs in the beamforming phase increases due to lower number of relays to beamform and hence lower achievable transmission rate. When $C_{BF} > \max\{C_D, C_{BD}\}$, the second phase is allocated shorter time and vice verse. At higher values of λ, C_{BD} is the limiting factor and hence more time is reserved for it to enhance the capacity of this phase. This is because as seen in the previous discussion, C_{BD} is the lowest of all other DSL rates. In order to maximize the gain in primary data transmission, t_1 is higher in order to meet the condition, $t_1 C_{BD} > \mathcal{T} C_D$. Following eq. 4, the division of the time is such that $t_1 C_{BD} = t_2 C_{BF} > \mathcal{T} C_D$.

The time reserved for secondary activity t_3 in the third phase is also shown. To compensate for their energy costs in the second phase and deteriorated rate performance due to interference in the third phase, the CRs are given a reasonably high time for their activity specifically at low CR densities. On the other hand, increasing λ decreases the time demand/share of the reimbursement phase. This is because of the increased interference due to higher λ as shown in fig. 3b. Improving SNR mostly improves the share of time t_3.

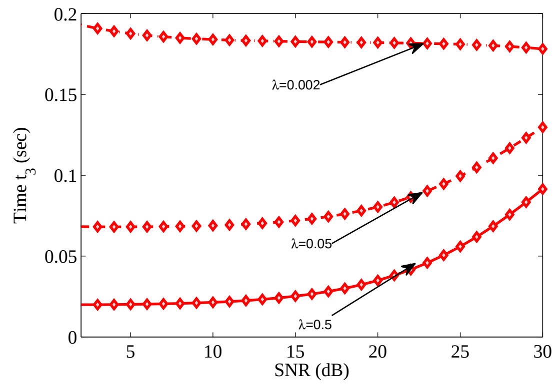
VII. Time-Bandwidth Gain

In this section, we are interested in knowing the potential benefit that the primary network can get by leasing the spectrum. We measure this gain in terms of a metric called the time bandwidth product (TBP) ratio denoted by β. It is defined as the ratio of the number of bits of primary data that are successfully transmitted in DSL based primary communication time to those transmitted via direct two-way transmission. Mathematically,

$$\beta = \frac{t_1 C_{BD}}{\mathcal{T} C_D} \tag{35}$$



(a) Division between DSL phase I and II, $\lambda = 0.5$ (solid), $\lambda = 0.05$ (dash), $\lambda = 0.002$ (dash-dot).



(b) Time reserved for DSL phase III

Figure 3. Division of time between DSL phases I, II and III. $T_L = 1$.

The alternative definition using the product $t_2 C_{BF}$ can be equivalently used in eq. (35).

In Fig. (4), we show the TBP ratio (β) achieved by using DSL under the considered geometric and Nash Bargaining setup. The results indicate that DSL provides a significant gain in the number of bits that are successfully transmitted in DSL as compared to the number of bits ($\mathcal{T} C_D$) in direct two way communication. This occurs because the geometric vicinity, network coding and beamforming services of the CR nodes provide higher transmission rates. Such enhanced performance is attained only when enough incentive is available for the secondary nodes to cooperate with the primary network. The division of leasing time T_L into t_1, t_2 and t_3 based on the optimization problem formulated in eq. 33 ensures that the TBP of phase I and II of DSL remains the same, (see eq. 33 constraint I) within the given leasing duration. For this reason, both TBPs, $t_1 C_{BD}$ and $t_2 C_{BF}$ are the same. Overall there is a gain from $3\times$ up to $17\times$ in β using the proposed DSL scheme. For further insights, there are two factors we study β against: 1) CR density and 2) length r_p of the primary link.

It can be seen from fig. 4 that for shorter primary link distance r_P, β increases with increase in the secondary density. It can be accredited to the fact that C_{BF} improves with increasing λ providing the beamforming gains with increase in the number of CR relays. However, the ratio reaches a maximum ($\sim$ $\lambda = 0.1$ for $r_P = 10$) after which further

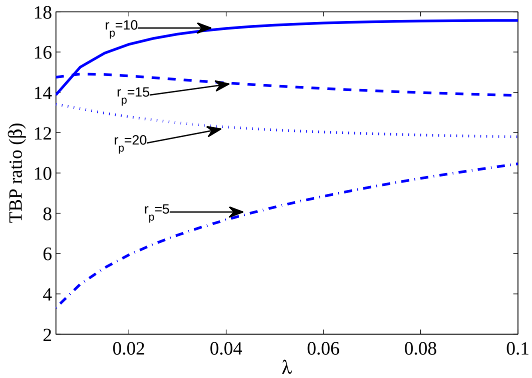
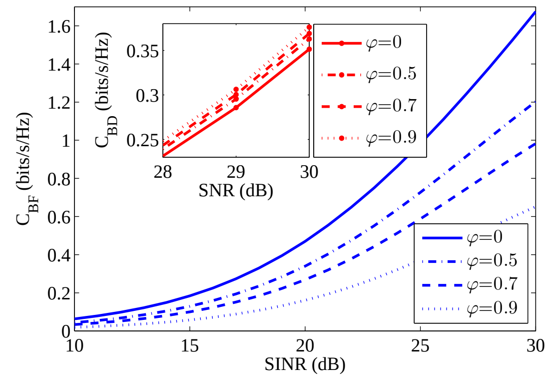
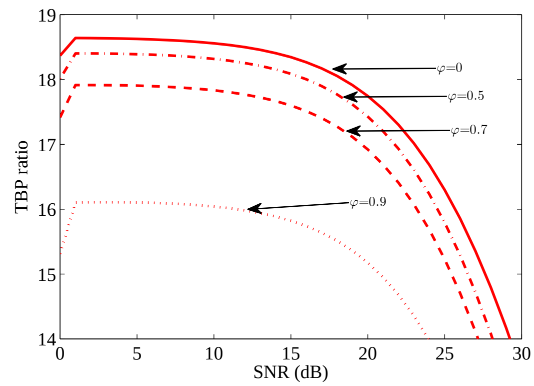


Figure 4. Time Bandwidth Product ratio $\mathcal{T} = T_L = 2$



(a) Effect of selfish behavior on C_{BD} and C_{BF} where $\lambda = 0.1$.



(b) Effect of selfish behavior on TBP where $\lambda = 0.1$.

Figure 5. Impact of selfish behavior on the performance of DSL.

increase in the secondary density slightly degrades β. This takes place since at high densities, C_{BD} decreases due to the increase in the link distance between the primary transmitter and the farthest relay. This phenomenon limits further increase in β by increasing λ. However, for longer link distances, i.e., $r_P = 15, 20$, β reduces with increasing secondary density since secondary transmit power p_s is quite low. In order to relay information between a longer link, it is better to adopt a multihop relaying rather than single hop relaying considered in this paper. Hence, Fig. 4 shows that DSL is most beneficial to the primary network at intermediary secondary densities i.e., not very sparse and not too dense secondary network for relatively shorter primary links. Practical example can be a Device-to-Device (D2D) network or a small cell network where two small base stations can exchange control/coordination information using the help of secondary nodes.

VIII. Impact of Selfish Behavior

So far we have analyzed the performance of DSL assuming all nodes are honest i.e., $\varphi = 0$. We now examine how the selfish behavior of some CR nodes effects the overall performance of the DSL mechanism. Fig. 5a shows that increasing φ marginally improves C_{BD} during phase I. This can be explained as a consequence of the decrease in the effective number of CR relays that actually receive the primary data to relay later on. Since this number decreases, hence, overall the distance of any primary node to the farthest honest CR relay decreases. However, the selfish behavior largely deteriorates the capacity in phase II, where a decrease of more than 2x can be observed from fig 5a when 70% of the CR nodes act selfishly. Such deterioration can lead to severe degradation in the quality of service of relaying promised by the CRs leading the primary network to incur loss in the expected C_{BF}. The primary agrees to leasing time t_3 on the understanding that all CRs honestly cooperate. The selfish behavior not only degrades the data rate of relaying of the primary data but also procures greater reimbursement as compared to the help offered to the primary network.

Fig. 5b shows the impact of selfish behavior when DSL provides the highest gains. It was shown in Fig. 4 that a relatively sparse CR density of $\lambda = 0.1$ results in the highest DSL. It is most important to quantify the impact of selfishness of the CR network for this network density. It can be seen from Fig. 5b that the TBP ratio decreases sharply by increasing φ in the network. Therefore, the increasing selfish behavior of CRs i.e., $\varphi = 0 \rightarrow 0.9$ can significantly degrade the performance of DSL.

IX. Conclusion and Open Issues

In this paper, we investigated the usefulness of DSL as a scheme which can improve the performance of primary network in terms of the number of bits that can be successfully transmitted between the primary sources. TBP ratio β indicated that DSL can improve the communication of the primary network as compared to direct communication more than 17 times. Specifically, a relatively sparse deployment of the CR network is favorable for both the primary and CR network. For the primary network, distributed beamforming and PNC with denoising are the key factors that result in enhanced cooperative relaying performance. Such high performance can be seen only when the secondary relay density is kept low. These performance determinants and their effect on the working of DSL can only be measured due to the detailed geometric modeling of the network. Hence denoise and beamforming based DSL provides an efficient alternative to direct two way communication for the primary network. Within the same available time and bandwidth, it allows the CR network to communicate with each other at an acceptable rate and QoS. We studied the presence of selfish CRs in the network and modeled their utility. We have shown that the selfish behavior by CRs can reduce the TBP ratio more to than $1/2$ at low densities densities. Dealing with selfish nodes and ensuring trust is a very important subject in existing and future wireless networks. As an extension of this work, it is important to quantify the level of trust between the network entities and make bargaining decisions based on this knowledge about trust. Moreover, it is crucial to devise mechanisms to discourage any selfish behavior in the network. Methods such as silencing the selfish nodes, charging penalties and pricing can be introduced to minimize selfish behavior.

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