Dynamic Spectrum Leasing for Cognitive Radio Networks—Modelling and Analysis

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Abstract Incentive based dynamic spectrum leasing (DSL) has been suggested as a type of cognitive radio (CR) based communication in which the legacy network allows the cognitive radio nodes to utilize its spectrum for their communication in exchange for cooperative relaying services. The key objective of this chapter is to investigate the design space of a DSL empowered large scale CR network (CRN) collocated with a point-to-point primary communication link. The ultimate design objective is to improve both the network level energy efficiency and the spectral efficiency through the exploitation of cooperation gains rendered by the proposed optimally dimensioned DSL mechanism. This chapter presents a DSL scheme where the CRs cooperatively relay the data of the primary network for a duration of time. As a reward for the cooperation, the CRs are granted exclusive access to the primary spectrum for some time. To harness maximum gains in terms of energy efficiency (EE) for the primary network while maintaining its required quality of service and spectral efficiency (SE) of the CR network, a comprehensive model of DSL is presented. To this end, an accurate quantification of the random locations of the CR nodes and the optimal division of leasing time between the primary and secondary activities are two crucial factors. In this chapter, we consider a large scale cognitive random network. The spatial dynamics are modeled by using point process theory from stochastic geometry. Mutual agreement of the primary and secondary nodes on the leasing time division is studied using a game theoretic framework. The analysis indicates that DSL enables the primary to attain its required transmission rate and from 20 up to 50 % of the total leasing time is also reserved for the secondary activity. It is shown that the bargaining powers of the primary and secondary networks strongly dictate the proportion of cooperation and leasing time. Further, the EE of DSL based on the network geometry and optimal leasing time is analytically characterized. The simulation results reveal that DSL operation under such considerations can be significantly more energy efficient as compared to direct communication. A closer look helps to ascertain that DSL with a sparse secondary network can serve to be more than 10 times energy efficient while maintaining the

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M.Z. Shakir et al. (eds.), *Energy Management in Wireless Cellular and Ad-hoc Networks*, Studies in Systems, Decision and Control 50,
DOI 10.1007/978-3-319-27568-0_10

same time-rate product as compared to direct communication for low CR densities. Hence DSL based communication enables the primary to communicate at its desired transmission rate and quality in an energy efficient manner and also enables the CR network to exploit the licensed spectrum for its own communication. In short, DSL is a useful technique for improving the efficiency of wireless communication with direct application to future networks.

1 Introduction

Over the last few decades, wireless communication has witnessed an immense growth in its technological sophistication and widespread deployment. It is been estimated that a capacity expansion by a factor of 1000 is needed in the next generation (5G) mobile networks [1]. In order to satisfy the sustained growth of mobile traffic, the development of more sophisticated and flexible radio networks is fundamental. This calls for additional spectral resources, planning/infrastructure deployment costs and energy requirements for the network operations. In the recent past, significant rise in the energy consumption of the communication networks has been recorded. Around 7.95 % rise in the energy demand of Telecom Italia network was observed in 2007. At the same time, British Telecom contributed to about 0.7 % of the total UK's energy consumption [2, 3]. It is predicted that in comparison to 2007, CO2 equivalent emissions of the communication network will increase by a factor of three until 2020. This corresponds to more than one third of the overall emissions in the UK [4, 5]. These alarming statistics and the rising costs have motivated the research and development community to target improving the energy efficiency of the mobile communication network by a factor of 1000 per transported bit for the emerging 5G networks [1].

A prime goal in the design of any wireless communication network is to maximize the spectral utilization while attaining the highest quality of communication. Increasing bandwidth and/or power are the two main approaches that directly follow from the Shannon's capacity of a wireless channel to enhance the communication rate [6]. Spectrum scarcity has already been recognized as one of the major problems faced in the deployment of new technologies and in the enhancement of the capacity of the existing ones. Moreover, the current energy consumption trends indicate that if the communication systems continue to develop and spread at the same pace, a significant portion of the total energy production of any country would be needed to meet the requirements of future communication systems [7, 8]. At this juncture, an ideal future wireless system would; (1) maximize the utilization of the existing bandwidth, (2) minimize the power consumption while supporting a high quality of communication.

Under-utilization of the electromagnetic spectrum due to the stringent spectrum allocation schemes has become a well established fact in a very short time [9]. This inefficient utilization of bandwidth is one of the main causes of the apparent free spectrum extinction. CRs are envisioned to be a possible solution to this problem.

They co-exist with licensed networks and enable optimum utilization of spectrum across both geographical and temporal domains. CRs dynamically exploit the spectral resources of the legacy (primary) network without causing any intervention in the primary network (PN) operations. Many different approaches to realize CRs have been suggested in [10, 11]. However, these approaches only provide intermittent/sporadic connectivity for the CRs without any QoS guarantees. Our goal here is to analyze a CR based architecture that exploits the licensed spectrum for its own utility and maintains the performance of the legacy network in terms of its communication rate while reducing the overall power consumption in the network. We aim to study that how the relaying services of a few geographically suitable CRs procures an exclusive spectral access to the entire CR network.

In contrast to passive spectrum sharing between a PN and a CRN (provisioned through hierarchical access mechanisms), DSL employs an active approach to improve the overall spectrum utilization through DSA [12]. This chapter is based on studying DSL where the PN leases a part of its spectrum to another spectrum-less network when the latter helps to improve the performance of the incumbent network. The aim of the chapter is to study DSL as a unified model for the mutual benefit of the incumbent spectrum users (primary users (PUs)) and non incumbent networks (secondary users (SUs) e.g., CRs). The primary metrics of quantifying the benefits of DSL are the spectral and energy efficiency of the network. This chapter explores how a network without having a pre-owned license to access the spectrum can help to improve the performance of a planned and deployed PN. It introduces a spectrum leasing framework that reconsiders spectrum allocation rights and policies, improves the current characterization by rigorously studying various degrees-of-freedom of the network, and also incorporates tools to enable the modelling of the intelligent and adaptive behaviour of such networks. It judiciously quantifies the service that a secondary network (SN) offers to get spectral access in return such that both primary and secondary network meet their own objectives of improved spectral utilization. It also studies how the proposed DSL schemes can help improve the energy efficiency of the primary network. More specifically, under DSL enabled DSA:

1. The PN has a certain incentive for rewarding the CRN with access to its licensed spectrum. Incentives can be either monetary or non-monetary in nature.
2. The PN can dynamically adapt the rewarding mechanism by observing changes in its incentive. In other words, the PN can actively control the amount of spectral resources it is willing to share across various dimensions of the Hertzian medium. Note that the radio spectrum has a multi-dimensional nature, i.e., variations across time, frequency, polarity, space, etc., all determine the available spectral resources.
3. The PN can ensure that the required quality of service (QoS) constraint for its own users is guaranteed. Thus transparency in terms of the performance of the PN is an intrinsic feature of DSL.

While it is easy to argue that DSL enabled CRNs have the potential to maximize the spectral utilisation, it is not clear if the potential gains are harnessed at a cost of increased energy consumption. This leads to the following design question:

> Is it possible to develop a DSL mechanism which maximizes the network level spectral efficiency (which is a function of individual spectral efficiencies of the PN and the CRN) while also ensuring an increase in the network wide energy efficiency?

Additionally, another related design issue stems from the fact that the existing literature on DSL, refrains from considering the impact of the network topology and propagation uncertainties on the promised potential gains. Specifically:

> Does DSL successfully deliver its promised spectral/energy gains under realistic channel propagation conditions while considering the topological uncertainties due to varying spatial dynamics of the CRN?

A practical DSL scheme that maximizes the spectral and energy efficiency of the network over a wide dynamic range of signal propagation conditions and node locations can be directly integrated in the design of future wireless networks. DSL provides a framework to caste the mutual interest of a variety of entities in the network to improve it overall performance by optimal division/allocation of available resources. The DSL scheme presented in this chapter finds direct application in efficient resource division in the 5G key concepts of carrier aggregation, license shared access (LSA), device-to-device (D2D) communication and offloading in heterogeneous networks etc. [13–15].

2 Research Objectives and Contributions

In this chapter, answers to the above-mentioned design issues/questions are investigated by developing a framework to quantify the performance of both the PN and the CRN under a proposed DSL mechanism. The aim of this chapter is to study how DSL can be used as an energy efficient alternative for PN communication while improving the spectral efficiency of the SN. The proposed DSL mechanism considers that in a dense CRN deployment, cooperation of the CRs with the PN can be traded for spectrum access opportunities. More specifically, the intrinsic distributed diversity gain provided by a cooperative relaying protocol and reduced propagation loss due to dense deployment can be treated as a resource which a CRN can offer to a PN to sustain its operations i.e., maintaining its QoS while reducing its energy expenditure. However, the improvement in the performance of the PN through cooperation comes at a cost paid by the CRs in terms of their energy consumption. Consequently, the CRs wish to trade the incurred cost for a spectrum access opportunity. Thus in a nutshell, the proposed DSL mechanism provides transmission opportunities to the CRs if they in return help in improving the energy utility of the PN through inter-network cooperation. Consequently by shrinking the transmission window of the PUs, during the remaining time the spectral resources are reserved to provide access to the cooperating CRs. Such a DSL approach for a CRN communication where the services of cooperative relaying by the CRs serve as an incentive for the PN spectrum leasing resulting in improved EE of the PN and better SE of the CRN is the focus in this chapter.

In the proposed DSL mechanism, the PN leases its spectrum to the SN, which in this chapter is a CRN, and forwards its data to the CRs for cooperative transmission. The SUs/CRs relay the PN data during some fraction of the leasing time. For the remaining leased time, the CRN exclusively uses the spectrum and carries out its own communication. The share in time and bandwidth for the secondary communication is the motivation for the CRs to cooperate with the PN. A PU is interested in maximizing the time for which the CR nodes relay its data. Greater negotiation power can help the PN to ensure that for most of the time the CRs relay its data. On the other hand, the CRs intend to schedule their own transmissions for most of the leasing time. The reward for the cooperative relaying of a few CRs can ripple across the entire CRN, enabling spectral access. However, the cooperating CRs need to negotiate with the PN to get a certain duration of leasing time so that the entire CR network can benefit from it. Such selfish yet rational behaviour of the PUs and SUs makes the appropriate division of the leasing time very important for successful DSL operation. An optimal division is described as a division which is mutually agreed upon and satisfies the demand of both networks. A greater negotiation power can help each network to procure more time for itself.

In this chapter, fundamental mathematical modelling and analysis of the proposed DSL mechanism for CRN is pursued. Despite the wide scale applicability and potential benefits of service based DSL, contributions in the existing literature are very limited. The following aspects of DSL for the CRNs need to be addressed:

1. In order to analyse a DSL empowered CRN, it is important to consider a realistic network topology for both the PN and the CRN. The necessity of a realistic geometry based network model manifests itself not only in topological considerations but also in terms of the efficient selection of the cooperation areas under the DSL mechanism. Unfortunately, it is common practice to ignore the network geometry in order to simplify the analytical model. However, such simplifications come at the cost of limited insights.
2. In order to ensure fairness and mutual satisfaction, it is important to divide the leasing time in a way that both the PUs and the CRs agree to their share of time. In previous studies, this division has been influenced more by the decision of the primary network which needs to possess cross-network channel state information (CSI) (i.e., CSI of the secondary network) to make the bargaining decisions. The CRN needs to observe the primary action and only decides in reaction to primary decision.
3. It is important to quantify how the division between cooperating and leasing time is dictated by the negotiating power of the PN and the CRN. Unlike existing studies, it is important to develop a comprehensive model to capture the scenarios where one network exercises greater influence on the decision, yet attains mutual agreement over the division of the leasing time and vice versa.
4. As mentioned earlier, the energy requirements of the design of any communication system has become a key concern due to the rapid growth in energy consumption. This warrants a formal analysis of the energy efficiency of leasing to measure its viability.

In summary, the main contribution of this chapter is to address the above mentioned design issues for enabling DSL based spectrum sharing in large scale wireless networks.

3 Key Findings

In this chapter, tools from stochastic geometry and game theory are used to build a quantitative framework for investigating the introduced design issues. The developed framework explicitly incorporates the impact of randomness rendered by the channel impairment process and geometry of the cooperation region on the DSL mechanism. In turn, these considerations demonstrate that a desired data transmission rate with a certain reliability can be provisioned for the PU links by leasing the spectrum to the CR nodes occupying spatially suitable locations. As a reward for cooperation, the entire CRN obtains access to the spectrum and thus the CRs can schedule their transmissions at a reasonable rate among themselves. The provision of negotiation between the PN and the CRN, over the division of leased time (reserved for cooperation with the PN and for the CRN communication) is ensured using the Nash bargaining framework. Unlike existing literature, a mutual agreement based division is attained that ensures proportional fairness for both networks. Also, the PN is not required to have CSI knowledge of the CRN. The work quantifies how the individual bargaining powers of the PN and the CRN can influence the division of cooperation and leasing time. Furthermore, it is shown that for equal bargaining powers, out of the total DSL operational time, 20–50 % of the time is reserved exclusively for the CRN which otherwise is dormant. It is demonstrated that the entire CRN can benefit from the leasing time that is procured by the cooperation of a few CRs with the PN. The variety of possible divisions of the leasing time ensures the flexibility and wide scale applicability of the considered DSL model. Moreover, the quantification of the energy requirements of the legacy and the DSL networks are established which to date was an open issue. The results indicate that DSL empowered networks can be more than 10x energy efficient as compared to traditional networks. It is shown that choosing a smaller cooperation area is more energy efficient for the PN. It is also shown that DSL is spectrally efficient at the network level where the CRN improves its spectral access considerably. At the same time, the QoS requirements for both the PN and CRN can be guaranteed.

4 Previous Work

Our work addresses three research areas in wireless communications (specifically CRNs); exploiting cooperative diversity, characterization of spectral leasing models and energy efficiency of the architecture. Energy efficiency has been explored in the context of cognitive radios by using adaptive modulation techniques [16] and optimal transmission duration estimation [17] in order to achieve power/bandwidth efficiency. Recently, cooperative diversity in cognitive radio networks has gained some attention. An overview of various possible ways of exploiting this diversity has been suggested in [18]. The existing literature on dynamic spectrum leasing can be characterized into three main types; (i) in which the incentive for leasing is based on monetary rewards, [19, 20], (ii) where leasing is allowed as long as the interference from the CRs is below an 'interference cap' [21, 22], (iii) where the incentive for leasing is based on service rewards [23–25], which is the model on which this study is based. For the first two types, numerous literary contributions exist, however, its survey is out of the scope of this chapter. Our focus is based on the third framework which was first explored by [23] where an analytical study of service based DSL is provided and cooperative diversity of the secondary relays has been exploited. In [24] the same framework is carried forward and applied in an ARQ based model where a portion of the retransmission slot is leased by the legacy network to the relays for their traffic in exchange for cooperative retransmission by the relays. In [25], the authors consider an infrastructured hierarchical spectrum leasing approach. In their work, they consider multiple primary nodes that select their respective individual relays for cooperation.

Game theoretic tools have been widely used to determine the amount and time for spectrum sharing. A comprehensive survey in [26] addresses the application of different games to model dynamic spectrum sharing. Previously, in [23, 25], a linear search based algorithm followed by a Stackelberg game was proposed to divide the leasing time between the primary and secondary activities. However, it does not cater for mutual agreement on leasing time division if (1) primary chooses a selfish time distribution as the leader and (2) the secondary in turn plays suboptimal strategy to hurt the interest of the primary in successive realizations of the game. The studies regarding the energy efficiency of CRNs mostly consider a generic scenario where spectrum sensing is employed. The study of the EE of DSL where nearest neighbor based communication is employed for the CR network is not studied in the literature.

Our work differs from the above in the following ways. Firstly, these studies abstract out the spatial geometry of the network. The impact of network geometry and provision of negotiation over the leasing time is not studied in these papers. Here, however, we investigate DSL in a geometric framework where the capacity of direct and DSL based communication is studied in terms of the spatial characteristics of the secondary network. Nash bargaining has been used for solving various problems of resource allocation in wireless networks [27, 28] and it is shown to attain a Pareto optimal solution that specifically discourages selfish behavior in the network. In [29] and its extension [30], DSL with spatial and bargaining based modeling was studied for spectral and energy efficiency gains for bidirectional communication. Physical layer techniques like network coding and beamforming were introduced to harness additional gains. However, in this work, the focus of the authors is to determine the fundamental behavior of DSL for unidirectional communication. The authors study the impact of bargaining powers of the two networks on the division of the leasing time. Also, unlike previous studies where a fixed geometric setup for CR receivers was considered, in this chapter a nearest neighbor based receiver model is considered. Nearest neighbor based receiver models find a direct application in future device to device (D2D) networks. The impact of the selection of the area of cooperation by the PN studied in this chapter is also a novel contribution. Finally, in this chapter, the entire CR network benefits from the leasing time which is a reward of the cooperative services of a few geographically suitable CR relays. To the best of our knowledge, the bargaining powers based modeling for DSL where the entire CR network communicates with nearest neighbors has not been carried out by any previous study. We use this framework to enable the primary and secondary users to reach a mutual agreement over the leasing time.

5 System and Network Model for DSL Empowered CRN

5.1 Network Geometric and Physical Layer Model

A primary link operating in the presence of a geographically co-located secondary network is considered. For simplicity, it is assumed that the primary communication link (P_{tx}, P_{rx}) is formed by a primary receiver (P_{rx}) located at the origin and a primary transmitter (P_{tx}) located at a distance $r_p > 1$ from P_{rx}. A region of 'exclusion' with radius ϵ is centred at the P_{rx}[1] to avoid excessive interference (see Fig. 1). Under the legacy operation of the PN, any transmission by the CRs is strictly forbidden within this exclusion area [31]. The secondary network is formed by the CR nodes, whose locations form a stationary Poisson point process (PPP) Φ of intensity λ. From the theory of PPP, the probability of finding $k \in \mathbb{N}$ CRs in an area $A \subset \mathbb{R}^2$ is given as

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

The average number of the CRs in an arbitrary region A with area $|A|$ is quantified as $\lambda|A|$. Each CR transmitter S_{tx} communicates with an associated CR receiver S_{rx} when spectral access is granted by the PN. In this chapter, it is considered that the CR receivers are associated with their nearest CR transmitter. In other words, 'nearest neighbour association' is adopted for the transmitter-receiver pairing in the CRN. Notice that such association mechanism indeed captures many emerging CR deployment paradigms. Specifically, it captures overlaid cellular CRN where the CR transmitters may be data aggregators for machine type communication or small cells associated with MUs based on the average path-loss, etc.

Based on the relative distances from the P_{tx} and the P_{rx}, the nodes lying within a radius r_p between the two primary nodes are expected to best serve as the potential relays for the PN in cooperation mode under DSL operation.[2] It is considered that

[1] Primary's exclusive region encapsulates those secondary nodes which are at such a small distance from the PU that any transmission from them directly interferes with the PN communication.

[2] Such a selection is inspired by the optimal forwarding area selection techniques [32, 33].

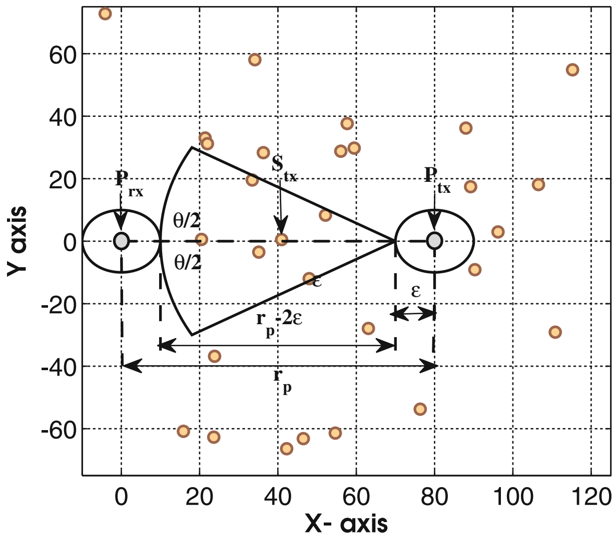


Fig. 1 Geometric model of the network

nodes within a radius ϵ from the P_{tx} or the P_{rx} are excluded from the cooperation phase of the DSL. This particular constraint reflects that only the nodes lying in the proximity of the half-way mark between the primary nodes can become cooperative relays. The key motivation behind such selection is to minimize the energy penalty, while balancing the average channel gain for the two hop communication. In other words, the condition where the average channel gain for the first hop is significantly larger than the second hop and vice versa are excluded. It is well known that an optimal relaying strategy can be devised by selecting relays which balance the average gains for both hops [32]. Consequently, the cooperation region, bounded by a sector, i.e., $\sec(\theta, r)$ of radius $r_p - 2\epsilon$ and an angle θ in radians, is considered to be the effective area of cooperation in DSL operation mode. Formally, it can be denoted as,

$$A_c\left(\theta, r_p, \epsilon\right) = \left\{(r, \theta) \in \mathbb{R}^2 : \epsilon < r \leq r_p - \epsilon \text{ and } \theta \in [0, 2\pi]\right\},$$

where $\epsilon \geq 1$. The selected relays also form a PPP $\Phi_r \subset \Phi$ with an average number of CR relay nodes $k = \lambda \left|A_c\left(\theta, r_p, \epsilon\right)\right|$ in the region $A\left(\theta, r_p, \epsilon\right) \subset \mathbb{R}^2$.

It is assumed that the wireless channel suffers from path-loss and small-scale fading. For a distance r between any arbitrary pair of nodes, the channel between them can be expressed as $ahl\ (r)$ [34] where the fading power gain h is an independent and identically distributed (i.i.d.) exponential random variable with a unit mean, a is a frequency dependent constant and $l(r)$ is the distance dependent path-loss function. For the sake of simplicity, a is considered to be unity throughout the rest of the discussion. The power-law path-loss function $l(r) = \min(1, r^{-\alpha})$ is upper bounded by unity which corresponds to the reference distance. Also, $\alpha > 2$ is the operational environment dependent path-loss exponent. The noise at the receiver front end, is considered to be additive white Gaussian noise (AWGN) with power σ^2. For a given transmit power P and link distance r, the SNR at a receiver is given as

$$\mathrm{SNR} = \frac{Phl\left(r\right)}{\sigma^2}. \tag{2}$$

Similarly, in the presence of co-channel interference, the received SINR is defined by adding the aggregate received interference power I in denominator of Eq. 2.

5.2 MAC Layer Model and Bargaining Game

A primary system in which there is a certain rate demand (R_{dir}) for a sustainable link operation at a desired reliability ($\tilde{\rho} = 1 - \rho$) is considered. In other words, the QoS demand for the PUs is completely characterized by the desired rate R_{dir} and the percentage of time $\tilde{\rho}$ over which this rate can be guaranteed. To meet this demand, the PU has a choice between continuing its communication in the legacy mode through direct communication or through the cooperative relaying of CRs via spectrum leasing mechanism. In direct communication, the primary transmitter communicates with its corresponding primary receiver at a rate R_{dir} for a duration T. The duration T corresponds to the duration of a temporal spectral resource such as the length of a transmission frame. Under DSL operational mode, the primary transmitter indicates its willingness to lease the spectrum for the same time duration T to the CR nodes inside a certain cooperation region $A_c\left(\theta, r_p, \epsilon\right)$. The choice of θ and willingness to lease are indicated over a dedicated control channel.

5.2.1 Phases of DSL

The process of dynamic spectrum leasing can be divided into three sub intervals:

BROADCAST The primary broadcasts its data to be relayed to the CR transmitters for a time $t_{ps} < T$.

COOPERATE During the second sub-interval, called the cooperation phase, k secondary nodes that are best suited for relaying on the basis of their geographical location, cooperatively relay the data of the P_{tx} to the P_{rx} for a time $t_{sp} < T$ by forming a distributed k-antenna array through ideal orthogonal distributed space time coding (DSTC) [35]. The details of DSTC codebook and operational parameters can be found in [35] and [23].

REIMBURSE Out of the total leased time T, the last sub-interval is reserved for the S_{tx_i} to carry out their own transmission to their respective receivers, S_{rx_i}. In other words, it is a fare that the primary has to pay in return for the relaying services of the secondary. In this duration $t_{ss} = T - t_{sp} - t_{ps}$, the primary refrains from transmission and grants exclusive access to the secondary network.

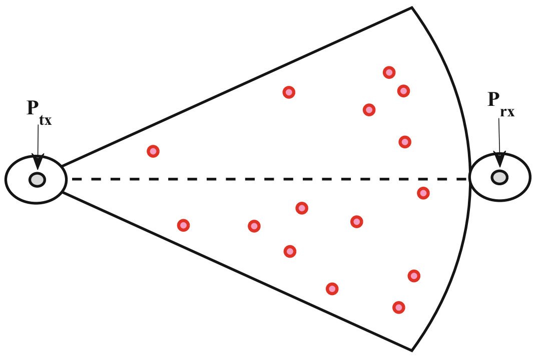


Fig. 2 Secondary nodes in the cooperation region

If the PN decides to seek the help of the CRs, it broadcasts a leasing beacon over the control channel. This beacon contains the information of cooperation and exclusion region θ, ϵ and the demand of relaying co-operation duration t_{sp}.[3] The concept of an exclusion region is exploited for minimizing the interference to the PU and also enhancing the cooperative transmission rate by selecting nodes within the exclusion region that lie between the primary transmitter and its corresponding receiver as shown in Fig. 2. The CR nodes employ listening mechanism over control channel. Beacon enabled signalling is adopted for DSL to initiate and agree on the leasing parameters. Listening only on the control channel is an energy efficient way for the CRs to monitor the primary activity. In this approach, the CRs only listen to short control messages, whereas, if the control channel is not used, then the CRs have to monitor the entire PU activity to learn about possible spectrum availabilities. The CRs are assumed to be aware of their location with respect to the primary transmitter and receiver. Upon the reception of the leasing beacon, only those CRs that lie within the desired cooperation region participate in cooperation. Based on the leasing information and the potential cooperation cost, the CRs also establish their reimbursement duration demand t_{ss}.[4]

The process of bargaining over the demand of t_{sp}, and t_{ss} is executed and if the negotiations are successful, a leasing agreement is reached. In DSL, during the first interval t_{ps}, the primary transmitter broadcasts its data to be relayed to the CRs at a low power, $\bar{P}_p < P_p$, since only geographically close CR relays need to receive and relay the data. In the second interval, the CRs cooperatively relay the data to the P_{rx} using DSTC for a duration t_{sp}. As a result of the leasing agreement, the entire CRN gets access to the spectrum for a duration t_{ss}. All the secondary nodes transmit with the same power P_s during the cooperation and reimbursement phase. P_s is significantly lower than the transmit power of the primary $P_s \ll P_t$. This maintains

[3]The PN is assumed to be aware of the average fading characteristics of its link with the secondary transmitters.

[4]The primary is assumed to be aware of the average fading characteristics of its link with the secondary transmitters.

low energy consumption in DSL and also ensures that in the last phase of secondary communication, the aggregate power of all the selected relay nodes does not increase excessively to avoid very high interference.

5.2.2 Bargaining Game

During the process of leasing, the most crucial factor is the division of leasing time between the above three phases. It is important that each operational element of the network gets enough share of time to meet its transmission throughput requirements. To ensure such a time division, a network level game is formulated where each of player, i.e., primary network (player 1) and the secondary network (player 2) engages itself in an arbitration for the time division over a control channel. As stated, the primary user initiates the leasing process. In response, the secondary users determine their demand and adopt a strategy according to the primary offer. If the offer is acceptable, the game is concluded and leasing is successful. If the CRs want to bargain further, another round of offer and respective response is played. In case the negotiations are unsuccessful, the game ends and the leasing is not done. It is further assumed that the CRs form a homogeneous network in terms of the hardware platform, leasing time demands and they do not show malicious or selfish behaviour.

During the process of leasing, the primary has a bargaining power Δp. The bargaining power of the primary determines the bias of the division of time in favour of the primary's demand. Similarly, the secondary CR network has a bargaining power Δs. The provision of variable bargaining powers in the model makes it flexible and adaptable to various real network settings. These include scenarios where the primary network has greater inherent power to determine the division of leasing time. For example, when the data traffic of the primary link is low or the channel conditions are favourable, the primary might have a greater bargaining power. Similarly scenarios where the CRs have a greater power can also be well studied using this model.

5.2.3 Assumptions

For simplicity and tractability of the analysis, it is assumed that the PN and the CRN are aware of the CSI within their respective networks. A practical implementation of such information exchange can be found in [36]. The CRs are aware of their location with respect to the primary transmitter and receiver. Moreover, the PU and the SUs are considered to be in perfect time synchronization with each other. Cost effective methodologies for implementing time synchronization in ad hoc networks have been suggested in [37], hence encouraging the proposal of the time sharing based communication scheme introduced here. The control beacon signal by the PU to initiate spectrum leasing can also be used for synchronization between the primary and the secondary nodes.

6 Analysis of DSL

6.1 Average Link Capacities R_{dir}, $\overline{R}_{ps}$, $\overline{R}_{sp}$ and $\overline{R}_{ss}$

Under conventional operation, the legacy network continues its communication over the direct link with its respective receiver at a certain rate R_{QoS}. Due to the small scale fading, the communication link is subject to outage. Thus, enforcing a certain reliability constraint restricts the operational rates to a limited regime. In other words, if $\tilde{\rho} = 1 - \rho$ is the reliability constraint, then the maximum rate which can be sustained is given as

$$R_{\mathrm{dir}} = \sup \left\{ R_{\mathrm{QoS}} : \mathrm{pout}(R_{\mathrm{QoS}}) \leq \rho \right\}, \tag{3}$$

where $\mathrm{pout}(R_{\mathrm{QoS}})$ is the link outage probability at a particular desired rate R_{QoS}. The performance of the direct link (P_{tx}, P_{rx}) pre-dominantly is noise limited, since it is assumed that there is no interference caused by the CRN to the primary transmission. The instantaneous capacity R_{QoS} of this link can be defined as,

$$R_{\mathrm{QoS}} = \log_2(1 + \mathrm{SNR}), \ (\mathrm{bits/s}) \tag{4}$$

where SNR is as defined previously and h_p is the channel power gain between the source and the destination, P_p is the transmit power and $l(r_p)$ is the distance dependent path loss between the nodes. The ρ-outage rate R_{dir} is defined as the largest rate of transmission R such that the outage probability of the direct primary link is less than ρ. For a conventional operation mode it can be quantified as follows:

Lemma 1 *The ρ-outage rate, R_{dir}, for the link (P_{tx}, P_{rx}) is given as,*

$$R_{dir} = \log_2\left(1 - \left(\frac{P_p h_p l\left(r_p\right)}{\sigma^2}\right) \ln\left(1 - \rho\right)\right), \ (bits/s) \tag{5}$$

Proof The result can be derived following the same lines as in [29] Sect. IV Lemma 1. □

When the spectrum is leased to the SUs, the cooperative link performance is dictated by the attainable rate over the relay link, i.e., the cooperative channel capacity. The cooperative channel capacity depends upon both (i) the transmission rate R_{ps} achieved between the primary transmitter and any selected relay during the first leasing sub-interval and (ii) the rate R_{sp} between the selected relay nodes and the primary receiver assuming that DSTC cooperation is employed. Also, as mentioned earlier, nodes centred only in the effective area of communication, $A_c(\theta, r_p, \epsilon)$, are considered for cooperation.

Lemma 2 *The average transmission rate from the primary transmitter to secondary relay,* $\overline{R}_{ps}$*, is upper-bounded as,*

$$\overline{R}_{ps} = \log_2\left(1 + \left(\frac{\exp\left(-\lambda\frac{\theta}{2}\left(r_p - \epsilon\right)^2 - 1\right)}{(r_p - \epsilon) - C}\right)^{\alpha}\frac{\bar{P}_p}{\sigma^2}\right), \; (bits/s) \tag{6}$$

where $C = \sqrt{\frac{\pi}{2\lambda\theta}}\exp\left(-\lambda\frac{\theta}{2}\left(r_p - \epsilon\right)^2\right) erfi\left(\sqrt{\frac{2\lambda\theta}{\pi}}\right)$ *and erfi(x) is the imaginary error function such that* $erfi(x) = 2\sqrt{\pi}\int_{t=0}^{x}\exp\left(-t^2\right)dt$.

Proof The result can be derived following the same lines as in [29] Sect. IV Lemma 2. □

In the second phase of cooperation, the selected secondary relays form a $k = \lambda A_c(\theta, r_p, \epsilon)$ antenna array and perform DSTC to send the data to the receiver with a rate R_{sp}. The rate of communication when DSTC is employed for multiple relay transmission to a common destination has been evaluated in [23, 35, 38, 39]. In the context of the geometric modelling of dynamic spectrum leasing, the DSTC communication rate is used and its mean value is determined considering the geometric parameters.

Lemma 3 *The average transmission rate,* $\overline{R}_{sp}$*, when k secondary relays, i.e.,* $k \in |\Phi_r|$ *form an antenna array, where secondary relay i is located at a distance* r_i *from* P_{rx} *is given by*

$$\overline{R}_{sp} = \log_2\left(1 + \frac{\lambda\theta P_s}{\sigma^2}\left(\frac{(r_p - \epsilon)^{2-\alpha} - \epsilon^{2-\alpha}}{2 - \alpha}\right)\right), \; (bits/s) \tag{7}$$

where, the secondary transmits with a power P_s*, the channel gain between* S_{tx} *and* P_{rx} *is* h_{sp_i}.

Proof The result can be derived following the same lines as in [29] Sect. IV Lemma 3. □

In the last phase of spectrum leasing, all the secondary transmitters communicate with their respective receivers. A nearest neighbour model of the CR source destination pairs is considered in this chapter where each transmitter only communicates with its nearest receiver [40] as shown in Fig. 2. It is of interest to know the average transmission capacity of the $\left(S_{tx}, S_{rx}\right)$ link, $\overline{R}_{ss}$. In this case, all the secondary transmitters in the CR network simultaneously communicate with their receivers in order to utilize the leased bandwidth for their own transmission. In this phase, similar to the direct communication, a realistic situation is considered under which the secondary network also operates under a fixed QoS constraint R_{QoS_s}.

Lemma 4 *The average rate, $\overline{R}_{ss}$, for the link (S_{tx_i},S_{rx_i}) where the channel power gain between the source i and its destination (nearest neighbour) is exponential h_{ss_i}, the transmit power P_s is given as,*

$$\overline{R}_{ss} = \frac{\pi^{\frac{3}{2}}\lambda}{\sqrt{\left(2^{R_{Qos_s}}-1\right)/\frac{P_s}{\sigma^2}}} \exp\left(\frac{\left(\pi\lambda\left(\tau\left(R_{QoS_s}\right)+1\right)\right)^2}{4\left(2^{R_{Qos_s}}-1\right)/\frac{P_s}{\sigma^2}}\right) \quad (8)$$

$$\times Q\left(\frac{\pi\lambda\left(\tau\left(R_{Qos_s}\right)+1\right)}{\sqrt{\left(2^{R_{Qos_s}}-1\right)/\frac{P_s}{\sigma^2}}}\right)\bar{R}_{th}.\,(bits/s) \quad (9)$$

where R_{Qos_s} is the desired threshold rate for secondary communication.

Proof The proof follows the same steps as in [41] in Sect. V. □

After computing the individual link transmission rates, the aim is to know the overall transmission rate achieved in the DSL operational mode. It is assumed that a decode and forward type single hop relaying mechanism is used in the cooperation phase. The effective DSL capacity R_{DSL} is then given as,

$$R_{\text{DSL}} = \min\{\overline{R}_{ps}, \overline{R}_{sp}\}.\,\text{(bits/s)} \quad (10)$$

6.2 Optimal Division of Leased Time for Cooperation and Secondary Activity

The most critical factor in the operation of spectrum leasing is the optimal division of the total leased time T between the time t_{sp} reserved for cooperation with the primary at a cooperative rate R_{DSL} and the remaining time t_{ss} for the secondary activity at a rate $\overline{R}_{ss}$. The goal of the primary node is to ensure that its rate and quality of communication, R_{dir} and ρ-outage probability respectively, are maintained by maximizing the time t_{ps} and t_{sp}. The primary node can ensure that $\overline{R}_{ps}$ attains the QoS rate R_{dir} by a proper choice of t_{ps} such that $t_{ps}\overline{R}_{ps} = T R_{\text{dir}}$. However, the remaining time ($T' = T - t_{ps}$) needs to be divided between phase two and three to get t_{sp} and t_{ss}.

The CR nodes intend to increase their benefits in terms of their spectrum utility and throughput by having spectrum access for maximum time and compensating for the cost of cooperation in relaying primary data. A very small fraction of t_{ss} will discourage the secondary, impacting cooperation and the overall throughput of the system suffers. On the other hand, prolonged t_{ss} will degrade the performance of the legacy network in terms of its bandwidth efficiency which is not acceptable in any case. Hence an intelligent division of time is very crucial for the operation of the network. Also, the secondary network must cooperate in relaying primary data for a time t_{sp} long enough so that the primary network maintains its communication standards. Hence the problem boils down to an optimal division of leasing time T' between phases two and three of DSL.

An optimal time division can be conveniently casted in the framework of Nash Bargaining: a game theoretic tool to model the situations of bargaining interactions. The situation can be modelled as a two player game using the Nash bargaining framework from cooperative game theory [42]. In this case, the primary transmitter is the first player whose utility is directly dependent upon the cooperation time t_{sp} and increases as it increases. For simplicity, we define the utility of the primary and the secondary node as;

$$\mathcal{U}_1(t) = t_{sp}, \tag{11}$$

and

$$\mathcal{U}_2(t) = t_{ss}, \tag{12}$$

respectively, where $t_{sp} + t_{ss} = T'$.

Bargaining as a two player game is considered because every single secondary node is representative of the utility of all the remaining secondary nodes as only the average rate values and equal transmit powers for all CRs are considered. The Nash bargaining framework is employed to model a situation in which the players negotiate for their agreement on a particular point out of a set of joint feasible payoffs $\mathcal{G}$. In this particular case, $\mathcal{G} \equiv \{g = (g_1, g_2) : g_i = \mathcal{U}_i(\mathbf{S}),\ i = 1, 2;\ \mathbf{S} \in S1 \times S2\}$, where the functions $\mathcal{U}_i(.)$ in this case of DSL are given in Eqs. 11 and 12. $\mathbf{S}$ is the strategy of the ith player in terms of the time it demands i.e., t_{sp}/t_{ss} from the strategy profile S_i. In Nash Bargaining, in case the negotiations render unsuccessful, 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 $(\mathcal{G}, g_0)$. A pair of payoffs $\left(g_1^*, g_2^*\right)$ is a Nash Bargaining solution if it solves the following optimization problem

$$\max_{g_1, g_2} (g_1 - g_{01})^{\Delta_p} (g_2 - g_{02})^{\Delta_s} \tag{13}$$

$$\text{subject to} \begin{matrix} (g_1, g_2) \in \mathcal{G} \\ (g_1, g_2) \geq \mathcal{G}_0 \end{matrix}.$$

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 a unique solution to the bargaining problem $(\mathcal{G}, g_0)$ corresponds to the unique solution of the optimization problem [27, 42].[5] Here Δ_p and Δ_s defined as $\left\{\Delta_p, \Delta_s \in [0, 1]\, |\, \Delta_p = 1 - \Delta_s\right\}$ correspond to the bargaining powers of the primary and secondary network. Greater values of Δ_p and Δ_s correspond to higher bargaining powers. Increasing the bargaining power of a player corresponds to greater weightage

[5] From Eqs. 11 and 12, the compactness and convexity of $\mathcal{G}$ can be seen.

of its preferences over the preferences of the other player. Increasing the power of one player implies decreasing power of the other.

In this case, the fraction of leased time should be large enough to ensure that the time-rate product of cooperation time t_{sp} and cooperative rate $\overline{R}_{sp}$ is at least equal or greater than the direct communication time T and rate R_{dir} product. During the second sub-interval, a secondary node must have enough time to at least overcome its cooperation cost cP_s given its average transmission rate $\overline{R}_{ss}$. Here c is measures the bits transmitted per unit of power consumed.

Theorem 5 *The optimal proportion of time for cooperative relaying is*

$$t_{sp} = \frac{\Delta_p T' + \Delta_s \left(\frac{R_{dir}}{\overline{R}_{sp}}\right) - \Delta_p \left(\frac{cP_s}{\overline{R}_{ss}}\right)}{\Delta_p + \Delta_s}, \tag{14}$$

where the disagreement vector is $\left(t_{0p}, t_{0s}\right) = \left(\frac{TR_{dir}}{\overline{R}_{sp}}, \frac{cP_s}{\overline{R}_{ss}}\right)$ *and secondary activity time* $t_{ss} = T' - t_{sp}$.

Proof From the definition of Nash Bargaining solution, the time division problem for a 2-player game can be written as

$$\max \left(\Delta_p \log\left(\mathcal{U}_1(t) - g_{01}\right) + \Delta_s \log\left(\mathcal{U}_2(t) - g_{02}\right)\right), \tag{15}$$

$$\text{subject to } T' = t_{sp} + t_{ss}.$$

From the definition of Nash Bargaining solution, the time division problem for a 2-player game can be written in a logarithmic form as above. Such representation of the maximization problem ensures proportional fairness of the solution for both the players. Here the minimum required time for both primary and secondary is given as $(g_{01}, g_{02}) = \left(t_{0sp}, t_{0ss}\right) = \left(\frac{TR_{\text{dir}}}{\overline{R}_{sp}}, \frac{cP_s}{\overline{R}_{ss}}\right)$, which is the least time required to meet the respective objectives of QoS and cooperation cost compensation.The corresponding Lagrangian for the above optimization problem can be written as,

$$\begin{aligned} L(t_{sp}, \lambda_1, \lambda_2) = \Delta_p \log\left(t_{sp} - t_{0sp}\right) + \Delta_s \log\left(t_{ss} - t_{0ss}\right) \\ - \lambda_1\left(T' - t_{sp} + -t_{ss}\right). \end{aligned}$$

The original maximization problem can be solved by replacing t_{ss} by $T' - t_{sp}$ and using the first order necessary conditions,

$$\frac{\delta L}{\delta t_{sp}} = \frac{\Delta_p}{t_{sp} - t_{0sp}} + \frac{\Delta_s}{t_{sp} - T' - t_{0ss}} = 0, \tag{16}$$

This follows from the definition of the Nash Bargaining problem that there exists a vector **S** such that the optimal value of the optimization problem is strictly positive. Solving for Eq. 16 by using simple algebra, the result can be obtained as,

$$t_{sp} = \frac{\Delta_p T' + \Delta_s \left(\frac{R_{\text{dir}}}{\overline{R}_{sp}}\right) - \Delta_p \left(\frac{cP_s}{\overline{R}_{ss}}\right)}{\Delta_p + \Delta_s},$$

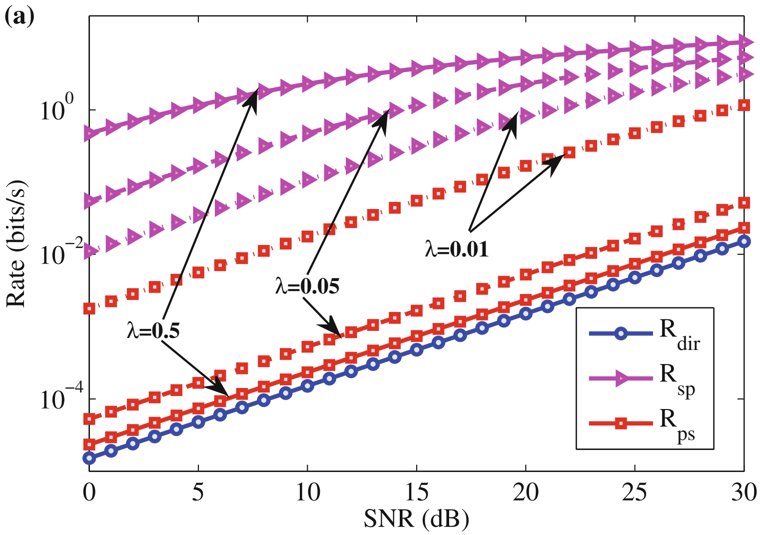
where the above equilibrium solution gives the optimal share of cooperation time t_{sp} out of the total leased time T that ensures a cooperative data transmission rate $\overline{R}_{sp} \geq R_{\text{dir}}$. It reserves the rest of the time for secondary user that at least allows the secondary to utilize the spectrum to compensate for their transmission cost during the cooperation phase. □

7 Performance Evaluation of DSL

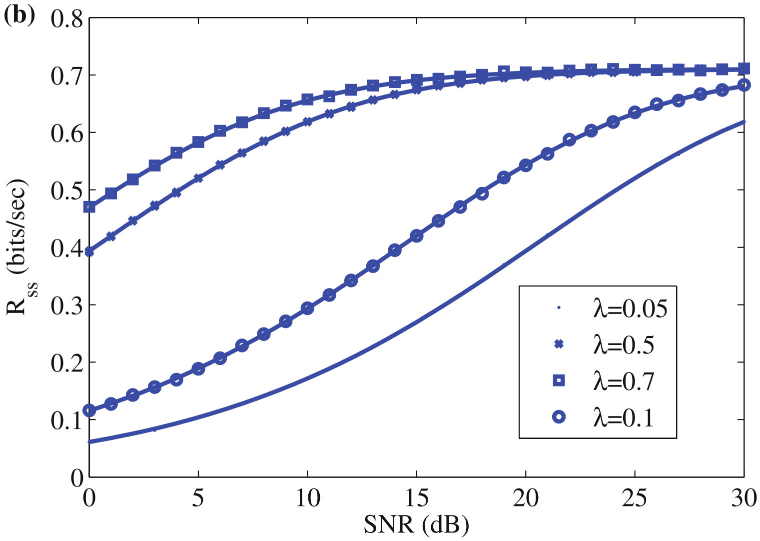
In this section, the design space of the DSL enabled CRN is investigated by employing the analytical model developed in the previous section. In order to verify the analysis and establish the validity of the assumptions made throughout, Monte Carlo simulations for the large scale DSL based CRN are performed. In order to simulate, a network radius of 200 m in which secondary nodes are Poisson distributed with mean λ is considered. Direct communication under an outage constraint ρ at a transmit power P_p is simulated. Similarly, the operational phases of DSL are simulated. For each realization of the Poisson network, a Rayleigh distributed channel coefficient is generated. The transmission rate at the receiver for each spatial instance of the network is averaged for 10^4 different channel coefficients. This process is in turn repeated for 10^4 realizations of Poisson distributed CR network with intensity λ and the transmission rate is averaged. Secondary network communication under interference considerations is also studied in a similar fashion. All the simulations are carried out in MATLAB. Normalized values for transmit powers P_p and P_s are used. It is assumed that the secondary network operates at a low power profile i.e., $\sim\frac{1}{10^{\text{th}}}$ of P_p. Similar power profiles can be found for devices like HeNB in LTE rel. 12 and other examples in heterogeneous networks [43, 44].

Firstly, the average achievable transmission rates under both the normal and leasing mode of network operation are studied as shown in Fig. 3a. The rate under normal primary communication at a transmit power P_p increases with improving channel conditions. Here, the reliability in terms of the probability of success ($p_{\text{suc}} = 1 - \rho$) of direct communication is assumed to be 90 %. The outage capacity, R_{dir}, defines the target capacity for communication in the primary network R_{th} for all operational modes i.e., direct and DSL. Under identical channel realizations, a demand for higher service quality (smaller ρ) straightforwardly results in lower R_{dir}.

For the capacity analysis of DSL, the average achievable transmission rates in the three phases of leasing are studied. The capacity of the primary to secondary communication in the first phase is strongly dependent upon the number of secondary nodes present in the area of cooperation. As mentioned earlier, in this analysis, the lower bound to this rate is studied by considering the average transmission rate between



Rates vs. SNR. $P_p = 1$,$r_p = 10$, $\bar{P}_p = P_s = 0.1$, $\epsilon = 1$.



R_{ss} vs. SNR, $P_s = 0.1$.

Fig. 3 Achievable data rate of direct and DSL communication. **a** Rates versus SNR. $P_p = 1$, $r_p = 10$, $\bar{P}_p = P_s = 0.1, \epsilon = 1$. **b** R_{ss} versus SNR, $P_s = 0.1$

the primary transmitter and the farthest relay. For very low secondary density, e.g., $\lambda < 0.01$, the probability of finding a neighbour in the region of cooperation is extremely low. For this reason, the capacity analysis for very sparse secondary network is not possible. For higher λ, it can be seen from Fig. 3a that the average transmission rate $\overline{R}_{ps}$ is greater than R_{dir}. This phenomenon is a consequence of cooperation region selection such that relays are located in close proximity to both P_{tx} and P_{rx}. Hence greater rate is attained due to shorter distance between the relay and P_{tx}. However, if the number of secondary users increases in the cooperation region, the average distance between P_{tx} and the farthest node increases. Hence $\overline{R}_{ps}$ decreases when λ increases (lower line in Fig. 3a). However, the cooperative relaying rate $\overline{R}_{sp}$ increases with increasing relay density due to the diversity gain. Increasing λ increases the number of cooperating nodes, consequently, the rate $\overline{R}_{sp} \gg R_{\text{dir}}$ for increasing values of λ.

Along with the analytically drawn results, achievable transmission rates under a practical Poisson network are also shown in Fig. 3a. A PN with two nodes and a CRN for various λ. are simulated in MATLAB. For each realization of the network, exponential distributed channel power gain is generated. The successful transmission probability at the rate $R_{\text{QoS}}/R_{\text{QoS}_s}$ at the receiver for each spatial instance of the network is averaged for 10^4 different channel coefficients. This process is in turn repeated for 10^4 network realizations. The practical simulation results are indicated by the lines running over the analytic results (analytic results are indicated with markers). It can be seen that the practical simulations closely match the analytic evaluation results. It validates the analytic formulation of DSL and the simplifying assumptions made for the simplification of the analysis.

It is shown that the communication rate $\overline{R}_{ss}$ also increases with improving SNR values in Fig. 3b (here the desired QoS of the secondary network in terms of desired rate $\bar{R}_{\text{th}}$ is 0.5 bits/s). This is a consequence of the improved signal strength at the receiver. As the density of the secondary nodes increases, the average transmission rate increases. However, $\overline{R}_{ss}$ tends to saturate with increasing SNR at higher values of λ. It is a consequence of the interference limited behaviour of the channel. Increasing interference due to increasing λ limits the increase in $\overline{R}_{ss}$. It is clear that increasing the desired threshold rate $\bar{R}_{\text{th}}$ causes the average rate to decrease because the decoding threshold at S_{rx} is raised. Hence, a graphical illustration of this result is intentionally skipped. The practical simulation results of $\overline{R}_{ss}$ are also shown in Fig. 3b which verifies the analytical derivations. It is to be noted that the rest of the results are based upon the communication rates of direct and DSL communication, which have been shown to be in a close agreement with each other. Therefore, the practical simulations of the remaining results can safely be assumed to be accurate and hence are skipped for the sake of brevity.

In order to intelligently exploit the diversity gains of DSL at low power, it is important to determine the appropriate operational time of each phase of DSL. The primary itself determines and communicates for time t_{ps} during the first phase such that $t_{ps}\overline{R}_{ps} = TR_{\text{dir}}$. In Fig. 4a, the time t_{ps} reserved for R_{ps} is shown. It can be seen that it increases with increase in the secondary network density. This behaviour follows from the lower transmission rate achieved with increasing λ as discussed

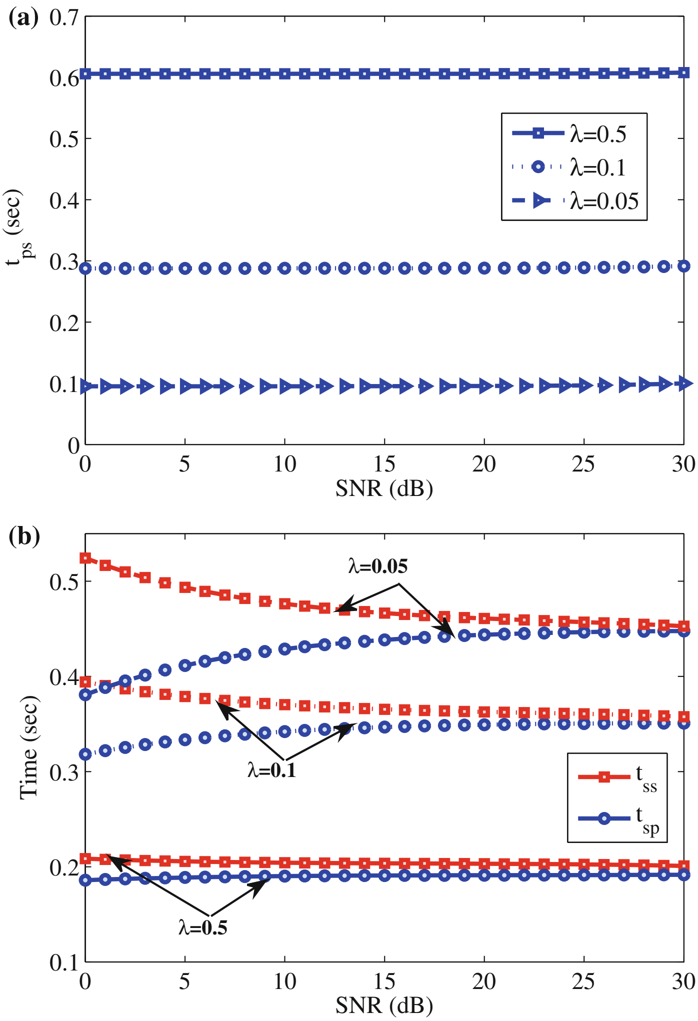


Fig. 4 Nash bargaining solution. **a** Time for first phase transmission R_{ps}. **b** Time bargain for primary and secondary transmitters. $T = 1$, $c = 0.05$, $\lambda = 0.5$

earlier. Correspondingly, the time share of t_{sp} and t_{ss} i.e., T' decreases with increasing λ since a major portion of the time is reserved for primary to secondary transmission in the first slot.

The optimal relation for the division of the remaining leased time T' is found in Eq. 14 and shown in Fig. 4b over a range of SNR values. At low CR densities, more time t_{sp} is required to harvest the gains from cooperative relaying. As the number

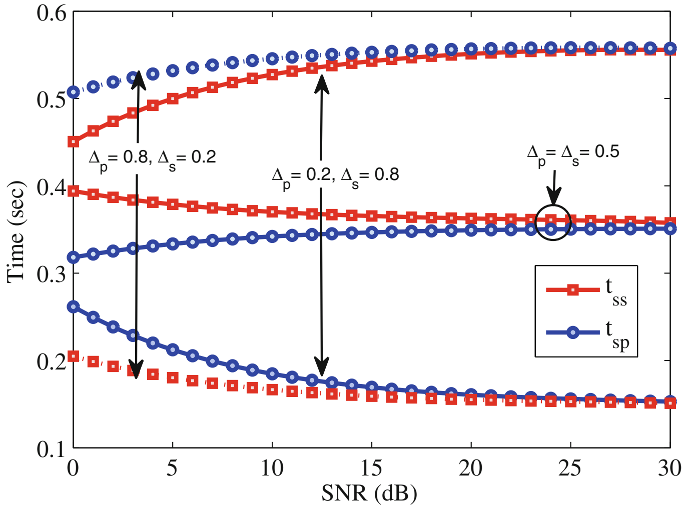


Fig. 5 Impact of bargaining powers

of cooperating CRs increases due to increasing λ, the time required for cooperative relaying decreases. However, for higher λ, as discussed earlier, t_{ps} gets the major share of time. Since more help of secondary nodes is required when the channel conditions are not favourable, CRs are reimbursed more at low SNRs. As the SNRs increases, t_{ss} decreases. However, t_{ss} is always long enough to satisfy the minimum reimbursement required by the CRs. Overall, both t_{sp} and t_{ss} assume low values at higher λ due to greater t_{ps} requirement as explained previously.

Figure 5, studies the bargaining powers of the two players and its impact on the division of time. It can be seen that the player with higher bargaining power is able to procure more time to increase its utility. The primary can get up to ∼20 % more time reserved for the cooperative relaying phase when its bargaining power is improved to 0.8 from 0.5. Similar increase in the CR bargaining power results in proportional increase in t_{ss}. The variety of possible divisions of the leasing time depicts the flexibility and wide scale applicability of the bargaining solutions. It can capture the scenarios where one player exercises greater influence on the decision.

8 Energy Efficiency of Spectrum Leasing Model

8.1 Analytical Quantification

In this section, the energy efficiency (EE) of the spectrum leasing model for cognitive radio networks is defined and quantified. The energy efficiency is the number of bits transmitted successfully across the channel per unit of energy consumed, given as,

$$EE = \frac{n_B}{J}, \text{ (bits/J)} \tag{17}$$

where n_B is the number of bits transmitted successfully and J is the energy consumed in Joules.

Theorem 6 *The energy efficiency of a licensed primary network employing direct communication EE_{dir} and while employing DSL, EE_{DSL} in terms of the number of successfully transmitted bits per unit energy can be given as*

$$EE_{\text{dir}} = \frac{n_{\text{dir}}}{TP_p}, \quad \text{and} \quad EE_{\text{DSL}} = \frac{n_{\text{DSL}}}{t_{ps}\bar{P}_p + t_{sp}P_s k}, \tag{18}$$

respectively, where n_{dir} is the number of successfully transmitted bits in direct communication, n_{DSL} are the successfully transmitted bits over the cooperative link.

Proof The number of bits successfully transmitted in the transmission duration of the direct link n_{dir} is given as [34];

$$n_{\text{dir}} = R_{\text{dir}} T, \tag{19}$$

where R_{dir} follows from the result in Lemma 1. In case the primary decides to lease the spectrum, the number of bits successfully transmitted in spectrum leasing is given as

$$n_{\text{DSL}} = \min\left(t_{ps}\overline{R}_{ps}, t_{sp}\overline{R}_{sp}\right), \tag{20}$$

where, $\overline{R}_{ps}$ and $\overline{R}_{sp}$ have been determined in Eqs. 6 and 7, respectively. The total energy consumed during direct communication is TP_p and that during DSL based cooperation is $t_{ps}\bar{P}_p + t_{sp}P_s k$ where the first term accounts for the energy consumed in P_{tx} to S_{tx} communication and the later for the energy consumption when k secondary transmitters cooperatively relay the data to P_{rx} for a duration equal to the leased time t_{sp} and then transmit their own traffic for a time t_{ss}. Similarly, we also quantify the energy efficiency of secondary communication phase as

$$EE_{\text{sec}} = \frac{n_{\text{sec}}}{P_s t_{ss}}, \text{ (bits/J)} \tag{21}$$

where $n_{\text{sec}} = t_{ss}\overline{R}_{ss}$. The total energy consumed when the secondary network communicates for a duration t_{ss} is $P_s t_{ss}$. □

8.2 Analytic Results

Following the analytical results for R_{dir}, $\overline{R}_{ps}$, $\overline{R}_{sp}$ and $\overline{R}_{ss}$, the energy efficiency is studied by observing both the direct link and DSL based communication over a variety of SNR values as shown in Fig. 6a. As in the discussion on the achievable

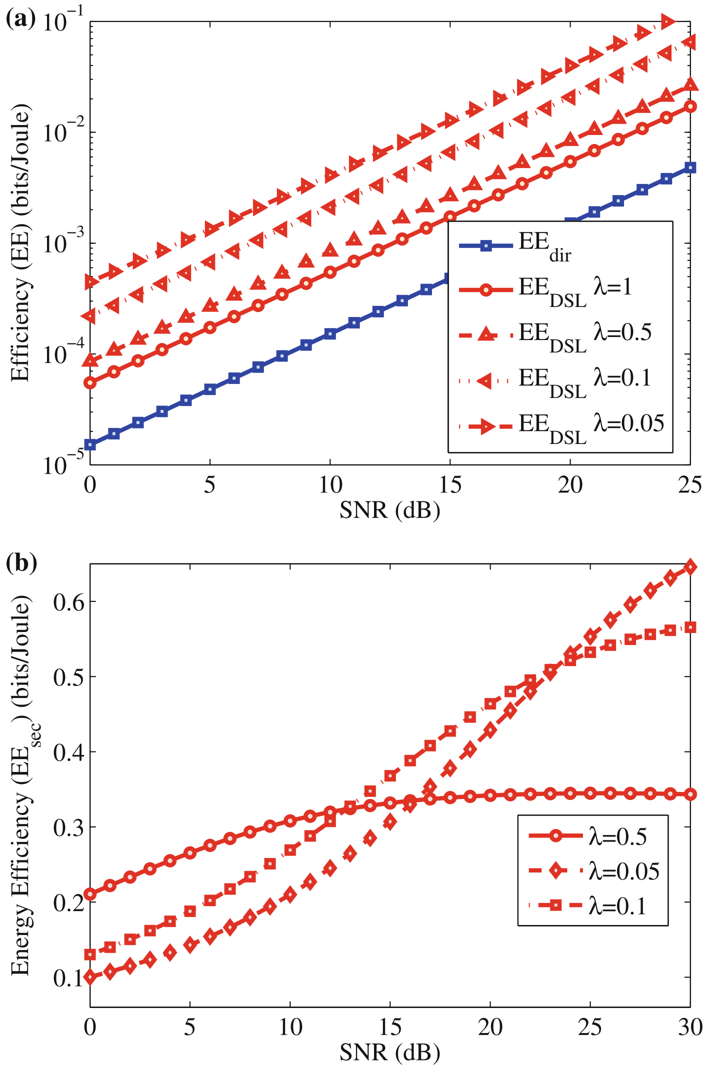


Fig. 6 Energy efficiency. **a** Direct communication EE_{dir} versus DSL communication EE_{DSL}, $P_p = 1,\ P_s = 0.1,\ T = 1, \theta = \frac{\pi}{4}$. **b** Secondary Network EE_{sec}, $P_s = 0.1$, time = t_{ss}

capacity and time division, the EE of direct and DSL communication is studied on the basis of secondary network density. It is clearly evident that the energy efficiency of DSL is significantly greater than that of the direct communication for smaller values of λ. This is because the transmit power of the primary and secondary in DSL mode is low. The selection of relays which are geographically closer to both P_{tx} and P_{rx} help in achieving the same transmission rate in shorter time and hence lower power. Also, the cooperative relaying based diversity benefits significantly increase the throughput at the primary receiver while maintaining a low transmit power. As λ increases, the EE of DSL decreases mainly due to two reasons;

1. The throughput of the cooperative DSL communication decreases as the average primary to secondary rate $\overline{R}_{ps}$ decreases with increasing λ (see Fig. 3a). The energy consumed in the first phase of DSL grows as the primary to secondary link operation time t_{ps} increases.
2. Also, in the second phase of DSL, aggregate transmit energy is higher due to increased number of relays.

It can be seen that the bargaining based leasing time division results in significantly more energy efficient communication via DSL as compared to direct communication when the secondary network is relatively sparse (i.e., $\lambda \leq 0.05$).

In Fig. 6b, we study the EE of the secondary network in the third phase of leasing. During this phase, the energy efficiency of the network improves with increasing SNR. It attains a maximum value as R_{ss} converges to a constant rate. Moreover, if the number of secondary transmitters is increased, the aggregate energy consumption is increased by the presence of greater number of interferes. Hence, the EE of the secondary network EE_{sec} decreases for high λ when DSL is operational in the interference limited regime. Hence, DSL for sparse secondary network is the most energy efficient solution for both primary and secondary networks.

Further, the effect of the angle θ of the sector of cooperation on the EE of DSL is investigated. From Fig. 7, it can be seen that the EE of DSL degrades with increasing the area of cooperation. This happens because increasing θ increases the number of cooperators which in turn increases the aggregate transmit power used for cooperation. Also, the probability of finding a farther neighbour increases as the area of

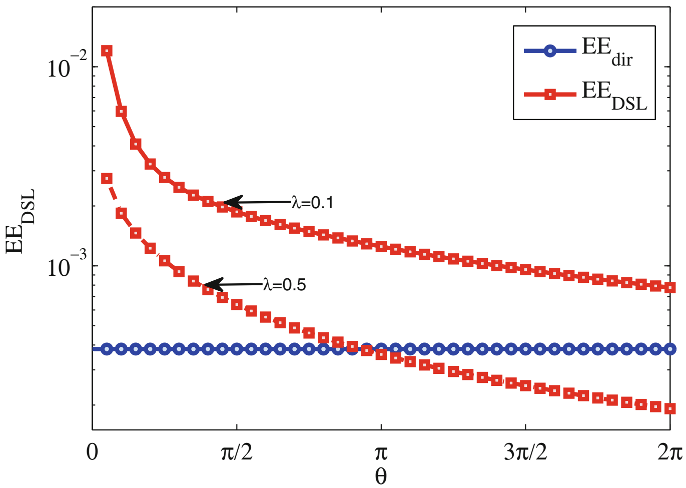


Fig. 7 Impact of θ on EE of DSL

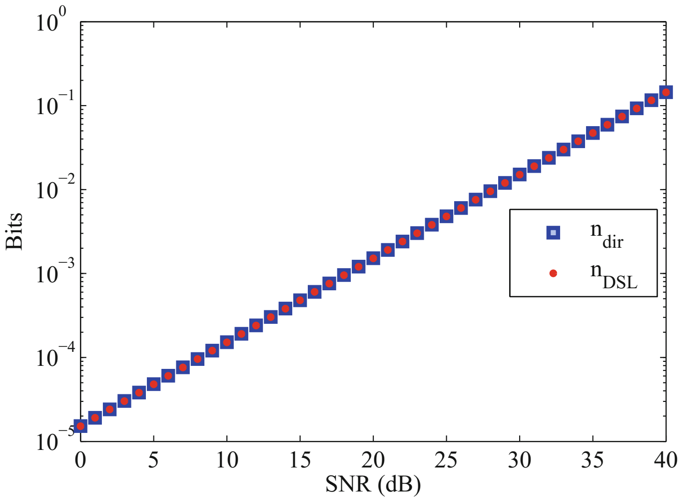


Fig. 8 Time-rate product: direct communication bits_{dir} versus DSL bits_{DSL} $\lambda = 0.5,\ T = 1$

cooperation increases and hence limits $\overline{R}_{ps}$ in the first phase. For low values of θ, $\overline{R}_{sp}$ is low due to limited number of cooperators. However, low θ results in high $\overline{R}_{ps}$, thus, an improved energy efficiency is observed. For very low values of θ, DSL is not viable because the probability of finding even a single relay is infinitely low. As soon as the cooperation area is wide enough to find a few relays in it, DSL becomes viable and most energy efficient.

Finally, the time rate product is analysed which determines the total number of bits that can be transmitted during both modes for a time T. The simulation results in Fig. 8 demonstrate the time-rate product of direct versus DSL communication. It can be seen that DSL communication achieves exactly the same performance in terms of the effective number of bits delivered to the primary receiver as compared to the direct communication. It simply implies that by using DSL, the primary can transmit the same amount of data as with direct communication. However, as discussed earlier, this transmission is more energy efficient than direct communication when the CR network is sparse. This result further verifies the practical viability and attraction for the legacy network to operate in DSL mode.

The entire discussion can be summarized as follows. DSL based transmission serves as an energy efficient alternative to direct communication when the secondary network is sparse. For these low populated networks, the aggregate energy and time requirements for cooperation and secondary network activity are low. Hence an intelligent relay selection based on the spatial characteristics of the network and the optimal leasing time division can help in exploiting the diversity gain of cooperative relaying to enhance the performance of legacy communication. It also allows the otherwise deprived secondary network to utilize its share in the bandwidth therefore improving the overall spectral utilization of the network.

9 Summary

In this chapter, a DSL scheme is presented that provides an elaborated implementation mechanism for dynamic resource sharing was presented. An analytical study of dynamic spectrum leasing based on a geometrical framework was presented and the relative link performances in terms of the achieved capacities in DSL and direct communication were evaluated. A Nash bargaining based approach for the determination of the appropriate leasing time was introduced. It was demonstrated that the proposed algorithm results in a division of time that satisfies the requirements of both primary and secondary networks. Based on these operational features, the energy efficiency was quantified and investigated through simulations. The results indicate that DSL is more energy efficient in most of the practical SNR regimes, hence making DSL a viable option for energy efficient communication. Such energy efficient solution can be achieved only if a sparse CR network is considered with DSL operation at a low transmit power as compared to that of the transmit power of the direct communication. DSL is shown to be more than 10x more energy efficient than direct communication when the CR density is low and/or the cooperation region is small. With only a few cooperating CR nodes, the entire CR network gets exclusive access to the spectrum. Hence DSL based communication enables the primary to communicate at its desired transmission rate and quality in an energy efficient manner and also enables the CR network to exploit the licensed spectrum for its own communication.

The scheme presented in this chapter can be further extended to study the possible delays incurred in the DSL communication. Also, the impact of the presence of any greedy CRs in the network is also an open issue. It is interesting to also consider individually autonomous entities in contrast to network level players in the game formulation of DSL. The energy and spectral efficiency of DSL under the above mentioned considerations is an important research question. In short, DSL is a useful technique for improving the efficiency of wireless communication with direct application to future networks.

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