

L-CAQ: Joint Link-Oriented Channel-Availability and Channel-Quality Based Channel Selection for Mobile Cognitive Radio Networks

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Abstract

Channel availability probability (CAP) and channel quality (CQ) are two key metrics that can be used to efficiently design a channel selection strategy in cognitive radio networks. For static scenarios, i.e., where all the users are immobile, the CAP metric depends only on the primary users' activity whereas the CQ metric remains relatively constant. In contrast, for mobile scenarios, the values of both metrics fluctuate not only with time (time-variant) but also over different links between users (link-variant) due to the dynamic variation of primary- and secondary-users' relative positions. As an attempt to address this dynamic fluctuation, this paper proposes L-CAQ: a link-oriented channel-availability and channel-quality based channel selection strategy that aims to maximize the link throughput. The L-CAQ scheme considers accurate estimation of the aforementioned two channel selection metrics, which are governed by the mobility-induced non-stationary network topology, and endeavors to select a channel that jointly maximizes the CAP and CQ. The benefits of the proposed scheme are demonstrated through numerical simulation for mobile cognitive radio networks.

Keywords: Channel availability, channel quality, channel selection, cognitive radio, mobile networks, mobility.

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1. Introduction

Channel selection is one of the important tasks in Cognitive Radio Networks (CRNs) to enable a Cognitive User (CU) to communicate with its neighbors. A common purpose of this task is to select the “best” channel among the list of available channels that maximizes the throughput and minimizes the interference to Primary Users (PUs). In the literature there exist two prominent metrics that are widely used for channel selection, namely Channel Availability Probability (CAP) and the Channel Quality (CQ). Herein the CAP corresponds the probability of a channel licensed to a PU being available for communications of unlicensed users [1] whereas the CQ is associated with the maximum amount of data per unit time that can be reliably delivered over the given channel [21]. Accurate acquisition of these features will enable the design of throughput-efficient channel selection that allows the CU to maximize the communication opportunities.

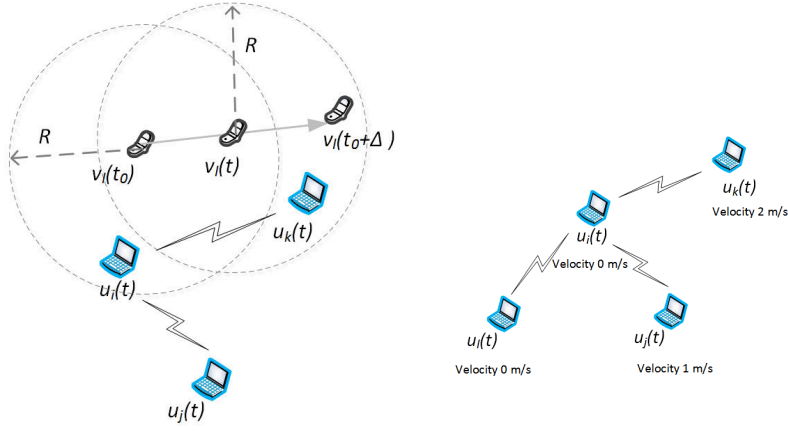
In static scenarios, referred to as Static CRNs (SCRNs) where all PUs and CUs are fixed and immobile, the first feature, namely CAP, depends only on the PU activity probability, i.e., the probability of the channel being occupied by the PU transmission, which can be estimated using the past channel occupancy history [1, 29]. On the other hand, the second feature, namely CQ depends on several factors such as the channel bandwidth, transmit power, overall medium attenuation and interference. In static scenario CQ remains relatively constant and similarly to CAP, the CU can also estimate CQ through the past channel history [3].

In mobile scenarios, referred to as Mobile CRNs (MCRNs) where the PUs and/or CUs are mobile, however, both the CAP and CQ vary not only with time but also with link.¹ In order to better illustrate this time and link variation, consider an example of MCRNs in Fig. 1. In Fig. 1 (a), at time t_0 , the i -th CU, u_i is inside the *critical range*² of the l -th PU, v_l , hence the CAP depends on the l -th PU activity probability. Due to the mobility of PU, the CU is outside the critical range at time t , therefore, the channel availability is independent whether the l -th PU is active or not. Mobility can thus change the dependency of CUs on the activity of existing PUs, leading to the time-variant CAP for each CU. In mobile scenarios, the CAP is time variant as shown and analyzed in [1] and a channel selection strategy based on this time-varying CAP has been proposed in [2].³ Another impact of mobility in CRNs is link diversity, which leads to link-variant CAP. For example, in Fig. 1 (b), we note that, at time t , the i -th and j -th CUs u_i and u_j are outside the critical range of any PU, but the k -th CU u_k is inside the critical range. In this case, the channel availability

¹Herein, the notion “link” refers to connection between a pair of communicating users.

²The CUs are able to detect active PUs within a range, referred to as *critical range*, determined by the PU transmission range and by the CU interference range [5, 6]. This range might vary for each CU especially in heterogeneous networks.

³See Section 2 for further discussion.



(a) CAP is not only time variant but also link variant (b) CQ measurement is also link variant

Figure 1: Channel availability and channel quality are time and link variant in MCRNs.

for the link between u_i and u_j does not depend on the PU activity probability whereas the channel availability for link between u_i and u_k , depends on the PU activity probability.

The availability of a channel for communication between a pair of CUs does not directly imply that the channel is of sufficient quality for data transmission. If the two nodes are communicating and if either one or both of them is/are mobile, then their CQ will be time variant. This is particularly due to the variation of relative distances between the nodes and changing of scattering objects in the environment, which lead to time-varying attenuation due to path loss and channel fading, respectively. Using the same reasoning as the link-variant CAP, the CQ also varies from one link to another due to a diverse mobility pattern. It is therefore crucial to incorporate both the time-varying CAP and CQ parameters to design a channel selection strategy that aims to maximize the rate of reliable data delivery.

In this paper, we propose a mobility-aware channel selection technique by jointly accounting for the parameters of time- and link-variant CAP and CQ for MCRNs. Underpinning this novel technique, the contributions of this work include the following.

- i) We derive link-based CAP (L-CAP) estimation based on the relative distances among PUs and CUs in a given temporal interval;
- ii) We obtain a mathematical expression that captures estimation of the link-based CQ (L-CQ) in mobile scenarios;
- iii) We propose a Link-oriented Channel-Availability and channel-Quality (L-CAQ) based channel selection strategy that aims to maximize the link throughput by taking into account two prominent channel selection metrics, namely L-CAP and L-CQ, which are governed by the non-stationarity of the network topology induced by the user mobility;

Acronym	Full Name
CRNs	Cognitive Radio Networks
CU	Cognitive User
PU	Primary Users
CAP	Channel Availability Probability
CQ	Channel Quality
SCRNs	Static Cognitive Radio Networks
MCRNs	Mobile Cognitive Radio Networks
L-CAP	Link-Channel Availability Probability
L-CQ	Link-Channel Quality
L-CAP	Link-Channel Availability Probability
RWPM	Random WayPoint Mobility
LUP	Location Update period

Table 1: List of frequently-used acronyms.

- iv) We demonstrate the benefits of the proposed strategy using numerical simulation for MCRNs.

The rest of the paper is organized as follows. For ease of reference, we provide the list of frequently-used acronyms in Table 1. In Section 2, we critically review and discuss related works. In Section 3, we state and formulate our approach to the problem of channel selection in MCRNs. In Section 4, we describe the network model of MCRNs. In Section 5, we present and discuss our main contribution of the L-CAQ strategy for channel selection. In Section 6, we evaluate the performance of this proposed scheme against the benchmark schemes through numerical simulation. Finally, Section 7 summarizes key points from this paper.

2. Review of Existing Works

Channel selection constitutes an important task for initiating communication in CRNs, which in turn is crucial for optimizing the network performance. Several works in the literature have emphasized the crucial roles of CAP and CQ in selecting an optimal channel from an available channel set. Most of the works, however, do not consider the impact of mobility on CRNs.

In [26], the authors proposed a method for channel availability analysis of the primary network by considering the Idle Probability of Consecutive Time Slots (IPCOTS) to be utilized in the sensing channel selection in CRNs. Based on discrete-time Markov model, the authors acquired the IPCOTS for every specific channel, according to a condition that its status in the primary network is distributed evenly. The sensing order of channel selection draws a suboptimal state-dependent policy, which is referred to as the IPCOTS policy. The channel analysis under the IPCOTS framework can provide extra information about the channel occupancy state in the primary network. Moreover, by using

the IPCOTS policy the proposed channel selection technique can minimize the predicted number of channel switching to achieve the initial objective.

In [27], the authors exploited the spectrum hole and channel characteristics, and proposed a multi-channel selection algorithm to enable the prediction of spectrum hole in order to minimize the CU's interfering period to the primary network and boost channel utilization. This scheme has jointly considered the interference range and channel capacity in order to reduce the interference to primary network and improve the system performance. Through a simple amendment of statistical parameters over the channel quality, the scheme can achieve a higher throughput while reducing the collision rate.

In [22], the authors proposed an opportunistic sensing strategy, where the reward is adapted to the PU-link channel state information (CSI) prior to sensing. To achieve effective collision resolution, this strategy is integrated with a novel multi-channel first-come-first-served medium access control scheme. Both the individual and network throughputs were shown to improve by the aforementioned adaptive technique prior to sensing and randomization of sensing decisions.

Several channel selection techniques are presented in literature [28] - [37]. In [28], A channel selection technique was proposed using a fuzzy logic based decision making algorithm. In [35], a Markovian-based cooperative spectrum sensing policy was studied. In [29], the authors introduced a routing metric that aims to minimize the interference of the CUs to the PUs by estimating the channel availability through the channel history. In [30], the authors presented a channel selection algorithm based on the ON-OFF time distribution in cognitive radio networks. The channel selection algorithm aims to let the secondary user to discover the empty channel and reduce the rate of channel switching in an efficient way. Through observing and calculating the heavy-tailed OFF times for the primary users, the channel selection algorithm can show a significant decrease in channel switching rate and save the energy consumption.

As discussed in the above works, CAP is more prevalent for channel selection in static scenarios of the CRNs due to time-invariant CQ. In such a case, the selection problem can be projected as selecting a CAP entry (entries) from a weighted CAP vector where the weights are determined by fixed CQs within a set of available channels.

A limited number of works have addressed channel selection in the CRNs with mobility scenarios. In [3], the authors proposed an optimal routing metric for both static and mobile CRNs. However, consideration of the channel availability depends solely on the channel occupancy history, which is less accurate for MCRNs. In [1], a channel availability model was designed by taking into account the PU mobility. Considering the same model, a mobility aware channel selection technique is proposed in [2]. However, considering only the PU mobility is deemed insufficient to capture diverse possibilities of MCRNs where both the PU and CU may have non-stationary characteristics.

Pushing further these aforementioned works, in this paper we propose a channel selection technique that considers the impact of both PU and CU mobility. We first formulate the network model of MCRNs and establish precise

mathematical expressions of the CAP and CQ that encapsulate time- and link-variant characteristics of the network. Using these mathematical expressions, we then propose a channel selection algorithm and evaluate its performance against a number of benchmark schemes to demonstrate its superiority.

3. Problem Statement

When an arbitrary cognitive node u_i wants to communicate with one of its neighbor nodes u_j , then u_i needs to select the best channel among the list of licensed channels. A widely-used criterion for determining the “best channel” is the *link throughput*, ψ_{ij}^m that corresponds to the amount of data per unit time that u_i can successfully transmit to u_j through an arbitrarily given channel m . At any given time t , based on the acquired values of CAP and CQ, user u_i can approximate its link throughput to user u_j at channel m using the estimate

$$\bar{\psi}_{ij}^m(t) = CAP_{ij}^m(t) \times CQ_{ij}^m(t) \times \psi^m \quad (1)$$

where $CAP_{ij}^m(t) \in [0, 1]$ is the channel availability probability for channel m at time t that equals to the PU inactive probabilities, denoted as $P_{off}^m(t)$; $CQ_{ij}^m(t) \in [0, 1]$ is the (normalized) channel quality of channel m ; and ψ^m is the ideal link throughput for channel m , i.e., when $CAP_{ij}^m(t) = CQ_{ij}^m(t) = 1$.

In static scenarios, the instantaneous values of the CAP and CQ can be a priori known (when, e.g., the propagation environment and PUs’ traffic are stationary) or simply estimated according to the channel occupancy and link quality history, respectively [29, 3]. Throughout the rest of the paper, we refer to a method of estimating $\psi_{ij}^m(t)$ via a priori available information or channel occupancy/quality history as the *Traditional Method*. It is customary that for the static scenarios with stationary environment and data traffic, both the CAP and CQ are time- and link-invariant (such that $CAP_{ij}^m(t) = CAP^m$ and $CQ_{ij}^m(t) = CQ^m$) and the link throughput solely depends on the activity of PUs across different network regions.

In mobile scenarios, the CAP and CQ are both time- and link-variant. Therefore, unlike the *Traditional Method*, the link throughput $\psi_{ij}^m(t)$ depends on three factors, namely: i) the Link-based $CAP^m(t)$, which will further depend on two factors, i.e., the PU inactive probabilities $P_{off}^m(t)$ and probability that a pair of CUs (e.g., u_i and u_j) communication does not interfere with the active PUs, denoted as NA_{ij}^m ; ii) Link-based $CQ_{ij}^m(t)$; and iii) ideal channel throughput ψ^m .

In order to clarify this issue, we consider an example shown in Fig. 2. The three PUs at time t are $v_l(t)$, $v_n(t)$ and $v_m(t)$ and they are active on channel a , b and c , respectively. The three CUs at time t who want to communicate one another are $u_i(t)$, $u_j(t)$ and $u_k(t)$ and their critical range are R_i , R_j and R_k , respectively.

For the sake of simplicity, we assume that the ideal channel throughput of channel a , b and c are 1 Mbps and the channel quality for all the links at time t are the same as depicted in Fig. 2. If we estimate the link throughput of link $u_i \leftrightarrow u_j$ and $u_i \leftrightarrow u_k$ at time t for each channel using the *Traditional Method*,

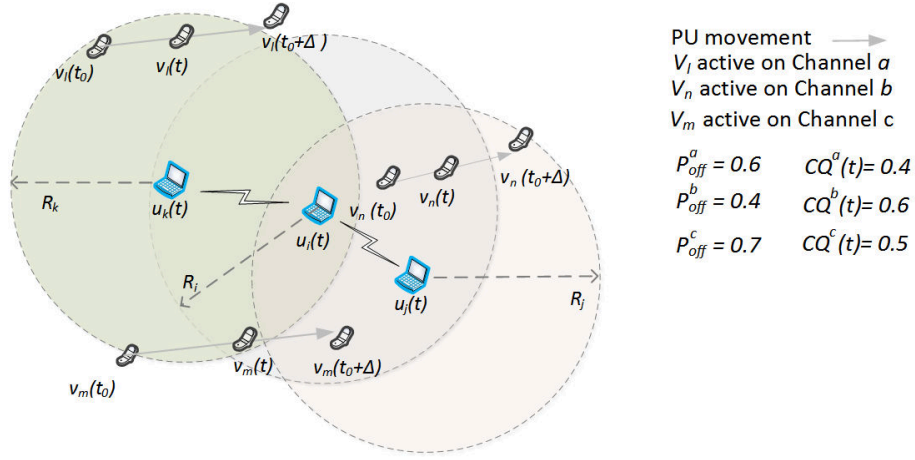


Figure 2: Channel selection in MCRNs.

then for both the links, we have $\bar{\psi}_{ij}^a(t) = \bar{\psi}_{ik}^a(t) = 0.24$ Mbps, $\bar{\psi}_{ij}^b(t) = \bar{\psi}_{ik}^b(t) = 0.24$ Mbps and $\bar{\psi}_{ij}^c(t) = \bar{\psi}_{ik}^c(t) = 0.35$ Mbps. The best channel at time t according to this method is channel c . On the other hand, if we estimate the link throughput at time t for each channel considering the mobility of users, we have that:

- For link $u_i \leftrightarrow u_j$: $\bar{\psi}_{ij}^a(t) = [P_{off}^a + (1 - P_{off}^a)NA_{ij}^a] \times CQ_{ij}^m(t) \times \psi^a = 0.4$ Mbps, $\bar{\psi}_{ij}^b(t) = 0.24$ Mbps and $\bar{\psi}_{ij}^c(t) = 0.35$ Mbps
- For link $u_i \leftrightarrow u_k$: $\bar{\psi}_{ik}^a(t) = [P_{off}^a + (1 - P_{off}^a)NA_{ik}^a] \times CQ_{ik}^m(t) \times \psi^a = 0.24$ Mbps, $\bar{\psi}_{ik}^b(t) = 0.6$ Mbps and $\bar{\psi}_{ik}^c(t) = 0.35$ Mbps.

According to this refined method, the best channel at time t for both links $u_i \leftrightarrow u_j$ and $u_i \leftrightarrow u_k$ are channels a and b , respectively, not channel c .

The aforementioned example demonstrates that in MCRNs, the CAP is not only time variant but also link variant, hence we refer to it as Link-based CAP (L-CAP). In addition to its time-variant nature due to changing distance and multipath propagation, the estimated channel equality will also be link-variant depending on the instantaneous distances of the CUs to the PUs. We therefore refer to this channel quality measure as Link-based Channel Quality (L-CQ) due to mobility variation of different CUs. We therefore envision to design a new channel selection strategy by exploiting both the L-CAP and L-CQ features that comprehensively capture the mobility characteristics of the network.

4. Network Model

We consider an MCRN where a set of CUs and PUs are mobile, denoted as $u_i \in U$ and $v_l \in V$, respectively. For the sake of simplicity, we assume that the CUs and PUs move according to the well-known Random WayPoint Mobility

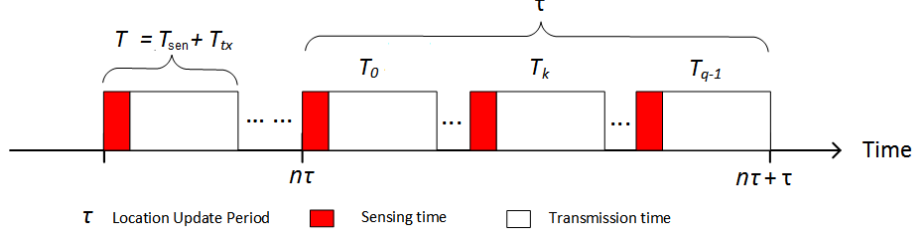


Figure 3: CU time organization related with location update interval (LUP).

(RWPM) model [11] inside a square network region $\mathcal{A}$. The vector $\mathbf{v}_l(t)$ denotes the two-dimensional position of the l -th PU at time instant t . The l -th PU traffic on the m -th channel is modeled as a two-state birth-death process [5, 12, 13] with death rate $\alpha_{l,m}$ and birth rate $\beta_{l,m}$. In the *on* state, the l -th PU is active on channel m , and the active probability can be calculated using

$$P_{l,m}^{on} = \frac{\beta_{l,m}}{(\alpha_{l,m} + \beta_{l,m})} \quad (2)$$

whereas in the *off* state it is inactive on channel m and the inactive probability can be computed using

$$P_{l,m}^{off} = 1 - P_{l,m}^{on}. \quad (3)$$

The vector $\mathbf{u}_i(t)$ denotes the two-dimensional position of the i -th PU at time instant t . We consider more realistic PU spectrum occupancy models where different PUs roaming within the network region share the same channel [12].

As depicted in Fig 3, the CU activity is organized into fixed-sized frames with each having duration of T . Each frame interval T is further divided into a sensing period T_{sen} [19, 20], which measures the portion of the time slot assigned to the spectrum sensing, and a transmission period T_{tx} , which measures the portion of the time slot devoted to the CU data transmission.

A pair of CUs can communicate with each other through licensed spectrum, which is organized in N distinct bands/channels. More specifically, at time t , an arbitrary node u_i communicates with another arbitrary node u_j through a channel $m \in \{1, \dots, N\}$. In order to select the best channel for communication, at time t , the CU u_i makes an attempt to estimate the link throughput $\psi_{ij}^m(t)$ for the link labelled by e_{ij}^m . This link throughput jointly accounts for two main metrics, namely L-CAP and L-CQ of the specified channel. These metrics are both time- and link-variant due to the mobility of PUs and CUs. As a consequence, in order to obtain the link throughput estimate $\bar{\psi}_{ij}^m(t)$, we assume that CU u_i is able to get the locations of its neighbors and the PUs periodically, which is governed by the Location Update period (LUP) τ as illustrated in Fig 3.⁴

⁴It is reasonable to assume that the CU cannot obtain the locations of its neighbors and

5. L-CAQ based Channel Selection Technique in MCRNs

In this section we analyze the mobility characteristics of the PUs and CUs to approximate the best channel that will enable communication between a pair of nodes. Since both the L-CAP and L-CQ are crucial for such a selection technique, we first discuss the estimation procedures of the L-CAP and L-CQ in mobile scenarios. We then discuss our proposed Link-oriented Channel-Availability and channel-Quality (L-CAQ) based channel selection technique for MCRNs.

5.1. L-CAP Estimation in MCRNs

As discussed in Section 4 and Fig. 3, the CU activity is organized into fixed-sized frames of T duration, which is further divided into a sensing period T_{sen} and a transmission period T_{tx} . We also assume that, each CU is able to update the locations of its neighbours and PUs every LUP $\tau = qT$. Due to the timing constraint of location acquisition, it is sensible to compute the L-CAP for every LUP. More specifically, with reference to Fig. 3, in order to estimate the L-CAP for a pair of nodes (e.g., u_i and u_j) in the next temporal period, i.e., $[n\tau, (n\tau + \tau))$, u_i has to take into account the impact of PUs activity on both nodes. For this purpose, we first precisely define the L-CAP parameters follows.

Definition 1 (L-CAP). *Link-based CAP (L-CAP) is the probability of a channel licensed to PU/PUs being available for the communication of a pair of neighbouring CUs over a given LUP τ .*

Computing the exact value of L-CAP for each LUP requires knowledge of the exact users positions at every frame $0, \dots, q$, which is not directly available. Approximating these positions can be facilitated using the distance estimation procedure as outlined in Fig. 9 and detailed in Appendix 9.1. Based on the estimated distances among pairs of PUs and CUs, we obtain the probability of an arbitrary channel m being available to CUs at frame $k \in \{0, \dots, q-1\}$ as in the following proposition.

Proposition 1. *At the time instant $t_0 = n\tau$, the i -th CU estimates the probability $p_{ij,m,\mathcal{L}}(T_k)$ of channel m that is licensed to a set of PUs $\mathcal{L}$ being available for a pair of i -th and j -th CUs in the next time slot $T_k = [n\tau + kT, n\tau + (k+1)T)$ for any $k \in \{0, \dots, q-1\}$ as*

$$\tilde{p}_{ij,m,\mathcal{L}}(T_k) = \begin{cases} 1, & \text{if } (\tilde{d}_{i,l}(t) > R_{i,l}) \text{ AND } (\tilde{d}_{j,l}(t) > R_{j,l}), \forall l \in \mathcal{L}, \\ \prod_{l \in \mathcal{L}} P_{l,m}^{\text{off}}, & \text{otherwise,} \end{cases} \quad (4)$$

PUs at every single time instant t due to time-varying user locations in MCRNs and processing complexity. The PU location can be typically obtained through either location estimation algorithms or dedicated databases [18] while the CU location can be estimated either directly via dedicated positioning systems (e.g., GPS), or indirectly through location estimation algorithms [14]. Analysis of these localization techniques is beyond the scope of this paper.

for all $t \in T_k$ where $R_{i,l}$ and $R_{j,l}$ denote the critical ranges of the l -th PU with respect to i -th CU and j -th CU, $\tilde{d}_{i,l}(t)$ and $\tilde{d}_{j,l}(t)$ denote the estimated distances between the i -th CU and l -th PU, and the j -th CU and l -th PU at time $t \in T_k$, respectively. These estimated distances are all computed at time t_0 .

Proof. The proof follows similar steps in [1] by modifying the distance estimation process among as discussed in Appendix 9.1 as well as considering the time- and link-varying nature of the connection between a pair of CUs i and j . $\square$

The L-CAP metric for every LUP can then be expressed in the following proposition.

Proposition 2. *At the time instant t_0 , the L-CAP $CAP_{ij}^m(t)$ for (i, j) -th link for time interval $t \in [n\tau, n\tau + \tau)$ is given by the estimate of the probability of channel m that is licensed to a set of PUs $\mathcal{L}$ being available in the next LUP $\tau = [n\tau, n\tau + \tau)$ as*

$$CAP_{ij}^m(t) = \frac{1}{q} \sum_{k=0}^{q-1} \tilde{p}_{ij,m,\mathcal{L}}(T_k) \quad (5)$$

where $\tilde{p}_{ij,m,\mathcal{L}}(T_k)$ has been given in equation (4).

Proof. This L-CAP expression follows from averaging $\tilde{p}_{ij,m,\mathcal{L}}(T_k)$ given in Proposition 1 over all frames $k = 0, \dots, q-1$ within the LUP. $\square$

5.2. L-CQ Estimation in MCRNs

Consider two CUs u_i and u_j separated by distance $d_{i,j}$ that communicate over an arbitrary channel m with bandwidth W . The channel quality of the link between u_i and u_j can be associated with the amount of data per unit time (in bits/s) that can be reliably transmitted over the given channel. Such a reliable transmission rate depends on not only channel characteristics, but also transceiver processing including coding and modulation techniques.

For a given specific modulation signal set $\mathcal{X}$ that may represent practical modulation techniques such as phase-shift keying (PSK), quadrature amplitude modulation (QAM) and pulse-amplitude modulation (PAM), the ultimate data rate for wireless information transfer over bandwidth W can be well characterized by the instantaneous mutual information [21]

$$I(\text{SNR}_m, g_m) = W \cdot \left(\log_2 |\mathcal{X}| - \frac{1}{|\mathcal{X}|} \sum_{x \in \mathcal{X}} \mathbb{E} \left[\log_2 \sum_{x' \in \mathcal{X}} e^{-|g_m \sqrt{\text{SNR}_m}(x-x') + Z|^2 + |Z|^2} \right] \right) \quad (6)$$

where the expectation $\mathbb{E}[\cdot]$ is evaluated over $Z \sim \mathcal{N}_{\mathbb{C}}(0, 1)$. Herein $|\mathcal{X}|$ denotes the cardinality of $\mathcal{X}$, g_m is the complex-valued small-scale fading gain at channel m and SNR_m denotes the signal power to noise ratio

$$\text{SNR}_m \triangleq \frac{P_m^{\text{rx}}}{N_0 W}, \quad (7)$$

where P_m^{rx} is the received signal power (watt) at channel m and N_0 is the noise spectral density (watt/Hz).

Mobility of users leads to variation in both the small-scale fading gain g_m and the strength of P_m^{rx} that is determined by the large-scale fading gain. The time-variation of g_m is mainly due to the change of scattering configuration can usually be captured by Rayleigh fading distribution in the rich scattering environments [23]. The time variation P_m^{rx} can be captured by linking its value with the transmit power P^{tx} as [23]

$$P_m^{\text{rx}} = P^{\text{tx}} \times C_0 \times f_m^{-2} \times d_{i,j}^{-2} \quad (8)$$

where $C_0 \times f_m^{-2} \times d_{i,j}^{-2}$ characterizes the path loss at a distance $d_{i,j}$ and carrier frequency f_m of channel m for some positive constant C_0 . It is clear from (8) that unlike static scenarios, P_m^{rx} varies with time due to variation in distance $d_{i,j}$ and directly depends on the operating frequency of the given channel m .

It is widely understood that (see, e.g., [23]) temporal magnitudes of the small- and large-scale fading vary at different rates of change. Small-scale fading g_m rapidly varies within a small period of time (short distance) whereas large-scale fading (path loss) fluctuates over a longer travel distance. We can thus reasonably assume for a mobile communication with frame structure in Fig. 3 and certain mobile speeds that the large-scale fading changes every $T_k = T$ and the small-scale fading changes B times for each T_k , $k = 0, \dots, q-1$. Therefore, the maximum data rate that can be reliably transmitted over a single sensing frame is given by the average mutual information of the block-fading channel with block size B , namely

$$R_{i,j}(\text{SNR}_{m;k}, \mathbf{g}_{m;k}) = \frac{1}{B} \sum_{b=1}^B I(\text{SNR}_{m;k}, g_{m;k,b}) \quad (9)$$

where $I(\cdot, \cdot)$ has been defined in (6) and $\text{SNR}_{m;k} = P_m^{\text{rx}}(k)/(N_0 W)$ is the effective receive SNR at frame time T_k , which depends on

$$P_m^{\text{rx}}(k) = P^{\text{tx}} \times C_0 \times f_m^{-2} \times d_{i,j}^{-2}(T_k), \quad (10)$$

where $d_{i,j}(T_k)$ is the distance between CUs i and j at frame time T_k .⁵ In equation (9), we have also defined $\mathbf{g}_{m;k} \triangleq [g_{m;k,1}, \dots, g_{m;k,B}]$ as the B realizations of the small-scale fading over time T_k . Note that the block size B in equation (9) is closely related to the vehicle speed as each fading block $b \in \{1, \dots, B\}$ can be defined by the coherence time of the channel, which is inversely proportional with the relative speed between two communicating devices [21, 24]. The faster the relative mobility, the value of B will be larger (i.e., channel changes quickly within a frame) and vice-versa.

⁵Herein we assume that the distance between (i, j) -th CUs is approximately the same for a single frame of duration T .

The average mutual information (9) well characterizes the instantaneous reliable transmission rate supported by the channel, taking into account the mobility of devices that induces fading. Based on this metric, we can define the L-CQ as follows.

Definition 2 (L-CQ). *The link-based CQ (L-CQ) per LUP $\tau = qT$ is defined by the average (normalized) mutual information over a period $[t_0, t_0 + \tau]$ where t_0 is the starting time of the LUP.*

A pair of communicating CUs u_i and u_j can then approximate their L-CQs over all unoccupied channels by estimating their corresponding channel states (based on the model in [25]) and distance, and calculating the average mutual information. Approximation of their L-CQ for channel m is discussed in the following.

As discussed in Section 5.1, each CU is able to accurately inform its neighbors and PUs locations at time t_0 , namely the beginning of LUP $\tau = qT$. Based on a predefined mobility pattern and initial positions at time t_0 , a communicating pair of (i, j) -th CUs can estimate their distance $\tilde{d}_{i,j}(t_0 + kT)$ for each transmission frame $k = 0, \dots, q - 1$ within a LUP (see Appendix 9.2). Based on this estimated distance, we can then estimate the effective receive SNR for frame k as

$$\tilde{\text{SNR}}_{m;k} = \frac{P^{\text{tx}} \times C_0 \times f_m^{-2} \times \tilde{d}_{i,j}^{-2}(t_0 + kT)}{N_0 W}. \quad (11)$$

In addition to this SNR estimate, each CU is assumed to be capable of acquiring small-scale fading information during the sensing time for each frame (cf. Fig 3) through pilot-aided channel estimation [38]. At frame k and fading block (coherence time) b , this estimation yields noisy channel estimate for channel m , which is a function of the actual fading $g_{m;k,b}$ [25]

$$\tilde{g}_{m;k,b} = g_{m;k,b} + e_{m;k,b} \quad (12)$$

where $e_{m;k,b}$ is the channel state error term that is distributed according to $\mathcal{N}_{\mathbb{C}}(0, \epsilon)$ for some error variance $\epsilon > 0$.

In a single LUP, the CUs u_i and u_j can then approximate their L-CQ at channel m by computing the average mutual information of (9) using the estimated values $\tilde{\text{SNR}}_k$ and $\tilde{g}_{k,b;m}$. By accounting for the effective time for data transmission, we state our L-CQ metric to compute the link quality in the following proposition.

Proposition 3 (L-CQ). *The L-CQ at channel m , $CQ_{ij}^m(t) \in [0, 1]$, where $t \in [t_0, t_0 + \tau]$ is given by the following expression*

$$CQ_{ij}^m(t) = \frac{T - T_{\text{sen}}}{T \times W \times \log_2 |\mathcal{X}|} \cdot \frac{1}{q} \sum_{k=0}^{q-1} R_{i,j}(\tilde{\text{SNR}}_{m;k}, \tilde{g}_{m;k}) \quad (13)$$

where T and T_{sen} are single frame time and sensing time, respectively (cf. Fig. 3), W is the bandwidth of channel m , $\mathcal{X}$ is the modulation signal set and q is the

number of frames per location update interval. In the above (13), $R_{i,j}(\tilde{\text{SNR}}_k, \tilde{\mathbf{g}}_k)$ is the computed rate per frame (9) estimated using $\text{SNR}_{m;k}$ in (11) and $\tilde{\mathbf{g}}_{m;k} = [\tilde{g}_{m;k,1}, \dots, \tilde{g}_{m;k,B}]$ where $g_{m;k,b}$ has been given in (12).

Remark 1. Here the estimated $\text{SNR}_{m;k}$ is time variant because of its one of the key parameters $\tilde{d}_{i,j}$ is time variant. The estimation process of $\tilde{d}_{i,j}$ at time t is discussed in Appendix 9.2.

5.3. Proposed L-CAQ Channel Selection

In the following we describe our proposed Link-oriented Channel-Availability and channel-Quality (L-CAQ) based channel selection strategy for MCRNs. In order to understand the concept of L-CAQ, we first define the term *efficient channel*, which is required for optimizing communication between a pair of CUs.

Definition 3 (Efficient Channel). An arbitrary channel m is said to be an efficient channel that is chosen by an arbitrary CU u_i to communicate with its neighbour u_j during the period $[n\tau, n\tau + \tau)$, if the estimated link throughput $\bar{\psi}_{ij}^m(t)$ of channel m is the highest compared to those of other available channels.

Note that estimation of the link throughput $\bar{\psi}_{ij}^m(t)$ is performed within the interval $[n\tau, n\tau + \tau)$, $n \in \mathbb{R}^+$ by taking into account the estimated L-CAP in Proposition 2 and estimated L-CQ in Proposition 3. The L-CAQ strategy then selects the efficient channel from the list of available channels as formalized in the following proposition.

Proposition 4. At the time instant $n\tau$, the i -th CU u_i selects an efficient channel $m_{\text{eff}}^{ij}(n\tau)$ based on the estimated link throughput, $\bar{\psi}_{i,j}^m(\tau)$ in order to communicate with its neighbour u_j by jointly incorporating the estimated L-CAP and L-CQ during the interval $\tau = [n\tau, n\tau + \tau)$ according to equation (1), i.e.,

$$m_{\text{eff}}^{ij}(n\tau) = \arg \max_m \bar{\psi}_{i,j}^m(\tau) = \arg \max_m \text{CAP}_{ij}^m(n\tau) \cdot \text{CQ}_{ij}^m(n\tau) \cdot \psi^m \quad (14)$$

where $\text{CAP}_{ij}^m(\cdot)$ and $\text{CQ}_{ij}^m(\cdot)$ have been given in Propositions 2 and 3, respectively, and ψ^m is the ideal link throughput of channel m .

In the following section we demonstrate that by exploiting the dynamic variation of the L-CAP and L-CQ caused by the PUs and CUs mobility, the proposed L-CAQ is able to outperform the existing methods. The simulation results highlight the benefits of using the proposed technique for channel selection in the presence of mobile PUs and CUs.

6. Simulation Results

In this section we discuss several numerical experiments to prove the effectiveness of both the L-CAP and L-CQ as metrics that are closely associated with the channel throughput as well as evaluate the proposed L-CAQ based channel selection technique in MCRNs for establishing communication between a pair of CUs. We numerically measure the performance of L-CAP, L-CQ and L-CAQ through 10^6 Monte Carlo runs.

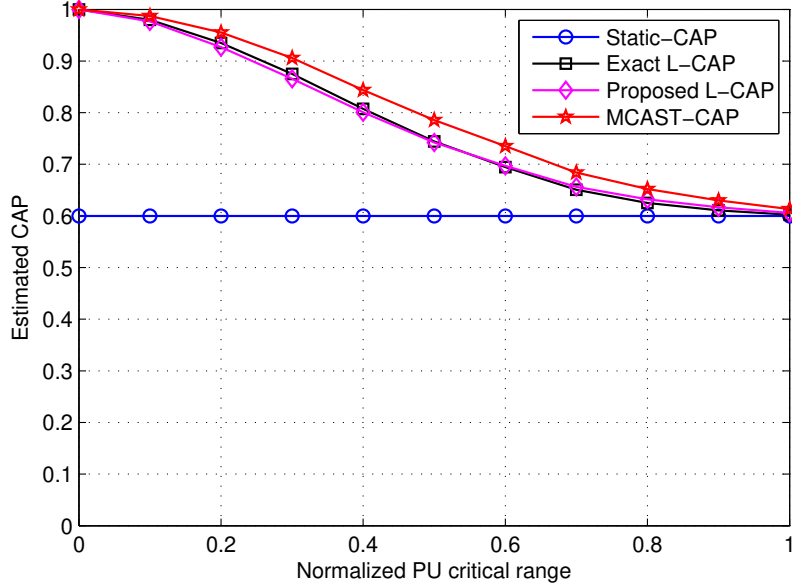


Figure 4: Estimated CAP versus PU critical range.

6.1. Effectiveness of L-CAP

In the following we demonstrate the effectiveness of our proposed L-CAP estimation (i.e., the estimated probability of a channel licensed to PU/PUs being available for the communication of a pair of neighboring CUs over a given interval) compared to the existing methods. Specifically, we consider four methods for estimating the CAP, namely : i) static estimation (i.e., based on only PU activity [29]), ii) Mobility-aware Channel-Availability probability based Channel Selection Technique (MCAST) [1], [2], iii) Proposed L-CAP with perfect knowledge of distance between i -th CU and l -th PU at time t , and iv) Proposed L-CAP with estimated distance between i -th CU and l -th PU at time t as obtained in Proposition 1. Both PUs and CUs move in a network region with area of 1000 m² according to the RWPM model with velocity uniformly distributed in the interval [5, 10] m/s. The considered simulation set is as follow: sensing time $T_{sen} = 1$ s, transmission time $T_{tx} = 3$ s, location update period $\tau = 20$, PU inactive probability = 0.6.

In Fig. 4, we analyze CAP by varying the normalized PU critical range. We can observe that CAP estimation based on the PU inactive probability, referred to as *Static-CAP*, does not depend on the PU critical range. In contrast, the other three estimation methods are significantly affected by the PU critical range. This is so because all these three methods are designed by taking into account the mobile nature of the network. Apart from the *Static-CAP* method, we notice that the estimated CAP value decreases while the PU critical

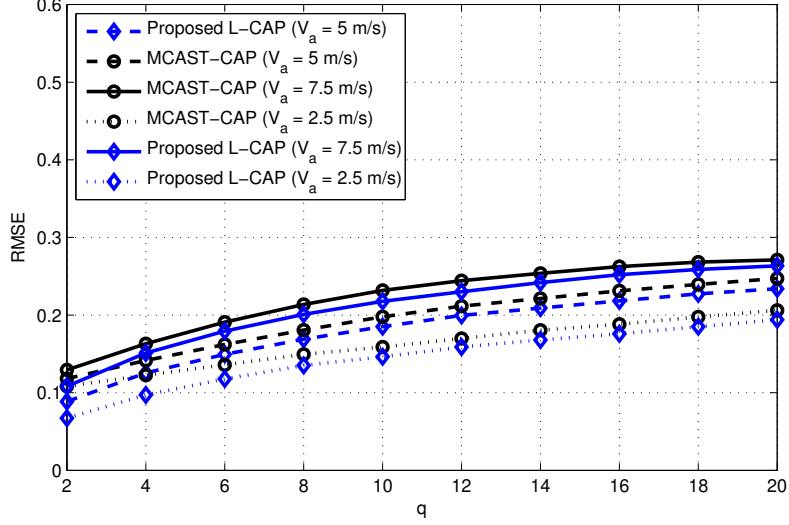


Figure 5: RMSE versus q for different mean velocities. Note that q herein is used to define variation in the LUP $\tau = qT$.

range increases. When all the network area is covered by the PU critical range (i.e., when the critical range = 1), then all four estimation methods produce similar CAP values. We further notice that our proposed L-CAP estimation method provides less error compared to the other mobility-aware CAP estimation method, namely MCAST-CAP that was proposed in [1], [2]. This is sensible because the proposed method takes into account the link-oriented CAP rather than the node-based CAP, as captured by Proposition 2.

The impact of localization error on CAP estimation is exhibited in Figs. 5 and 6 by adopting a similar simulation set to Fig. 4. There is an inherent trade-off between the network overhead and estimation error, i.e., the larger the time interval of the LUP τ is, the lower will the PU and CU position update rate be. Nevertheless, the larger τ causes a higher distance estimation error (see Appendix 9.1) that can be assessed by means of Root Mean Squared Error (RMSE). The estimation error can be further affected if the velocities of the PU and CU increase and/or the relative distance of the CUs for each link increases. In both cases, however, our proposed L-CAP estimation has comparatively less RMSE values than the MCAST-CAP, as shown in Figs. 5 and 6, respectively. This is so because the MCAST-CAP does not fully consider both the PU and CU mobility in the distance estimation procedure.

6.2. Effectiveness of L-CQ

The proposed L-CQ measure in Proposition 3 mainly depends on the accurate estimation of the received SNR and small-scale fading parameter. In Fig. 7, assuming no localization error (the computed distance is accurate), we verify the

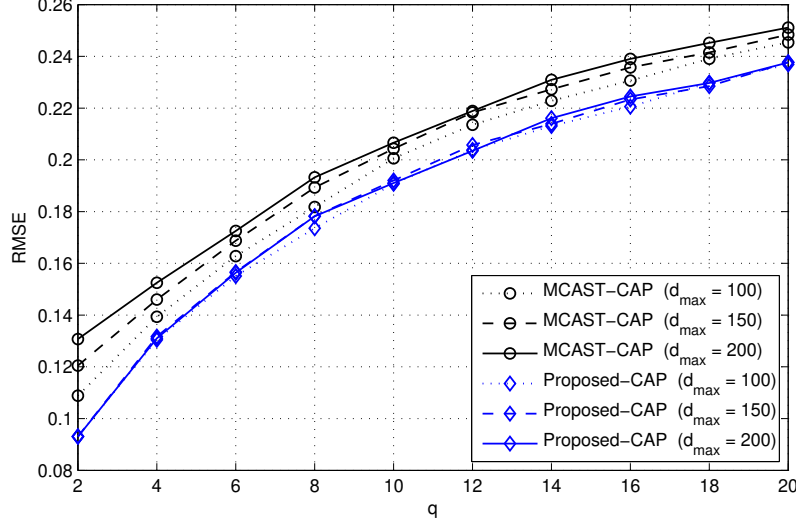


Figure 6: RMSE versus q for different d_{max} (i.e., the maximum allowable distance between a pair of CUs to establish communication). Note that q herein is used to define variation in the LUP $\tau = qT$.

sensitivity of L-CQ with respect to variation in distance and carrier frequency. As captured by equation (10), the link quality decreases exponentially with the increases in both distance and carrier frequency. A larger distance implies a significant attenuation in transmit signal power and a higher frequency leads to a shorter transmission range.

The small-scale fading parameter represents rapid-fluctuation (in the order of milliseconds) of transmit signal due to Doppler-induced mobility. The error in fading estimation (12) is directly proportional to the Doppler/terminal speed [38]. In order to maintain the same level of estimation accuracy, the time resources for channel estimation will need to increase linearly with the mobility speed, which lead to reduction of the amount of data that can be reliably transmitted. This latter point implies a lower L-CQ for a higher mobility speed.

6.3. Effectiveness of L-CAQ

In the following we demonstrate the effectiveness of our proposed L-CAQ method in Proposition 4 compared to the existing mobility-aware channel selection strategy, namely MCAST which selects the channel based on the maximum channel availability probability (MAX-CAP) metric. As argued in Sections 2 and 3, however, MAX-CAP may be insufficient in order to select the best channel under mobile scenarios due to both the time- and link-variation of the channels. Instead, we envisage to select the best channel that has the highest link throughput $\psi_{i,j}^m(t)$. In practice the time- and link-variant nature of the

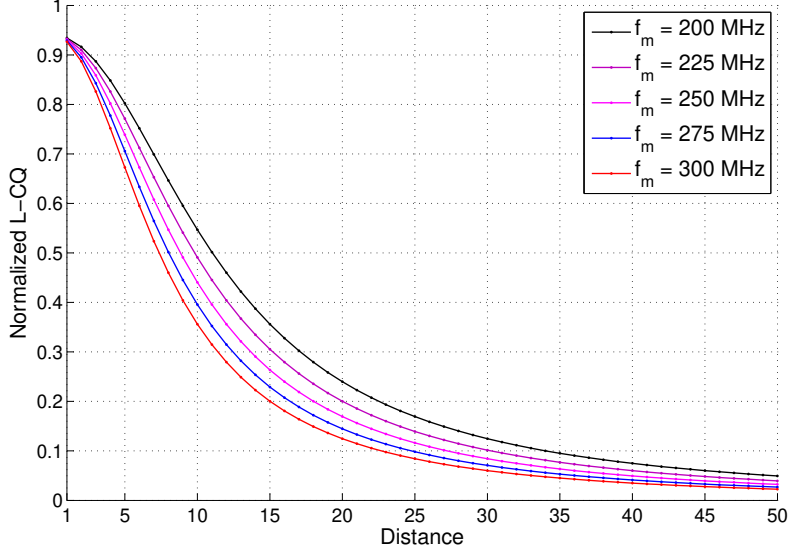


Figure 7: Normalized L-CQ vs Distance with the varying of channel frequency.

channel implies that computing the exact $\psi_{i,j}^m$ is challenging due to unavailability of required prior information. Our approach in this paper is to estimate the $\psi_{i,j}^m$ by individually estimating and subsequently multiplying the L-CAP and L-CQ values according to equation (1), which is possible through exploitation of LUP and sensing time per frame. In this way both the L-CAP and L-CQ are jointly taken into account when devising a channel selection strategy. For the purpose of comparison, we adopt the following simulation set: Number of PUs = 10; number of channels = 5 where 2 PUs are licensed on each channel, i.e., Multiple PUs for Channel [5]; PU inactive probability and ideal link throughput (ILT) for channels $\{1, 2, 3, 4, 5\}$ are given by $\{0.6, 0.2, 0.3, 0.5, 0.4\}$ and $\{2, 2.5, 5, 7.5, 10\}$, respectively; sensing time $T_{\text{sen}} = 1$ s; transmission time $T_{\text{tx}} = 3$ s; and LUP $\tau = 20$.

Four strategies for estimating the normalized link throughput (i.e., keeping the value of Link Throughput in between 0 to 1) are compared in Fig. 8, namely: i) Channel selection technique based on the highest ILT (labelled as *MAX-ILT*), ii) Channel selection technique in MCAST [1],[2], iii) Proposed channel selection technique with perfect knowledge of distance between (i, j) -th CUs and l -th PU at time t (labelled as *Exact*), and iv) Proposed channel selection technique with proposed estimated distance between (i, j) -th CUs and l -th PU at time t (labelled as *Proposed*). We note that the link throughput decreases with the increase of PU critical range in all the channel selection strategies due to a similar reasoning to that in Fig. 4. In the case of MCAST, the estimation error (i.e., its gap from the *Exact* method that indicates the actual link throughput)

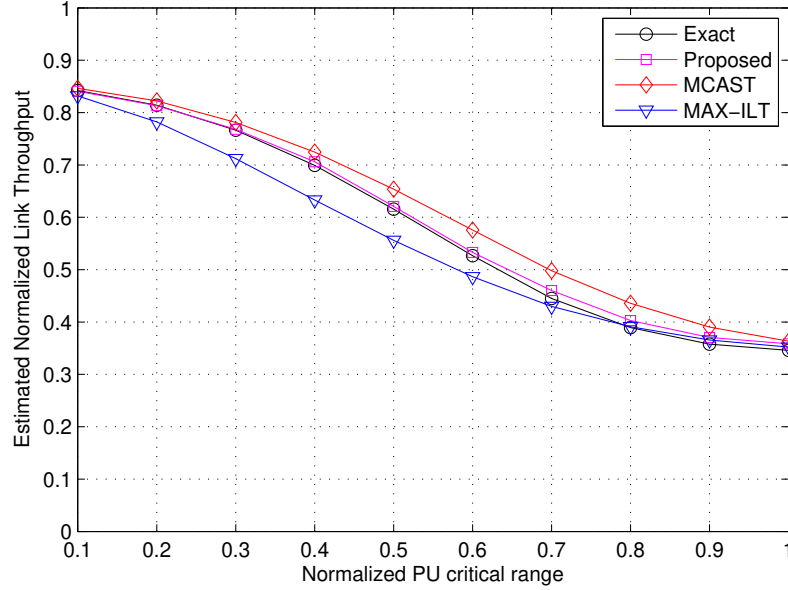


Figure 8: Estimated Normalized Link throughput versus PU critical range.

is large since it selects the channel according to only the node-based CAP. The *MAX-ILT* method is neither accurate to capture the actual link throughput as the *ILT* criterion does not take into account the impact of users mobility to the time- and link-variant nature of the channel. On the other hand, joint consideration of both the *L-CAP* and *L-CQ* in the design of channel selection makes our proposed method attractive since it provides the most accurate link throughput estimate. This can be observed from a small gap between two curves in Fig. 8, namely the *Exact* and *Proposed* curves.

7. Conclusion

In this paper we have proposed a joint *L-CAQ* based channel selection technique for MCRNs. Based on the relative distances among PUs and CUs in a given temporal interval, we have first derived an estimate of the link-based channel availability probability (*L-CAP*). We have then obtained a mathematical expression that estimates the link-based channel quality (*L-CQ*) in mobile scenarios. By incorporating both the *L-CAP* and *L-CQ* metrics that are governed by the non-stationarity of the network topology in MCRNs, we have designed an effective channel selection strategy that maximizes the estimated link throughput. Numerical results have revealed the effectiveness of adopting the proposed scheme in MCRNs.

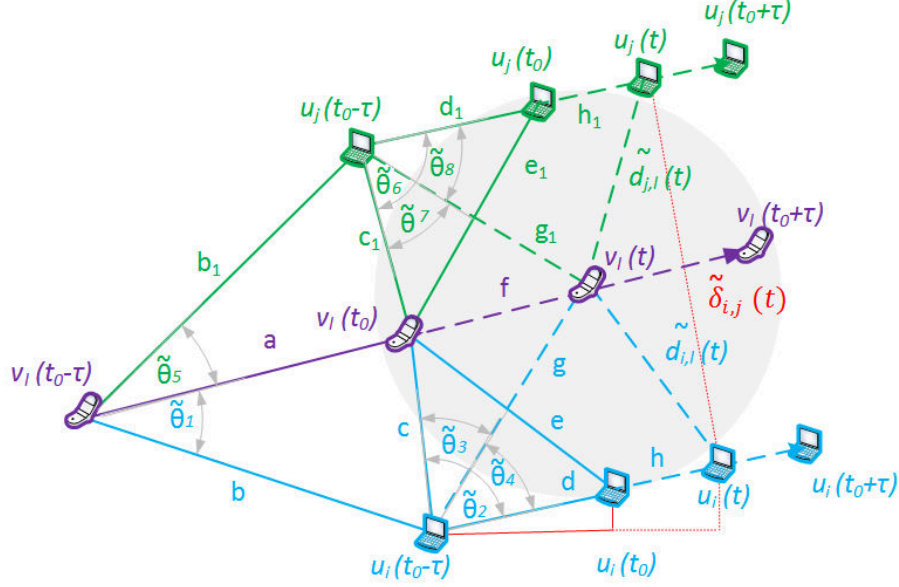


Figure 9: Distance estimation procedure.

8. Acknowledgement

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9. Appendix

9.1. PU-CU Distance Estimation and Connection to Channel Availability

At time $t_0 = n\tau$, CUs u_i and u_j estimate the trajectory of PU v_l for the time interval $[t_0, t_0 + \tau)$ by exploiting to locations of these PU and CUs at time instant $t_0 - \tau$ and t_0 and assuming that the PU does not change its direction in this interval. This assumption is reasonable because of the considered mobility model (RWMP) and the small value of the LUP τ [1].

The distance estimation procedure at time $t \in [t_0, t_0 + \tau)$ is depicted in Fig. 9. At time t , u_i estimates $\tilde{d}_{i,l}(t)$ by applying the law of cosine to the $\triangle$: $u_i(t_0 - \tau)$, $u_i(t)$ and $v_l(t)$, i.e.,

$$\tilde{d}_{i,l}(t) = \sqrt{g^2 + (d + h)^2 - 2g(d + h) \cos(\theta_4)} \quad (15)$$

where

- g can be achieved by applying the law of cosine to the $\triangle$: $u_i(t_0 - \tau)$, $v_l(t)$ and $v_l(t_0 - \tau)$, i.e.,

$$g = \sqrt{(a + f)^2 + (b)^2 - 2(a + f)b \cos(\theta_1)} \quad (16)$$

where $\theta_1 = \cos^{-1}(\frac{a^2 + b^2 - c^2}{2ab})$ and $f = a(t - t_0)/\tau$;

- $h = d(t - t_0)/\tau$;
- $\theta_4 = \theta_2 - \theta_3$ where θ_2 and θ_3 can be acquired from the $\triangle$: $u_i(t_0 - \tau)$, $v_l(t_0)$ and $u_i(t_0)$ as well as the $\triangle$: $u_i(t_0 - \tau)$, $v_l(t_0)$ and $v_l(t)$, respectively;
- a , b , c , d , and e can be directly calculated using the locations information.

At time t , u_j estimates $\tilde{d}_{j,l}(t)$ by applying the law of cosine to the $\triangle$: $u_j(t_0 - \tau)$, $u_j(t)$ and $v_l(t)$, i.e.,

$$\tilde{d}_{j,l}(t) = \sqrt{g_1^2 + (d_1 + h_1)^2 - 2g_1(d_1 + h_1) \cos(\theta_8)} \quad (17)$$

where a_1 , b_1 , c_1 , d_1 , e_1 , f_1 , g_1 , h_1 and θ_8 can be obtained using similar steps to compute g , h and θ_4 , respectively, as outlined for the case of $\tilde{d}_{i,l}(t)$ in equation (15).

After getting the estimated distances $\tilde{d}_{i,l}(t)$ and $\tilde{d}_{j,l}(t)$, if both $\tilde{d}_{i,l}(t) > R_{i,l}$ and $\tilde{d}_{j,l}(t) > R_{j,l}$, then the CUs u_i and u_j can use the channels licensed for the PU v_l since both the CUs are outside the critical range of v_l (i.e., $\tilde{p}_{ij,m,\mathcal{L}}(T_k) = 1$), otherwise, u_i and/or u_j are inside the critical range of PU (i.e., $\tilde{p}_{ij,m,\mathcal{L}}(T_k) = \prod_{l \in \mathcal{L}} P_{l,m}^{off}$). This approach is sensible since it aligns with the policy of minimizing the interference on the PU transmission.

9.2. Distance Estimation between a Pair of CUs

The distance between CUs i and j , i.e., $d_{i,j}(t)$, can be estimated by exploiting the CUs locations at time $t_0 = n\tau$ and $t_0 - \tau$ and assuming that the CUs do not change their direction within the interval $[t_0, t_0 - \tau]$. This is reasonable for the same reasoning as in Appendix 9.1.

From Fig. 9, let us consider that at time t_0 and $t_0 - \tau$, the exact locations of CUs u_i and u_j are given by $(u_i^x(t_0); u_i^y(t_0))$ and $(u_j^x(t_0); u_j^y(t_0))$, and $(u_i^x(t_0 - \tau); u_i^y(t_0 - \tau))$ and $(u_j^x(t_0 - \tau); u_j^y(t_0 - \tau))$, respectively. If we know the two locations of node u_i at two different time instants t_0 and $t_0 - \tau$, we can then draw a Right-Angle-Triangle, as shown in Fig. 9, and obtain the angle between *hypotenuse* and *adjacent* from the following equation, i.e.,

$$\theta_{h,a} = \cos^{-1} \left(\frac{u_i^x(t_0) - u_i^x(t_0 - \tau)}{d} \right). \quad (18)$$

Since we assume that the CUs do not change their direction from $t_0 - \tau$ to $t_0 + \tau$, the new position of the u_i at time t can therefore be estimated as $u_i^x(t)$

$= \cos \theta_{h,a} \times (d + h)$ and $u_i^y(t) = \sin \theta_{h,a} \times (d + h)$. The position of u_j at time t can also be estimated by invoking the same steps. After approximating both the positions of CUs u_i and u_j at time t , the estimate of $d_{i,j}(t)$ can then be obtained by using the following equation

$$\tilde{d}_{i,j}(t) = \sqrt{(u_i^x(t) - u_j^x(t))^2 + (u_i^y(t) - u_j^y(t))^2}. \quad (19)$$

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L-CAQ: Joint link-oriented channel-availability and channel-quality based channel selection for mobile cognitive radio networks

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