RECOG: A Sensing-based Cognitive Radio System with Real-Time Application Support

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***Abstract*—While conventional cognitive radio (CR) system is striving at providing best possible protections for the usage of primary users (PU), little attention has been given to ensure the quality of service (QoS) of applications of secondary users (SU). When load real-time applications over such a CR system, we have found that existing spectrum sensing schemes create a major hurdle for real-time traffic delivery of SU. For example, energy detection based sensing, a widely used technique, requires possibly more than 100 ms to detect a PU with weak signals. The delay is intolerable for real-time applications with stringent QoS requirements, such as voice over internet protocol (VoIP) or live video chat. This delay, along with other delays caused by backup channel searching, channel switching, and possible buffer overflow due to the insertion of sensing periods, makes supporting real-time applications over CR system very difficult if not impossible.**

In this paper, we present the design and implementation of a sensing-based CR system - RECOG, which is able to support realtime communications among SUs. We first redesign the conventional sensing scheme. Without increasing the complexity or trading off the detection performance, we break down a long sensing period into a series of shorter blocks, turning a disruptive long delay into negligible short delays. To enhance the sensing capability as well as better protect the QoS of SU traffic, we also incorporate an on-demand sensing scheme based on MAC layer information. In addition, to ensure a fast and reliable switching when PU returns, we integrate an efficient backup channel scanning and searching component in our system. Finally, to overcome a potential buffer overflow, we propose a CR-aware QoS manager. Our extensive experimental evaluations validate that RECOG can not only support realtime traffic among SUs with high quality, but also improve protections for PUs.

***Index Terms*—Wireless cognitive radio networks, QoS, VoIP, Wireless streaming, Measurement, Testbed, Software defined radio (SDR).**

I. Introduction

Cognitive radio (CR) systems and networks are expected to become available for commercial use in the next few years. Multiple technologies such as WiFi over Whitespace [1], and standards such as 802.22 [2] and ECMA392 [3] have targeted infrastructure-based CR systems where Access Points (or Base Stations) provide opportunistic connectivity to secondary users (SU) over the primary user (PU) licensed spectrum.

Realtime applications such as VoIP, live video streaming, and video-chat services over cellular networks have become prevalent. Traditional realtime applications over such networks are designed and implemented presumably for licensed users. Recently, realtime applications for SUs have gained increasing interest. For example, extension of long term evolution (LTE) operational mode over TV white space is expected to support realtime communication among LTE clients [4], and realtime visualized location service is listed as a priority for National Emergency Number Association for its next generation public safety architecture that is expected to support opportunistic spectrum usage [5]. It is therefore important to consider supporting such traffic over CR systems.

Secondary access to license spectrum requires SUs to adhere to certain rules for incumbent protection to avoid interference to PUs. For example, if PU is present on a channel currently used by SU, *spectrum evacuation* is performed where SU leaves the current channel. Geo-location database and spectrum sensing are the two most popular approaches for incumbent protection. The former requires SUs to have geo-location capabilities, and meanwhile requires the database to have updated information for the statuses of primary channels. Such requirements are not realistic when SUs are located in indoor and/or PU activities are relatively dynamic. Therefore, we consider spectrum sensing as the mechanism used for incumbent protection in our work[1].

In general, spectrum sensing needs to be supported by an appropriate media access control (MAC) structure at a SU where sensing periods need to be interleaved within a sequence of transmission periods. Sensing period is the time period reserved for sensing the presence of PU without any local transmissions at SU. Standards that allow for spectrum sensing such as 802.22 and ECMA392 support this MAC structure.

In this paper, we focus on satisfying QoS requirements of VoIP over CR since if the system is capable of supporting VoIP, other realtime applications with less stringent quality of service (QoS) demands can be readily supported (experimental results for live video streaming are also presented in Section §V). Supporting VoIP over a CR MAC with periodic

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[1]At this time, it is unclear if a method based on incumbent database access would enable fast spectrum mobility required to support realtime applications at SUs.

sensing period/transmission period entails the following observations and challenges:

First, the length of a sensing period has to be large enough (to collect enough signal samples) to detect the presence of a PU with the required (high) reliability; at the same time, a long sensing period means delaying as well as shrinking the following transmission period, assuming a fixed sensing/transmission period structure, which lead to unacceptable delay and jitter for SU (realtime) traffic.

One question is what should be the choice of sensing algorithms to achieve desired balance between PU protection and SU QoS requirement. Energy detection has been traditionally considered a technique of choice for spectrum sensing due to its simplicity and the fact that no deterministic knowledge of PU signals is needed. However, to meet stringent requirements for protecting PU, energy detection requires a long sensing period for reasonably small signal-to-noise ratios (SNRs), at which it is often difficult or even infeasible to support VoIP (shown in Section §II-B). Second, when a PU's presence is identified during a sensing period, switching SUs to a new unoccupied channel from the current channel, called *spectrum mobility*, should be performed in a fast and accurate fashion in order to avoid an interruption to SU traffic. Impromptu switching may result in switching time far beyond the delay/jitter requirements of VoIP and/or other realtime applications. What mechanism should the system have for enabling seamless spectrum mobility? Third, even if the sensing period is small enough that the subsequent transmission period is not delayed enough to affect SU traffic, as we show later, it may still lead to buffer overflow at SU. This will have an adverse effect on this traffic.

Based on the above observations and associated technical challenges, we design and implement an end-to-end sensing-based CR system (which we refer to as RECOG) on a software defined radio (SDR) platform. In what follows, we summarize our main contributions.

Main contributions

1) We identify key challenges in supporting real-time applications over a CR system with an interleaved sensing/transmission period structure. Along with many other problems, fundamentally, the insertion of long sensing periods makes it very difficult to satisfy the stringent QoS requirements of real-time applications for CR systems.
2) We integrate spectrum sensing, on-demand sensing, backup channel scanning/searching, and a CR-aware QoS manager seamlessly into a full-fledged system design. We implement the proposed system design into a fully-functional prototype on a SDR platform, that can run real-time applications such as VoIP, live video streaming (evaluation results in Section §V), interactive video conference and video chat (video demo in Section §VI). To the best of our knowledge, RECOG is the first system to demonstrate the feasibility of supporting real-time applications over a CR system for SUs.
3) We conduct extensive experiments to evaluate the prototype system. Our experimental results reveal that compared with existing solutions, RECOG decreases the PU detection speed by 60% in a low SNR region, reduces channel searching delay by one order of magnitude, and improves the performance of real-time applications significantly across a variety of wireless scenarios.

II. Background and Motivation

In this section, we first introduce the VoIP QoS requirements, then describe the assessment of VoIP quality and finally explain the challenges of enabling a CR system to supports VoIP.

A. Incumbent Protection

As mentioned earlier, geo-location database and spectrum sensing are the two popular approaches for incumbent protection. Due to the fact that spectrum sensing is not mature enough for commercial use at the current stage, the recent ruling by Federal Communications Commission (FCC) only enforces the geo-location database approach for incumbent protection over TV white space (TVWS). Since PU activities over TVWS are very static, the database does not need frequent updates. As long as SUs have geo-location capacities, the database approach is feasible for TVWS. In this study, we are, however, not restricted to TVWS. We consider application scenarios, in which SUs may not have geo-location capabilities or PU activities are relatively dynamic. In such cases, the database approach is no longer feasible and spectrum sensing becomes an essential means for incumbent protection.

B. VoIP QoS Requirements and Assessment

R-Score: To measure the quality of a VoIP call, a model called the E-Model is normally used [6]. This model takes into account mouth-to-ear delay, loss rate, and the type of the vocoder. VoIP quality is measured by the *R-Score* [7], a scalar measure provided by the E-model that ranges from 0 (poor) to 100 (excellent) where acceptable quality is considered to be more than 70.

QoS Requirements: To provide an acceptable voice quality for VoIP, the following requirements need to be considered: **a)** *Delay sensitivity*: Non-realtime traffic can tolerate delays of a few seconds without impairing user experience. In contrast, VoIP traffic can only tolerate an end-to-end delay of up to 100 ms. **b)** *Jitter sensitivity:* If the jitter is large enough to cause packets to be received after their playout time, these packets are discarded, and thus perceived voice quality is degraded. **c)** *Loss sensitivity:* VoIP traffic is particularly sensitive to frame loss. For example, given the same delay of less than 100 ms, 5% packet loss can downgrades R-Score from 80 to 70. More than 5% of packet loss will make the quality of a VoIP flow unacceptable.

C. Challenges in supporting VoIP

To illustrate the challenges faced, we conduct two sets of experiments on our SDR platform. The first set demonstrates that low PU SNRs (although the SNR is still well above the 802.22 standards requirements for detection) require a long sensing time with conventional energy detection schemes. The second set follows this up and considers VoIP quality in the presence of these long sensing time. We prototype a CR system on the WARP platform, and use a USRP node to emulate a PU, both of which are operated over 5 GHz ISM band to avoid interference. For the detailed CR MAC and system configurations, please refer to Section §IV-B and Section §V-A respectively.

Minimum sensing period versus target SNR: We consider the well-known energy detection based spectrum sensing algorithm. We present results from this study to motivate the fact that energy detector, if used to sense a PU's signal at low SNR, leads to a long sensing time.

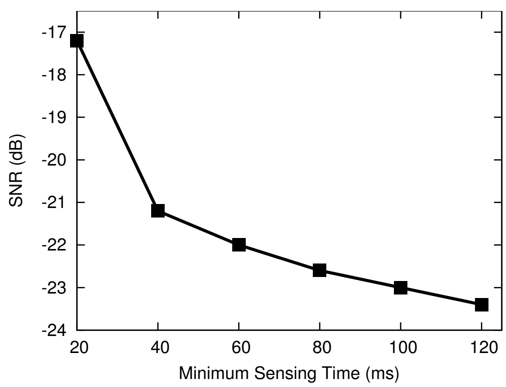
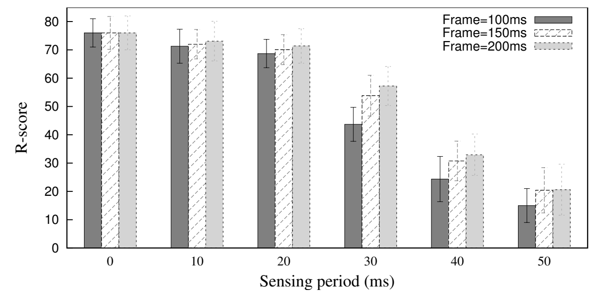


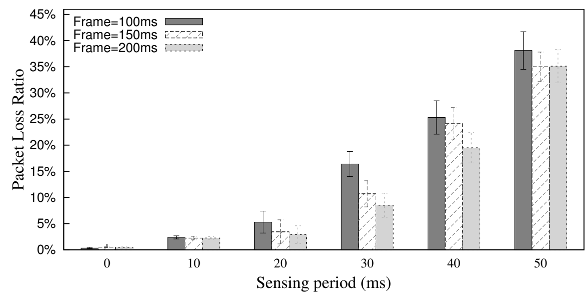
Fig. 1. Minimum required sensing time for energy detection based on experiments.

Figure 1 depicts the minimum required length of sensing period vs. different SNR values for energy detection. The longer the sensing period is, the more samples a CR system collects. Thus the mis-detection probability will be small. For each sensing period, we also change the PU transmit power. For a target mis-detection probability of less than 10% and false-alarm probability of less than 10%, we evaluate how low the detectable target SNR can be decreased. We conclude that at a low SNR level, the required length of a sensing period increases dramatically when the SNR decreases. The measurement results are consistent with theoretical findings.

Sensing period versus VoIP performance: Figure 2 illustrates the relationship between the length of a sensing period and the quality of VoIP in terms of R-score. We first explain the experiment setup. In this experimentation, VoIP traffic is generated via the Distributed Internet Traffic Generator (D-ITG) [6] according to the G.729a vocoder (commonly used in wireless VoIP clients). We also implement a VoIP quality analyzer to interpret the output from D-ITG, which allows us to estimate the R-Score, delay and packet loss ratio. Each packet from a G.729a vocoder is sent every 20 ms per VoIP call, i.e., 50 packets/second.



(a) VoIP R-score vs. length of a sensing period



(b) VoIP packet loss ratio vs. length of a sensing period

Fig. 2. Impact of sensing periods on VoIP performance.

We use a 100 ms playout buffer. In addition, we vary the total frame length to test the performance. The average R-Score and packet loss ratio for 15 VoIP calls are calculated to evaluate the voice quality. The error bar shows 95% confidence interval. The average delay is slightly less than 70 ms, thus has negligible impacts.

We have made the following observations. 1) As the length of a sensing period increases from 0 to 50 ms, the VoIP performance decreases dramatically, particularly when the length of a sensing period exceeds 30 ms. 2) A small increase in the length of a sensing period incurs dramatic packet loss due to buffer overflow, which is a major cause of R-Score reduction. VoIP flow is small in packet size, but comes with a large quantities, thus easily exhaust available buffers with a reasonable long delay. 3) One key observation from this test is that quality degradation has less to do with the ratio of the length of a sensing period over the frame length, but has more to do with the actual length of a sensing period. The frame length also has impact on VoIP performance, because sensing periods interrupt VoIP less frequently with a longer frame length. For instance, three cases 20/100, 30/150 and 40/200 in Figure 2, all of which have the same ratio but different lengths of sensing periods, have considerably different R-scores and packet loss ratios. We also conduct similar experiments for live streaming, and conclude with the same observations. For space limit, we omit the results here.

III. Design of RECOG

This section describes the design of RECOG, a CR system that supports VoIP and/or other realtime applications with good QoS at SUs.

A. In-Band Sensing Algorithms

We call the channel where SUs are currently operating, in-band channel. In-band sensing is referred as to the process of detecting the status (free or occupied) of the in-band channel. The goal of in-band sensing is to distinguish between the following two hypotheses: H_0 (PU absence): $y_i = w_i,\ i = 1, 2, \ldots$, and H_1 (PU presence): $y_i = s_i + w_i,\ i = 1, 2, \ldots$, where y_i is the ith received signal samples at SU, w_i is the ith noise sample, and s_i is the ith faded primary signal sample. In this work, we assume that the fading coefficient remains fixed for the entire sensing process.

Most existing research in spectrum sensing has primarily focused on protecting PUs. The issue of how spectrum sensing impacts the QoS of realtime applications at SUs, has not been well-studied. As clear from Figure 2, in-band sensing algorithm with a short sensing period is preferred from a secondary QoS perspective. However, a short sensing period often leads to a poor sensing accuracy, especially at low SNR. It is of practical importance to develop an in-band sensing algorithm that achieves a desirable balance between PU protection and SU QoS.

Energy detection is the most popular in-band sensing algorithm, primarily due to the fact that it has low implementation complexity and does not require any deterministic knowledge of PU signals. In energy detection, the energy of received signal samples collected within a sensing period is first computed and then is compared with a predetermined threshold at the end of each sensing period. Mathematically, the testing procedure can be described as:

$$T_e = \frac{1}{N}\sum_{i=1}^{N} |y_i|^2 \underset{H_0}{\overset{H_1}{\gtreqless}} \lambda \tag{1}$$

where T_e and λ denote the test statistic and the threshold for energy detection, respectively, and N is the number of samples collected in a sensing period. The parameters N and λ are determined by target false-alarm and mis-detection probabilities. One major drawback in energy detection is that it requires a large sensing period at a low SNR level and thus has difficulty in complying with the requirements to support realtime applications.

To overcome this drawback, a multi-interval energy detection (M-ED) algorithm has been proposed [8]. In M-ED, the length of a sensing period is chosen to be much smaller than that in the original energy detection. To achieve the same detection performance as energy detection, M-ED needs to collect received signal samples over multiple sensing periods separated by transmission periods. Since the decision is always made after a fixed number of sensing and transmission periods, M-ED introduces much longer interference to PUs as compared with the original energy detection, which may potentially lead to a poor PU protection.

To alleviate this adverse effect, we propose to use a simple sequential spectrum sensing algorithm that is capable of achieving desirable balance between PU protection and secondary QoS. The idea is to not only break a long sensing period into a shorter blocks, but also compare with the two thresholds, instead of one threshold, at the end of *each* short period. The scheme is derived from a well developed statistical theory - sequential shifted chi-square test (SSCT), and thus is termed as B-SSCT since it is block-based.

The test statistic at the pth block is computed as follows:

$$\Xi_p = \sum_{i=1}^{P\times L} \left(|y_i|^2 - \Delta\right),\ p = 1, 2, \ldots \tag{2}$$

where Δ is a predetermined constant, p is the sensing period index, L is the number samples collected within a sensing period, and P is the maximum allowable number of sensing periods. The testing procedure in B-SSCT is given as

Reject H_0 :
if $\Xi_p \geq b$ and $p \leq P-1$ OR if $\Xi_P \geq c$ and $p = P$;
Accept H_0 :
if $\Xi_p \leq a$ and $p \leq P-1$ OR if $\Xi_P < c$ and $p = P$;
Continue Sensing :
if $\Xi_p \in (a, b)$ and $p \leq P-1$

where a, b, and c are three predetermined thresholds with $a < 0$, $b > 0$, and $a < c < b$, and P is the maximum block number of the test. These parameters can be selected beforehand, as we will show in Section §IV-C.

Like M-ED, B-SSCT uses short sensing periods to enable realtime SU traffic. The key difference between B-SSCT and M-ED is that in M-ED, decision is always made at the end of the last sensing period, while in B-SSCT, decision can be made at the end of any sensing period.

B. Cross-Layer On-Demand Sensing

In IEEE 802.22 and ECMA 392, a secondary system is allowed to use adaptive scheduling of sensing periods to balance secondary QoS and PU protection. Such functionality is named *on-demand sensing* in ECMA 392, but it does not stipulate when and how on-demand sensing should be used. Besides regular in-band sensing mechanism, an on-demand sensing functionality that uses the information of MAC-layer is included in our system to increase PU protection.

In our system, we require only access points (AP) to have sensing capability while clients do not need that capability, mainly because in practice it is desirable to simplify client side design and keep it backward compatible. In the scenario where a PU is located outside of regular sensing coverage of AP but is quite close to clients, PHY-layer regular sensing algorithms performed by AP may require more samples to achieve a certain sensing accuracy within a required time frame. Since SU traffic will be interfered by the PU instantly, certain abnormal behaviors at the MAC-layer such as a sudden increase in retransmissions or timeout packets can be observed at AP quickly. After observing these abnormal behavior, an on-demand sensing mechanism can be triggered by increasing the length of a sensing period and/or the frequency of sensing periods.

At MAC-layer, there are several performance metrics such as throughput, outgoing queue length, average retransmission times and packet delivery ratio. Throughput can be an accurate metric reflecting channel quality only if the link is always saturated. If the link is under-loaded, then throughput of the network will not be affected by a short term fluctuation in channel quality. Also outgoing queue is insensitive to channel fluctuations in a short time frame. Packet delivery ratio, on the other hand, can show how many packets are successfully received by an SU. If the client of SU is overwhelmed by primary transmissions, it is likely to lose some packets from AP. The average number of retransmissions can be converted to packet delivery ratio, and is thus an equivalent metric. We therefore use a window based packet delivery ratio to infer the current network performance.

As a long delay degrades the performance of secondary networks, inserting an arbitrary long sensing period is usually not desirable. But if secondary network has already suffered from serious packet loss and its performance has degraded to an unacceptable level, inserting large sensing periods will not have much impacts on the performance. The detailed procedure of choosing the right length of a sensing period can be found in Section §IV-C.

Briefly, on-demand sensing works as follows. Every a few hundred of packet transmissions, the packet delivery ratio is recalculated based on the number of packets being acknowledged. If, compared with the most recent calculation, a *significant* drop is observed yet sensing at PHY does not seem to detect anything, it is reasonable to insert additional sensing time. In case the packet delivery ratio decreases gradually, the instantaneous delivery ratio is also of our interests. As a rule of thumb, the delivery ratio is calculated every 500 packets; if the ratio drops more than 20 percentage points or the absolute delivery ratio is less than 50%, on-demand sensing is triggered.

C. Backup Channel Scanning/Searching

Upon return of PUs, SU is required to evacuate from its current operational channel within a short amount of time. To maintain QoS at SU, SU needs to quickly and accurately locate a backup channel. Typically, the search for a backup channel consumes non-trivial time, particularly when both the number of candidate channels and the channel occupation probability are large. Traditional algorithm senses candidate channel one by one and removes channel with fine sensing results. If the search starts right after detecting the return of PUs, secondary network may experience a long delay and thus suffer from substantial degradation.

To cope with this problem, we search the backup channel *progressively*. Based on the samples collected within a short sensing period, it is difficult to make an accurate decision. Nevertheless, roughly a channel with a higher received signal level is more likely to be occupied by a PU. The observation helps us remove the channels that have high probability of being occupied while maintaining a subset of channels that have high probability of being accessible. This way, it reserves precious sensing resources for the most promising channels.

Specifically, the progressive searching algorithm works as follows. First, It needs to sense candidate channels for the same amount of time, but spends shorter time on each of them, compared to the traditional approach. After each round of sensing, it sorts the channels by the summation of collected signal strength of individual channel. It then eliminates one fourth of channels, and remains the rest for further sensing. The process is repeated until three channels are left. Finally, a fine grained sensing on each of channels can help make an accurate decision, based on which the backup channel is finally decided.

Normally, the backup channel searching can be conducted in parallel with regular data transmissions (by a dedicated sensing radio), but that does not guarantee the availability of backup channels. If, in a worse case, previous backup channel list is just expired and PU is presents, the progressive searching will dramatically reduce the searching overhead when the candidate pool is large, and it outperforms the traditional searching for its promptness and accuracy.

D. CR-Aware QoS Manager

Just as other infrastructure-based networks, our system consists of two links. AP and SUs communicate over wireless, and backhaul links connect secondary access router and Internet. Since the data rate of the backhaul link is usually higher than that of wireless, the downstream traffic is likely to be buffered at AP. Buffer overflow may happen at AP due to 1) drastic short-term variations over wireless channels, 2) periodic silence periods for spectrum sensing and 3) channel evacuation. The first phenomenon is prevalent in almost all wireless networks. The second and the third however, are unique to CR systems. AP needs to buffer all incoming packets during sensing periods. Since generic off-the-shelf APs only have buffer ranging from a few to a few dozen packets, it will be challenging to support traffic such as VoIP packets, where each packet is small but the total number of packets is large. The situation is even worse when the traffic becomes bursty and is mixed with other traffic.

One intuitive solution will be to enable a large buffer size at the AP. However, central control architectures with a thin-AP approach have gained popularity for efficient radio resource management in 3G cellular systems, WLANs or base stations because APs play the limited role of physical transmitting receiving with some simple functions. Access routers, typically, manage most of radio resources including buffer management.

It is easier to buffer downstream packets at access routers, since they are usually equipped with a large buffer that would otherwise be given to its subordinate APs. The benefit also lies in its flexibility. The router has more resources to deal with special cases when traffic destined to one particular AP is bursty, or when long sensing period or on-demand sensing period is required to extended. It is then crucial to control the rate between the router and the AP. The rate should not be too high as it will cause the buffer overflow at the AP, nor should it be too low as that will starve AP and induce unnecessary delays.

Briefly, the proposed scheme works as follows. During transmission periods, AP periodically measures its queue

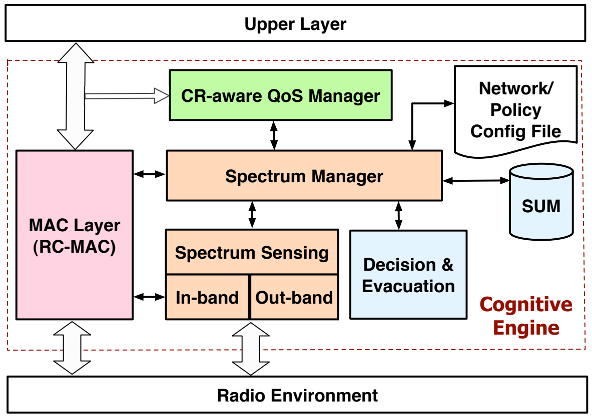


Fig. 3. RECOG system architecture.

status and sends feedback to its access router. The router buffers the downstream traffic and then deliver to AP at a rate based on the feedback. When AP enters to a sensing period, it sends feedback to the router to pause the data transmission temporarily, and will resume once it returns to transmission phase. Such a CR-aware QoS manager has been included in our system.

IV. Implementation of RECOG

We prototype the RECOG system with WARP, a SDR platform [9]. In this section, we describe some relevant implementation details.

A. System Overview

Figure 3 shows a simplified block diagram of the RECOG system. The cognitive engine is the heart of the CR system. The spectrum manager not only monitors the in-band channel for PU detection but also controls searching for and switching to a backup channel. Implicitly, the cross-layer sensing scheme is also embedded in the in-band sensing module. The QoS manager keeps track of the queue information at MAC layer and continuously controls the packet delivery rate.

B. Cognitive Radio MAC

The realtime cognitive radio MAC protocol is a standard compliant MAC protocol which allows APs to sense licensed bands either periodically during the sensing periods or dynamically based on the needs. It is an overlay cognitive radio MAC that works on top of CSMA/CA MAC. Figure 4 shows the MAC frame structure, which consists of beacon period (**B**), transmission period (**TxP**) and sensing period (**SP**). During beacon periods, the AP periodically broadcasts two types of messages: (i) routine message such as length of SP and TxP, backup channel list, and (ii) evacuation message when PU is present.

C. Selecting Parameters for In-Band Sensing

In a real environment, selecting design parameters such as sample size and thresholds for energy detection and B-SSCT is fairly challenging. This is primarily because the theoretical approaches to determining these parameters rely on assumptions that are often invalid in a real environment. As an example, we find that experimental results barely match with theoretical results that are obtained using the i.i.d. assumption of noise samples. We adopt values of received signal strength indicator (RSSI) in our signal model since RSSI is a linear function of received signal powers. As the first step of our implementation, we first validate our RSSI signal model.

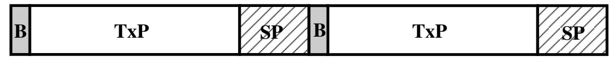


Fig. 4. RECOG MAC frame structure: B - beacon period; TxP - transmission period; SP - sensing period.

RSSI Signal Model Validation: To validate RSSI signal models, we first implement energy detection in a real environment for the purpose of comparison. Let R_i be the RSSI value for the ith received signal sample. We replace $|y_i|^2$ in (1) with R_i. According to the central limit theorem (CLT)[2], the PDF of T_e under H_0 can be well approximated as $T_e|H_0 \sim \mathcal{N}(\mu_{e0}, \sigma_{e0}^2)$, for a relatively large N, where μ_{e0} and σ_{e0} denote the mean and standard deviation of T_e under H_0, respectively. For any given target false-alarm probability $\bar{P}_{FA}$, the threshold λ for energy detection is determined as

$$\lambda = Q^{-1}(\bar{P}_{FA})\sigma_{e0} + \mu_{e0} \tag{3}$$

where $Q(\cdot)$ denotes the complementary distribution function of the standard Gaussian random variable. The false alarm probability P_{FA} can be computed as

$$P_{FA} = Q\left((\lambda - \mu_{e0})/\sigma_{e0}\right). \tag{4}$$

Using the mean value of RSSI, we define SNR as $\xi := (\mu_{e1} - \mu_{e0})/\mu_{e0}$. For any given $\bar{P}_{MD}$ and ξ, the target variance of PU signals needs to satisfy

$$\sigma_{e1} \leq \frac{Q^{-1}(\bar{P}_{FA})\sigma_{e0} - \xi\mu_{e0}}{Q^{-1}(1 - \bar{P}_{MD})}. \tag{5}$$

As illustrated in Figure 5, the target standard deviation σ_{e1} of PU signals decreases as the sample size N increases. The relationship between σ_{e1} and N can be obtained during a training phase. Using the σ_{e1}-N relationship depicted in Figure 5, we can determine the minimum value of N such that (5) is satisfied. The corresponding mis-detection P_{MD} can be evaluated as

$$P_{MD} = 1 - Q\left((\lambda - \mu_{e1})/\sigma_{e1}\right). \tag{6}$$

At this point, we are ready to summarize the design procedure for energy detection:
1) measure μ_{e0} and σ_{e0} of noise;
2) input target false alarm probability $\bar{P}_{FA}$, target mis-detection probability $\bar{P}_{MD}$, and ξ;
3) determine the threshold λ using (3);
4) compute the upper bound on σ_{e1}^2 in (5);
5) determine the minimum N such that Eqn. (5) is met using Figure 5.

[2]The RSSI values are approximately treated as independent as a low sampling rate is adopted in our experimentation. The generalized CLT is applicable to independent samples with certain regularity conditions.

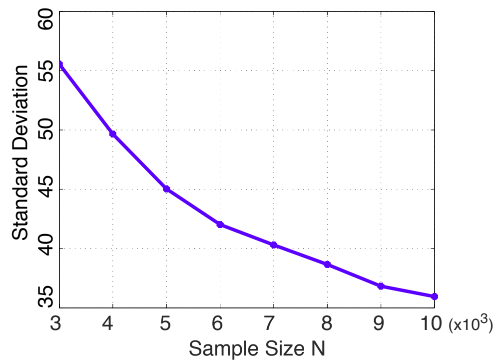


Fig. 5. RSSI Variances versus Sample Size N.

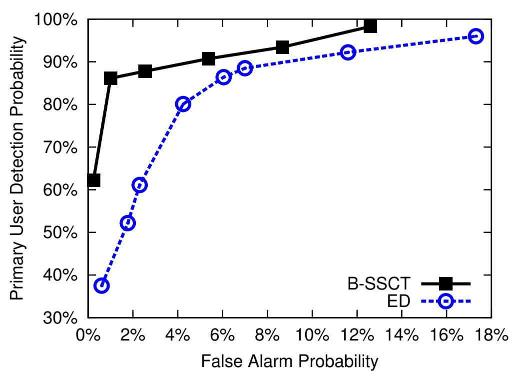


Fig. 6. ROC Performance: B-SSCT versus Energy Detection.

Table I compares detection error probabilities P_{FA} and P_{MD} obtained by numerical calculations and experimentations for $N = 7000$. In the table, numerical results of P_{FA} and P_{MD}, which are indicated by "NUM" in parenthesis, are obtained by (4) and (6), respectively, and experimental results indicated by "EXP" are obtained by experimentation using our RECOG test-bed. As can be seen from the table, experimental results match well with numerical results.

B-SSCT Implementation: In [10], a recursive numerical algorithm was proposed to compute P_{FA}, P_{MD}, and the average block number (ABN). Similar to the energy detection case, this algorithm still relies on the i.i.d. assumption of noise samples. Let μ_{b0} and μ_{b1} denote the mean of Ξ_1 under H_0 and H_1, respectively. Let σ_{b0}^2 and σ_{b1}^2 denote the variance of Ξ_1 under H_0 and H_1, respectively. Based on CLT, we can approximate the distribution of Ξ_0 and Ξ_1 as

$$\Xi_1|H_0 \sim \mathcal{N}(\mu_{b0}, \sigma_{b0}^2) \text{ and } \Xi_1|H_1 \sim \mathcal{N}(\mu_{b1}, \sigma_{b1}^2). \quad (7)$$

Table II compares detection error probabilities and ABN obtained by Monte-Carlo simulation indicated by "SIM"

TABLE I
P_{FA} AND P_{MD} COMPARISONS (ENERGY DETECTION)

P_{FA} (%) (NUM)	1	5	10	15	20
P_{FA} (%) (EXP)	0.99	4.96	10.1	15.1	20.1
P_{MD} (%) (NUM)	1	5	10	15	20
P_{MD} (%) (EXP)	1.21	4.55	10.5	15.2	20.1

TABLE II
P_{FA}, P_{MD} AND ABN COMPARISONS (B-SSCT)

P_{FA} (%) (SIM)	0.96	4.57	10.4	15.1	20.0
P_{FA} (%) (EXP)	1.68	4.98	10.5	15.2	20.1
P_{MD} (%) (SIM)	1.67	6.61	12.8	17.6	22.2
P_{MD} (%) (EXP)	4.79	7.76	12.9	17.4	22.1
ABN_0 (SIM)	5.84	2.79	1.83	1.41	1.12
ABN_0 (EXP)	5.72	2.70	1.82	1.40	1.16
ABN_1 (SIM)	5.87	2.76	1.79	1.39	1.11
ABN_1 (EXP)	5.52	2.79	1.80	1.40	1.17

and experimentation for $L = 7000$. In Table II, ABN_0 and ABN_1 denote ABN under H_0 and H_1, respectively. In our comparison, we first measure μ_{b0}, μ_{b1}, σ_{b0}^2, and σ_{b1}^2 in a real environment in our training phrase. The parameter Δ is selected as $(\mu_{b0} + \mu_{b1})/(2L)$ as suggested in [10]. With these parameters, we use Monte-Carlo simulation to select appropriate thresholds a, b, c, block size L, and the truncated block number P in B-SSCT using approximation (7). Using the design parameters obtained from our simulation, we perform experimentation in a real environment. As clear from these two tables, experiment results match well with simulation results when target P_{FA} and P_{MD} are not too small.

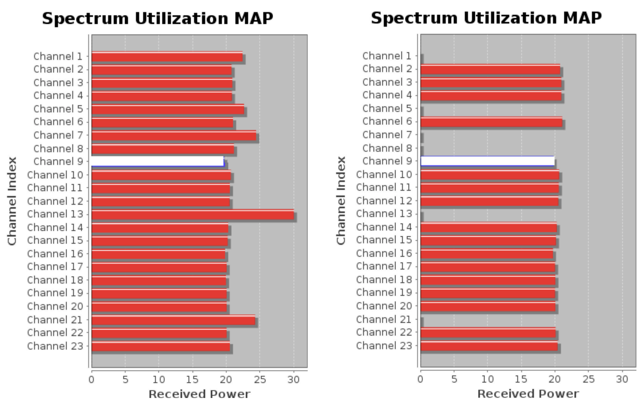
D. Searching Backup Channels

Like many other CR systems [11] [12], only AP is equipped with two radio interfaces. One is dedicated for continuous channel monitoring, and the other is used for regular data transmissions. To demonstrate the process, we develop a graphic user interface (GUI) to show real-time spectrum utilizations as well as the elimination process. Due to the space limit, we show one example of the first two stages of progressive sensing in Figure 7. X-axis indicates the strength of received signals from each channel, and Y-axis shows the number of all candidate channels. The stronger the received signal is, the less likely it is accessible. The channel with least signal strength (the most promising channel) is highlighted with a light color.

Figure 7 (a) shows the sensing results for the first round. It is easy to see that channels 13 and 21 that receive the strongest signals should be remove for the next stage (along with channel 1, 5, 7, 8), as shown in Figure 7 (b). The elimination process is repeated until only a small set of candidate channels are obtained. The final decision can be made based on a thorough sensing results on each of them. Given the number of candidate channels, sensing time allocated to each channel is about 4 ms, which is far away from enough for accurate detections.

E. Implementing CR-Aware QoS Manager

The access router (emulated by a standard dual-core Linux machine) is connected to the AP (on a WARP board) via backhaul link (emulated by a 100 Mbps ethernet link). The CR-aware QoS manager in *ReCog* system is comprised of two components: a feedback reporter at the AP; a CR-aware rate controller at the access router. We implement a



(a) PG-Sensing - 1st stage. (b) PG-Sensing - 2nd stage.

Fig. 7. Operations of Progressive Sensing.

feedback reporter at AP to provide information about the buffer usage as well as packet drop ratio due to buffer overflow. We also implement a CR-aware rate controller on the access router using the Click Modular Router Framework [13] as a user-level module that intercepts all data packets to AP. The CR-aware rate controller listens on a control socket for messages from the feedback reporter.

V. Evaluation

We now evaluate the performance benefits offered by RECOG in detail. We design many scenarios to evaluate to these components. Since we will show that B-SSCT supports VoIP with good QoS in Section §VI, we now only focus on the performance of B-SSCT for PU protection. Although on-demand sensing is an enhancement to regular PU protection, our interest is mainly on how it can benefit the QoS of SUs. Backup channel scanning/searching is helpful only when a SU switches to a new channel, and ideally it should be oblivious to real-time applications. Hence, we characterize its impact during channel switching. In general, the CR aware QoS manager improves the delivery capability of RECOG. We show how it can improve QoS at SU and save buffer size.

A. Experimental Configurations

System properties: We use the WARP SDR platform, where one node serves as an AP and the other serves as a client. PU is emulated by a USRP GNU Radio. Due to the limitations of WARP hardware, we conduct all of our experiments over the 5GHz ISM band. But the proposed schemes and algorithms can be readily applied to other bands such as TV white spaces. Our design is based on OFDM reference design v16.1, which loosely follows IEEE 802.11 with an OFDM PHY layer and CSMA/CA MAC layer, but is operated over a 10 MHz band instead of a regular 20 MHz band. Our CR MAC sits on top of the CSMA/CA MAC.

Spectrum sensing: Generally speaking, sensing performance is characterized by false alarm and mis-detection probabilities, and sensing time. For example, in the 802.22 standard, at an SNR of -116 dBm, digital television signals should be detected with at most 10% false-alarm probability and 10% mis-detection probability, and the entire detection process should complete within 2 seconds [14].

In our experiments, instead of using sensing receiver sensitivity measured by dBm, we use a received SNR at the sensor. The received SNR is calculated by a ratio of two RSSI values, in the unit of dB. The denominator in the ratio measures the noise level when no PU is present, and the numerator in the ratio measures the signal strength when PU presents.

VoIP content: Similar to the settings in Section §II-B, VoIP traffic is generated according to G.729 vocoder every 20 ms. To measure delay/jitter, AP and clients are synchronized through a separate 802.11g link. Each round of VoIP testing lasts around 60 seconds. Fifteen VoIP calls are supported between telephony users bidirectionally, if not stated otherwise.

Video content: We use two standard video clips, called Soccer and Ice, to test RECOG, which are encoded to MPEG-4 format by using *ffmpeg* tool. The rates of encoded video are 1264 kbps and 706 kbps, respectively, and the frame rate is 30 frames per second. A playout buffer of 1 second at the receiver is introduced. Each video is looped three times to get a playback length of 30 seconds. We use *VLC* to stream video clips.

Performance metrics: Quality of VoIP is evaluated by R-score, as explained in Section §II-B. Quality of video is measured by another widely used metric - peak signal to noise ratio (PSNR). The PSNR of a video clip is converted to a mean option score (MOS), a subjective metric for the video quality perceived by users. Generally, PSNR greater than 37 is considered excellent, and PSNR below 25 is considered poor [15]. All results are calculated based on the average over multiple trials, and error bar shows a 95% confidence interval.

Scheme comparisons: We compare RECOG with a primitive CR system (abbreviated as Trad.) that uses energy detection for in-band sensing and does not have any intelligent components such as backup channel scanning and searching, on-demand sensing and a CR-aware QoS manger.

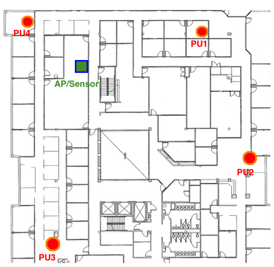
B. Experimental Results

In this section, we show how RECOG improves the QoS of real-time applications in different aspects: 1) advantages in PU detection accuracy and speed when compared to energy detection based sensing schemes; 2) performance gains in supporting real-time services by opportunistically detecting PUs out of the regular sensing area; 3) negligible interruption time when RECOG searches and switches to a backup channel; and 4) substantially reduced buffer size.

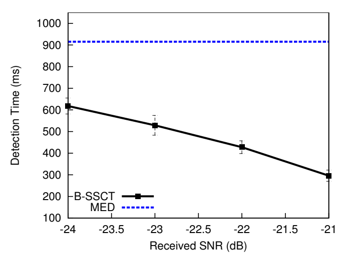
Detection Accuracy - B-SSCT vs. ED: To be consistent with standard measurement techniques, we use mis-detection probability, false-alarm probability, and detection time to quantify the results at a given SNR. To get a benchmark of detection performance, we generate complex sinusoid signals from a PU (an USRP Radio) and then we compare the receiver operating characteristic (ROC) performance of B-SSCT with that of energy detection. For the same target SNR, we vary the detection threshold to obtain the ROC curve.

The PU and the sensor at AP are separated about 5 meters apart with a line-of-sight channel in between. In addition, we carefully configure the transmit power of PU such that the average received SNR at the AP is maintained around −23 dB. Note this level of SNR is already in the low end of detectable SNR region, and thus our results here can be considered as the worst case analysis. Figure 6 shows the ROC curves of B-SSCT and energy detection. B-SSCT consistently detects PU more accurately than energy detection.

Detection Speed - B-SSCT vs. M-ED: We also measure the detection time at different received SNR levels. To make testing scenario more realistic, we place the PU at different locations; the PU signal is transmitted over multi-path channels. As explained before, energy detection needs a long sensing period to make detection decisions and thus makes support for real-time applications impossible. We therefore compare the detection speed of B-SSCT with that of multi-interval energy detector (M-ED).



(a) Locations of PUs

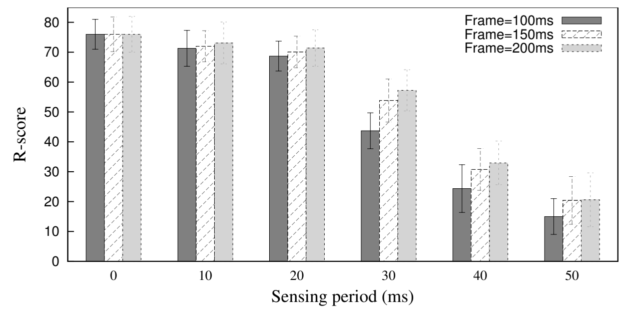


(b) Comparisons of detection time of B-SSCT and M-ED

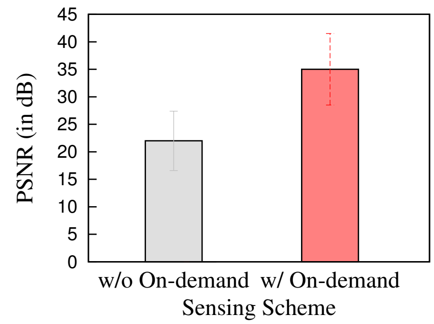
Fig. 8. Detection speed: B-SSCT vs. M-ED

The PU locations are depicted in Figure 8 (a), where the square indicates the location of AP/sensor and the circles indicates the locations of PU. Only one PU is active at a time, and the average received SNR from each PU ranges from −21 dB to −24 dB. The target detection SNR is set to −23 dB for both schemes. The thresholds are carefully chosen (with the method introduced in Section §IV-C) such that both the false alarm rate and the mis-detection rate are less than 5% at −23 dB. The actual received SNR during the experiments, however, can be higher or lower than the target SNR, depending on the PU location and fluctuations of wireless channels.

Figure 8 (b) compares the detection time of B-SSCT and M-ED. We assume that both schemes can vacate from the currently occupied channel within 1 second once the PU is detected. However, B-SSCT consistently detects PU faster than M-ED. This is because, even if the average received SNR is the same, the instantaneous SNR can vary dramatically. While B-SSCT can take advantage of the instantaneous high SNR to make quick decisions, M-ED has to wait until sufficient samples are collected regardless of the received signal strength. Our result also shows that B-SSCT can satisfy the requirement based by IEEE 802.22 standard that the secondary network should vacate from its operational



(a) R-score of VoIP



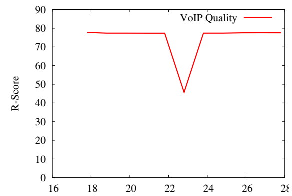
(b) PSNR of Video streaming

Fig. 9. QoS performance improved by on-demand sensing.

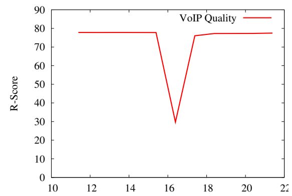
channel within "*2 seconds*". In addition, the detection speed of B-SSCT is increased with an increase of received SNR. Faster detection not only provides better protection to PUs, but also reduces the interference time from PUs to SUs. Therefore, B-SSCT improves the QoS at SU as well.

Performance gain via on-demand sensing: We design three scenarios to test on-demand sensing. The first one is when PU is *not* present and the AP uses B-SSCT with a sensing period of 10 ms (*benchmark* case). The other two are when the PU is present far away from the AP but close to the client, and the AP uses B-SSCT with (*regular* case) and without on-demand sensing (*on-demand* case). In the last two cases, the PU returns to the SUs transmission channel after the SUs communicate for about 10 seconds. In each scenario, Soccer video is streamed live and 15 VoIP calls are transmitted, respectively. In addition, we also repeat the experiment with changes to PU's relative locations and transmit power.

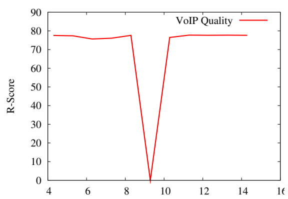
In the *benchmark* case, PSNR of video is about 63 dB and R-score of VoIP is around 76. In the *regular* case, PSNR of video ranges from 16 dB to 28 dB, and R-score of VoIP fluctuates between 36 and 52, as shown in Figure 9; in the *on-demand* case, the quality of video and VoIP improves dramatically, up to a PSNR of 42 dB and an R-score of 71, respectively. Without on-demand sensing, it takes longer time to detect the presence of the PU further away, which is most likely beyond the AP's target sensing capability. If the PU and the SU interfere with each other, the performance of real-time application will be degraded. However, if on-demand sensing is enabled, then the AP can detect the PU much faster and can switch to a backup channel right away. The difference in detection speed results in application-level



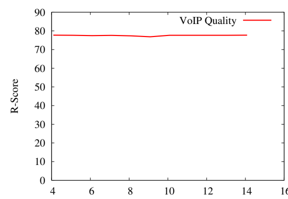
(a) Traditional searching with 30% PU channel occupation.



(b) Traditional searching with 60% PU channel occupation.



(c) Traditional searching with 90% PU channel occupation.



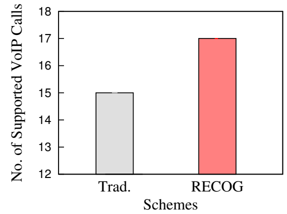
(d) PG-Sensing in RECOG with 90% PU channel occupation.

Fig. 10. Impacts of backup channel searching on VoIP quality.

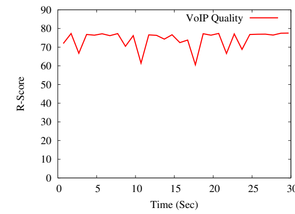
performance differences.

Performance enhancement via backup channel searching: Backup channel searching benefits the system upon channel switching. Again, we consider a worst case that the backup channel searching is started right after the switching. For instance, no channel is found available from previous background backup channel searchings, or a previous searching result needs to be updated. We compare two methods, *traditional channel searching* (use energy detection to search channels one by one) and *PG sensing*, with different PU occupancy ratios among channels (23 channels for ISM 5 GHz). **i).VoIP**: To differentiate the evacuation delay from other normal fluctuations, we use 3 VoIP calls in this experiment.

Figure 10 shows how the average R-score drops during the channel switching with the traditional approach. When the channel occupancy ratio increases from 30%, to 60% and 90%, the channel searching time increases from 131 ms, to 324 ms and 878 ms, respectively, which causes R-score degradation of more than 30. On the other hand, with the PG sensing, no perceivable degradation during the VoIP calls even 90% of channels being occupied. **ii).Video**: Both Soccer and Ice videos are streamed over similar scenarios, as shown in Figure 11. Even when the channel occupancy ratio is 30%, traditional approach degrades average PSNR of video streaming to an unacceptable level, due to buffer overflow.



(a) Increased VoIP calls.



(b) Stable VoIP quality.

Fig. 12. VoIP capacity increased by CR-aware QoS Manager.

Performance improvement by CR-aware QoS manager: The CR-aware QoS manager has two possible benefits to RECOG. If a relatively larger buffer size is available at AP, the QoS manager at access router can improve the overall system capacity. If, otherwise, only a small buffer is available, the QoS manager can help improve the hardware efficiency. **i). VoIP**: Figure 12 (a) shows increased capacity of VoIP calls by using the CR-aware QoS manager. Without the QoS manager, RECOG can support up to 15 voice calls with a satisfactory quality (R-Score of all calls is higher than 70). With the help of the QoS manager, the maximum number of supportable calls increases to 17 due to stabilized queueing and thus less packet drops. Figure 12 (b) shows the stable average R-Score of 17 calls over time. **ii). Video**: Figure 13 shows the impact of buffer size at the AP on the quality of video streaming with or without the QoS manager. Without the QoS manager, both Soccer and Ice videos can hardly achieve good quality using the buffer size of 5. A satisfactory PSNR can be achieved if the buffer size is tripled to 15. With a buffer size of 5 but with the QoS manager enabled, we are able to have the same or even better video quality than using a buffer size of 15.

VI. Video Demo of RECOG

A video demo shows the RECOG system implementation is presented [3] . Both AP and clients in RECOG are implemented on WARP. Supported by a realtime CR MAC, video telephony users communicate with each other. We implement sensing on an additional WARP; sensing outcomes are communicated to AP continuously. USRP is used to create PU traffic. First, we establish a video chat session (VoIP +

[3] http://www.youtube.com/watch?v=Y8mQ6AcFfDI&list=HL1339195358&feature=mh_lolz

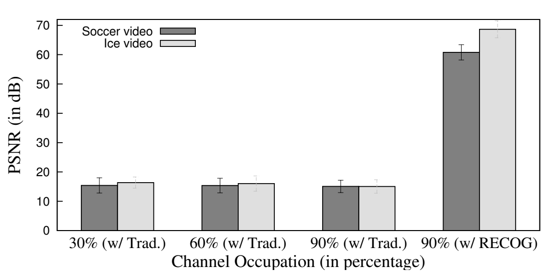


Fig. 11. Impact of channel searching on video streaming.

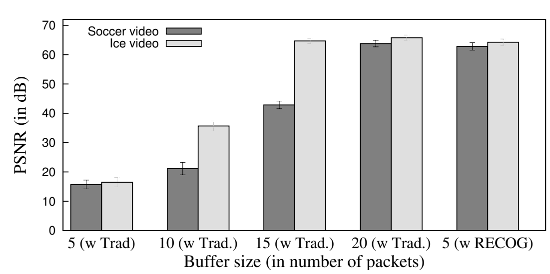


Fig. 13. Video quality improved by CR-aware QoS manager.

video) between two video telephony users, one on a wired network and the other on a CR network. Based on sensing results, AP selects an available channel running realtime CR MAC. The PG-Sensing process is demonstrated. During this video chat, one video telephony user starts counting from 1 to 10. Around a count of 2, PU starts transmitting on the same channel. In-band sensing immediately identifies the return of PU on the current channel. AP and clients are quickly switched to another channel selected. The video chat is seen to be stalled only momentarily (the user's count of 3 and 4 are slightly delayed as can be seen).

VII. Related Work

Systems: prior work has mostly focused on just one aspect of CR system. This involves design of software defined radio system - WARP [9] SORA [16], accurate spectrum sensing [8] [17], spectrum usage monitoring - PINOKIO [18], agile and efficient spectrum assignment - KNOWS [19], Jello [20], FAVICS [21], and WhiteFi [12].

To compare, WhiteFi and RECOG share one similar challenge - finding an unused channel over a large number of channels. RECOG additionally recognizes the challenge in achieving the balance of protection for PU and realtime application QoS provision for SU, while WhiteFi simply assumes proper sensing scheme is in place.

In addition, Jello designs a MAC overlay that can sense unoccupied spectrum and adjust the channel width based on the demand of applications [20]. FAVICS exploits the spectrum diversity to improve the quality of wireless streaming without modifying existing wireless PHY [21]. However, neither of them is designed for an environment with strict CR requirements. RECOG is dedicated for CR, and additionally considers problems such as in-band sensing, out-of band searching and QoS management. Even if Jello also proposes an edge detection scheme for spectrum detection, it only applies to a scenario where wireless nodes are densely deployed and power leakage to adjacent channels is possible. It is therefore not suitable for generic PU detections, particularly not sufficient for the protection of PUs in low SNR region. In contrast, RECOG relates the QoS of SU network performance with the underlying mechanism of spectrum sensing for PU. To the best of our knowledge, RECOG is the first prototype that demonstrates the feasibility of supporting real-time applications over CR systems.

Spectrum sensing and channel searching: A histogram approach was proposed to choose appropriate parameters for energy detection [22]. It requires a lengthy training phase to obtain accurate probability distribution of the test statistic in the presence of PUs. In [10], it proposes a block-based sequential shifted chi-square test, but only provides theoretical analysis and simulations based on an ideal model - noise samples are i.i.d. Gaussian random variables. However, in a real environment, this assumption is not necessarily hold, which leads to a significant mismatch between simulation and measurement results, and a serious detection performance degradation. RECOG carefully revises the process of parameter selections and strives to make the system work in practice. An algorithm similar to our progressive searching is proposed in [23]. However, its analysis and simulation are based on the collected samples, thus could not provide an insight on how well the algorithm can perform in practice. What's more, it does not correlate the algorithm to applications in a CR system.

VIII. Conclusions

In this paper, we present the design and implementation of a CR system called RECOG that is able to support VoIP traffic and live video streaming at SUs. Multiple novel components had to be designed and implemented within the system to achieve this capability. As we observed that conventional energy detection based sensing technique was not a viable option, we identified and implemented a block-based sequential sensing algorithm for our CR system. In the process of implementing the algorithm, we observed that the theoretical method of selecting design parameters for the algorithm is invalid in a real environment. We propose a novel design method for selecting appropriate parameters in a real environment. We showed that the implemented sensing algorithm leads to small sensing periods sufficient to support fast in-band sensing that is within VoIP delay/jitter requirements. We also observed that spectrum mobility is a challenge when QoS constrained traffic needs to be supported at SU, hitherto not a well studied issue. To handle this issue, we designed and implemented PG-Sensing that enables quick spectrum mobility, sufficient to support VoIP. We further found that even with sensing periods that are not very long, transmission periods at SUs could be delayed and also become small enough that packet losses at SUs could adversely affect VoIP traffic. In order to solve this problem, we incorporated a CR-aware rate control mechanism that reduces the packet losses thereby mitigating this adverse effect. The RECOG system that includes the above components was thoroughly evaluated to validate its efficacy in supporting high quality VoIP traffic (R-Score above 70) and live video streaming at SUs.

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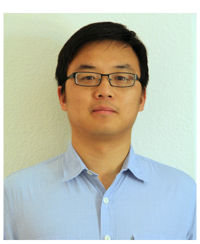

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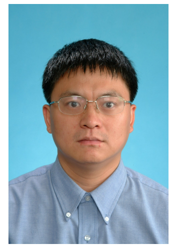

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