Challenges of Spectrum Handoff in Cognitive Radio Networks.

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ABSTRACT

Cognitive Radio (CR) with Dynamic Spectrum Access (DSA) could alleviate the shortage of radio resources. Secondary Users (SUs) (unlicensed users) could access the spectrum when Primary Users (PUs) (licensed users) are inactive. The service interruption loss arises as secondary users try to handoff the channel to the legitimate users of the channels, the primary user. This new type of loss is different from losses as a result of network congestion and channel errors, experienced also by conventional wireless networks. Transport layer protocols' performance of an SU could be degraded significantly as it tries to handoff channel due to the arrival of a PU. The need to investigate SU's TCP performance during this period of sensing, hand-off, and looking for an alternative channel to continue transmitting is a challenging one. This paper presents a study of the challenges of spectrum handoff as PUs in CR networks appear in the course of an on-going transmission by the SUs. A TCP rate adapting algorithm that ensures seamless spectrum handoff as PUs appear is proposed.

(Keywords: cognitive radio, primary users, secondary users, service interruption, handoff, TCP)

INTRODUCTION

The recent explosion in the use and transmission of multimedia applications has made the demand for increased wireless spectrum unabated. The concept of Cognitive Radio (CR) which enables a wireless device to sense the environment and adapt itself accordingly, though has been with us for some time now, still remained elusive because most its expected functionalities/potentialities are yet to be fully explored. This concept could alleviate the radio resource shortage if carefully and efficiently deployed. The need to guarantee smooth transmission of delay-sensitive multimedia data in the presence of licensed primary users is a challenging research area.

A report (FCC, 2002) published by the Federal Communication Commission (FCC) asserts that large portions of the spectrum are underutilized. This fuelled an upsurge in the current interest in CR technology as a key player towards achieving Dynamic Spectrum Access (DSA) requirements of licensed bands of the spectrum. This is to say that significant improvement in spectrum utilization could be realized if unlicensed users are granted access to licensed bands.

The prospect of having a CR network in which a secondary user (SU) can take advantage of DSA to use primary users' (PU) channels when available introduces a different type of packet loss called the service interruption loss (FCC, 2002). The service interruption loss arises as secondary users try to handoff the channel to the legitimate users of the channels, the primary user. This new type of loss is different from losses as a result of network congestion and channel errors, experienced also by conventional wireless networks. Transport layer protocols' performance of a SU could be degraded significantly as it tries to handoff channel due to the arrival of a PU. The need to investigate SU's TCP performance during this period of sensing the presence of a PU, handing-off of channels due to the arrival of a PU, and looking for an alternative channel to continue transmitting serves as a motivation for this project.

In this paper, we investigated some of the research challenges of CR technology and identified notable problems which make TCP implementation in CR networks different from that of the conventional wireless network. We propose a TCP rate adapting algorithm with the aim of ensuring seamless spectrum handoff of channels by SUs as PUs appear in order to transmit their data. The rest of this article is organized as follows. A concise survey of the CR networks is first presented, with an objective to highlight the characteristics of the CR networks, its capabilities, architectural taxonomies, and critical factors influencing its protocols design. A detailed study on transport layer research issues and challenges in CR networks is then presented. This helps to identify the spectrum handoff challenges and present the proposed rate adapting algorithm to handle this problem. We conclude with the highlights of some of the algorithmic design issues that need to be considered in order to implement the proposed algorithm and future research direction.

COGNITIVE RADIO NETWORKS: A SURVEY

Evolution of CR Networks

According to GENI (2006), the term cognitive radio was first publicly used in an article by Joseph Mitola III where it was defined as:

"The point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs."

This definition was coined in the perspective of a Software-Defined Radio (SDR) (Mitola and Maguire, 1999), which was defined by the FCC as "one in which operating parameters such as frequency range, modulation type, or output power can be altered by software without making any changes to the hardware components". Generally speaking, today's usage of the term Cognitive Radio is normally referred to mean a radio system that has the cognitive ability to sense its radio frequency environment and adapt itself accordingly to benefit from this cognitive ability. This means that the cognitive radio could sense the spectrum, analyze the spectrum and take corresponding decision to reconfigure itself to benefit from the result of this analysis.

Functionalities and Capabilities of CR Networks

According to Kurose and Ross (2008), some features and capabilities of CR networks include the following:

- **Current Radio Frequency Spectrum Environment Sensing**: CRs are able to measure frequencies being used, when they are used, estimate transmitters and receivers location. The outcome of this sensing could then be used to determine radio settings.

- **"Plug-and-Play" and Self-Configuration Capability**: A CR network can automatically configure itself for operation and radios may also be assembled from several modules.

- **Adaptive Capability**: Cognitive radio is able to sense its environment, adhere to policy and configuration constraints, and negotiate with peers to best utilize the radio spectrum and meet user demands.

- **Distributed Collaboration Capability**: Cognitive radios are able to exchange current information on their local environment, user demands, and radio performance between them on a regular base. Radios are able to use this information to determine their operating settings.

Access Methods of CR Networks

Broadly speaking, two types of access methods exist for CR networks:

1) **Overlay CR Networks:** this approach is otherwise known as the interference-free approach. The secondary/unlicensed users only access part of the spectrum that is not occupied by the licensed/primary users. This is depicted in Figure 1.

2) **Underlay CR Networks:** in this configuration (otherwise called, interference-tolerance approach), unlicensed or secondary users operate below the noise level of primary users by spreading their signals over the available spectrum. The unlicensed users could interfere with licensed users to a certain tolerable extent.

Architectural Taxonomies of CR Networks

According to Issariyakul et al., two generalized architectural taxonomies exist for CR networks:

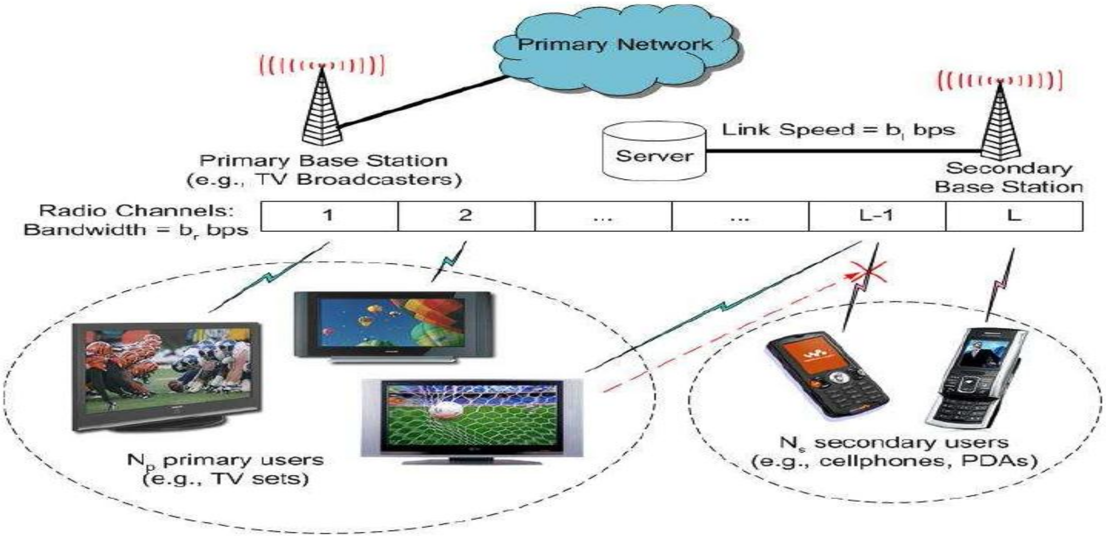


Figure 1: System Model of an Overlay CR Network (Issariyakul et al.).

Centralized CR Network Architectures

These consist of two main entities namely, the base station that schedules user's data transmission; and the spectrum broker (could be a primary or secondary base station (Balakrishnan et al., 1997), or a dedicated entity dealing with spectrum allocation (Weiss and Jondral, 2004; Buddhikot et al., 2005), that allocates the radio resources to users of the CR networks. In this architecture, the sensing functionality is done by the spectrum broker or secondary users. Examples of this architecture include:

DIMSUMnet: This is short for Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile network as proposed in (Buddhikot et al., 2005). A contiguous portion of the spectrum is owned by the spectrum broker who, in turn, leases this chunk to users for specific amounts of time based on their requests.

Spectrum Pooling: According to Weiss and Jondral (2004), spectrum from different vendors is aggregated together as a common pool. Since it is based on Orthogonal Frequency Division Multiplexing (OFDM), interference to the primary users can be reduced if zero power is allocated to other subcarriers in the network.

Distributed CR Network Architectures

This is similar to the conventional wireless *ad hoc* networks with the exception of the presence of secondary network users. It does not have a central agent (spectrum broker or base station) coordinating secondary users' spectrum access. This type of architecture brings about the concept of service interruption (Issariyakul et al.). There are two sub-classes of the Distributed CR networks:

Cooperative Network: A Distributed CR network is said to be cooperative if the users determine spectrum allocation based on shared interference information. Though users of this approach achieve better throughput, the users may incur extra overhead as a result of periodic communication among users. A typical example of a cooperative distributed CR network is CORVUS (Cognitive Radio approach for usage of Virtual Unlicensed Spectrum) (Brodersen et al., 2004), though it could also be implemented in a Centralized CR networks. In CORVUS, a Secondary User Group (SUG) is formed by the secondary users, which help each other in sensing channel for primary user activity.

Non-Cooperative Network: When users access the spectrum based on their local policies without exchanging interference information, it is said to be non-cooperative.

CHALLENGES OF COGNITIVE RADIO NETWORKS

Cognitive Radio Network Application Challenges

The emergence and the eventual dominance of CR networks along with vast application potentials brought a huge amount of challenges that are intense in their complexities and concern. For instance, utilizing unused spectrum involves discovering the spectrum hole. This process might be misguiding in the sense that primary user absence is only determined by SNR to indicate availability of spectrum (Cabric et al., 2004). In Arslan and Ahmed (2007), it was believed that any large or small scale fading could cause a dip in the signal strength that may lead to a wrong conclusion. If primary users' presence is detected through collaborative effort of secondary users, this will impinge on the power consumption of secondary users. It is no gainsaying that power management is a very crucial factor in CR network. Identifying the exact transition time when a secondary user needs to hand over the spectrum to the primary user could also be very challenging.

Evaluating the suitability of a new available spectrum for usage and selecting the best channel among available multiple channels could also be very challenging. The channel's parameters in terms of channel width, bandwidth, rate, etc. needs to be evaluated before such a decision is taken and this could be a complex process. Should a secondary user grab as many channels as are available and use them for transmission or should he judiciously selected a certain amount are some of the challenging issues that need to be addressed in CR networks.

Another challenging issue reiterated by Arslan and Ahmed (2007) was the power level control of each user in the presence of multiple concurrent users over the same band (such as multiple users on ISM band), to mitigate undesired interference. The need to address and protect privacy through encryption and encoding techniques in such a scenario was also emphasized in Gultchev et al. (2002).

Charging the SU for spectrum usage is a topic that seems intractable as well. The licensed spectrum services are provided to the consumers through a pre-established pricing mechanism. In order to avoid unnecessary exploitation of secondary spectrum and to eliminate unfairness to the licensed owner, some pricing mechanism needs to exist for secondary usage (Arslan and Ahmed, 2007).

Summarizing the above mentioned challenges, the following open research issues that need to be examined for the full deployment of the CR networks are identified:

- Reliably detecting primary user signals through spectrum sensing.
- Spectrum capacity estimation and different QoS requirements necessitates new adaptive spectrum decision models.
- New mobility and connection management approaches need to be designed to reduce delay and loss of information during spectrum handoff.
- Novel algorithms are required to ensure that applications do not suffer from severe performance degradation when they have to be transferred to another available frequency band due to the appearance of a primary user.

Transport Layer Challenges in CR Networks

Transport layer protocols for CR networks constitute an area that has not been fully explored since most research in this area has been focused at the lower layers and the network layer. Several of such studies have been proposed to improve both the performance of TCP (Stevens, 1994) and UDP in conventional wireless networks (Fouliras et al., 2004; Akan and Akyildiz, 2004; Balakrishnan et al., 1997; Polyzos et al., 2001; DeSimone et al., 1993; Bakre and Badrinath, 1997).

TCP performance degrades significantly in mobile *ad hoc* networks (Holland and Vaidya, 1999; Fu et al., 2002). In such networks, nodes move arbitrarily, cooperating to forward packets to enable communication between nodes not within wireless transmission range. Route failures due to mobility are the primary reason for most of packet losses (Fu et al., 2002). Since TCP assumes that packet losses occur because of congestion, it will invoke congestion control mechanisms for packet losses caused by route failures, resulting in the reduction in throughput. Several transport layer mechanisms (Holland and Vaidya 1999; Dyer and Boppana, 2001; Liu and Singh, 2001) have been proposed to address the problems caused by mobility. One of the promising approaches is to provide link failure feedback to TCP so that TCP can avoid responding to route failures as if congestion had occurred (Yu, 2004).

In this paper, we focus on the performance of TCP in a CR network. The parameters for measuring TCP performance are (1) packet loss probability and (2) the Round Trip Time (RTT). Packet loss probability in CR networks is not only a function of the access technology, but also that of the frequency in use, the interference level and the available bandwidth (Balakrishnan et al., 1997). Hence, the TCP performance in CR networks needs to be carefully examined to see how it meets with these new challenges. Likewise TCP's RTT also depends on the frequency of operation, the interference level and the medium access control (MAC) protocol. Therefore, the RTT observed by a TCP protocol in a CR network will be different from that of the conventional wireless network. This is because the frequency of operation of a SU in a cognitive radio may vary from time to time as a result of spectrum handoff latency.

Balakrishnan et al., (1997) asserts that the spectrum handoff latency can increase the RTT which in turn causes retransmission timeout (RTO) and results to reduced throughput in CR networks. Therefore, TCP needs to be redesigned in such a way that they are not affected by undesirable effect of spectrum mobility.

TCP Performance in CR Networks

Initially envisioned for wired networks, and later enhanced for wireless networks, TCP was developed as a means to mitigate and control network congestion and serve as a means of providing reliable end-to-end user's data delivery. TCP packets are acknowledged cumulatively when they arrive in sequence but with duplicate acknowledgements when they arrive out of sequence. Packet loss is detected by the sender (1) if triple duplicate acknowledgements are received for the same packet sent or (2) an absence of acknowledgement within a timeout interval. Congestion occurs when routers are overloaded with traffic that causes their queues to build up and eventually overflow, leading to high delay and packet losses (Polyzos et al., 2001).

TCP assumes that all losses are as a result of network congestion and as a result, reacts by reducing its transmission window size before retransmitting packets. This reduction in window size eases the load on intermediate links, hence controlling congestion in the network. Further increase in window size depends on whether TCP is in slow start phase or congestion avoidance phase. In the slow start phase, the window size grows linearly, in response to every acknowledged packet, while the window size grows sub-linearly in the congestion avoidance phase. Generally, the vital functionality of TCP remains the same, despite the modifications to improve its performance (Issariyakul et al.; Kurose and Ross, 2008; Polyzos et al., 2001).

Service Interruption Loss in CR Networks

Most of packet losses in wireless network can be attributed to channel errors due to fading, interference and shadowing or packet collisions due to simultaneous access of the channel by more than one mobile user. The concept of DSA introduces another type of loss experienced by secondary users due to the intervention of primary users while transmitting the data. This is regarded to as the service interruption loss (for the secondary users of an overlay CR network (Issariyakul et al.)

Solutions to improve TCP performance in the presence of losses due to channel errors and packet collisions have been studied extensively (Polyzos et al., 2001; DeSimone et al., 1993; Balakrishnan et al., 1997; Bakre and Badrinath, 1997; Ludwig and Katz, 2000; Yu, 2004) and grouped as end-to-end solutions, split-connection solutions, or link-layer solutions (most popular since it does not require any modification of the TCP operation) (Balakrishnan et al., 1997). The service interruption loss is illustrated in Figure 2. This diagram illustrates what a secondary user experiences when a channel (Channel 1) which was previously occupied by the secondary user has to be vacated for a primary user.

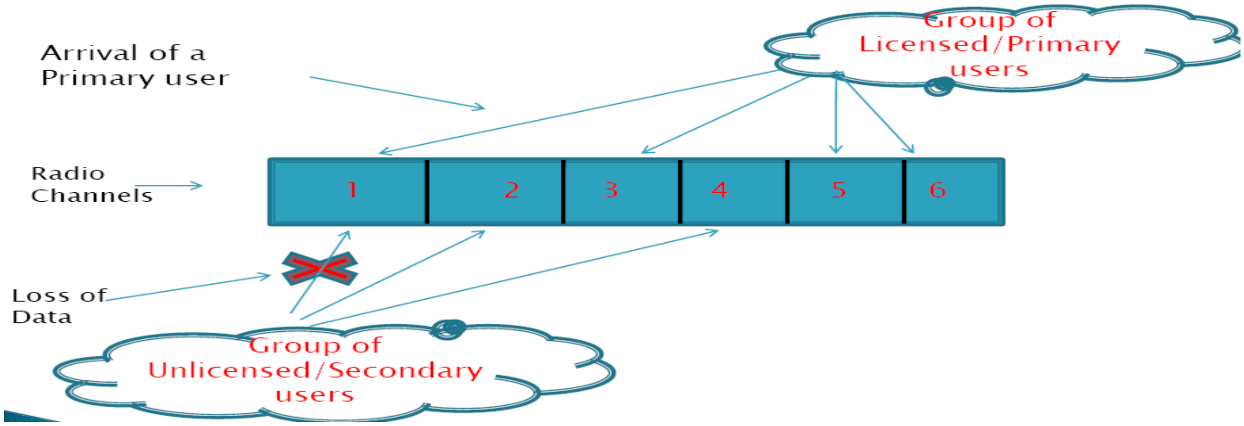


Figure 2: Service Interruption Loss.

The service interruption loss as a result of Dynamic Spectrum Access (DSA) on the other hand, depends solely on the amount of primary users' activity in the spectrum. According to Issariyakul et al., primary user activity is expressed as:

$$A = \frac{T_{ON}}{T_{ON} + T_{OFF}} \times \frac{N_p}{L}$$

T_{ON}= primary users mean ON time
T_{OFF}= primary users mean OFF time
N_p= number of primary users
L = total number of channels in the spectrum.
A =amount of traffic generated by all primary users on a single channel.

It can be seen from the above expression that a higher value of A implies lower aggregate TCP throughput of the Secondary users. As a result, TCP performance under this condition could be different significantly from its performance in a conventional wireless network.

RELATED WORK

Tuning Radio Resource in an Overlay Cognitive Radio Network for TCP

In this work, each secondary user employs TCP new Reno to upload the file and chooses transmission probability value (*p) equal to 1/*N_s, where N_s =number of secondary users. They made the assumption that there are no losses due to channel errors (or) buffer overflow on all the TCP flows of secondary users.

They showed via simulations that the *TCP performance under service interruption loss in an overlay CR network is significantly different to its performance in a conventional network.* In particular, they observed that in an overlay cognitive radio network that adopts DSA, there exists an optimal number of channels that the secondary users need to capture, to maximize their aggregate TCP throughput.

As depicted in Figure 3, the aggregate secondary user TCP throughput versus the maximum channels for secondary users (*Ls*) in the presence of service interruption due to 30 primary users was investigated. The figure shows that the throughput is no longer monotone after a time with respect to *Ls*. They concluded that the TCP throughput of a secondary user does not always increase with the available radio resource. Due to service interruption from the primary user, TCP performance of a secondary user could degrade when it tries to acquire too much radio resource. Hence, there exists a well defined optimal value of *Ls* which maximizes the aggregate TCP throughput

TP-CRAHN: A Transport Protocol for Cognitive Radio Ad-hoc Networks

In this work (Chowdhury, 2009), the author through simulation study show how classical TCP increases the *cwnd* as it probes for the additional bandwidth available on a single link in a CR Network environment.

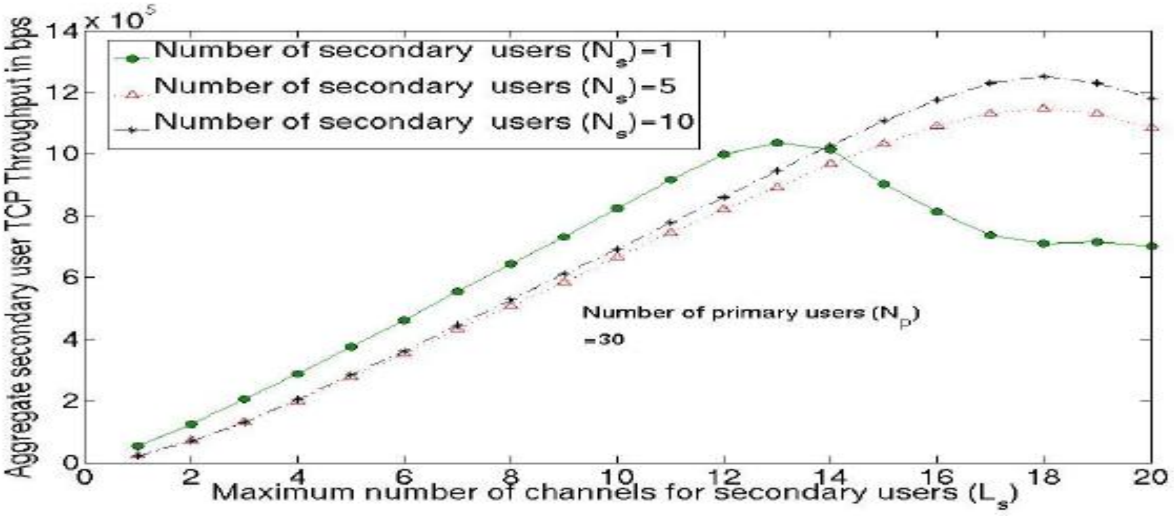


Figure 3: There Exists an Optimal Number of Channels that Maximizes TCP Throughput (Issariyakul et al.).

When the PU arrives, the CR user switches to a different channel, and consequently TCP must adjust to the new available bandwidth. From Figure 4, it was observed that the *cwnd* is unable to correctly track the available bandwidth. Moreover, the spectrum opportunity is often lost before the *cwnd* has increased to half the segments that may be supported on the new channel. A similar conclusion is drawn in (Slingerland, 2007), where TCP cannot effectively adapt to brief reductions in capacity, if the end-to-end delay is large. We believe that the *cwnd* in TCP must be scaled appropriately to meet the new channel conditions. They therefore conclude that periodic spectrum sensing, channel switching operations, and the awareness of the activity of the primary users (PUs) are some of the features that must be integrated into the protocol design.

PROPOSED TCP RATE CONTROL ALGORITHM FOR SPECTRUM HANDOFF IN CR NETWORKS

To provide seamless communications, spectrum mobility gives rise to a new type of handoff, the so-called spectrum handoff, in which users transfer their connections to an unused spectrum band (Akyildiz et al., 2009). New mobility and connection management approaches need to be designed to reduce delay and loss of information during spectrum handoff. Novel algorithms are required to ensure that applications do not suffer from severe performance degradation when they have to be transferred to another available frequency band due to the appearance of a primary user.

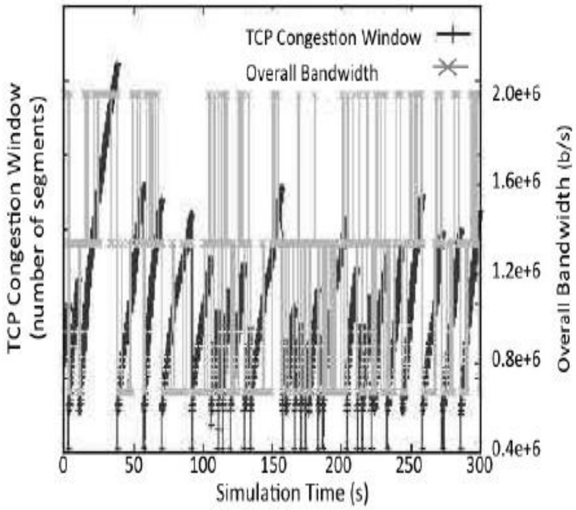


Figure 4: Effect of Changing Channel Bandwidth on CWND.

In order to allow *cwnd* in TCP to scale appropriately to meet the new channel conditions periodic spectrum sensing, channel switching operations, and the awareness of the activity of the primary users (PUs), the TCP rate control algorithm is proposed so that these features could be integrated into the protocol design.

Spectrum handoff can be implemented based on two different strategies. In reactive spectrum handoff, CR users perform spectrum switching after detecting link failure due to spectrum mobility. This method requires immediate spectrum switching without any preparation time, resulting in significant quality degradation in on-going transmissions. On the other hand, in proactive spectrum handoff CR users predict future activity in the current link and determine a new spectrum while maintaining the current transmission, and then perform spectrum switching before the link failure happens (Yang et al, 2007).

The proposed TCP rate control algorithm was designed to handle spectrum handoff using proactive spectrum handoff strategy. This ensures that the current transmission is maintained while searching a new spectrum band and the spectrum switching is faster.

TCP rate is frozen or reduced during the period that the SU senses the current channel for the arrival of a PU as well as when it senses an alternative channel to move its transmission to when the PU eventually arrives. With this implementation, the service interruption loss is reduced significantly and the TCP cwnd is maintained in such a way that it could take the advantage on any sudden increase in bandwidth, as well as reducing its rate when there is lower bandwidth without significant data loss. This design will also ensure that the network stays connected throughout the handoff procedure.

This model is depicted in Figure 5, which illustrates how a SU periodically senses its current channel as well as an alternative channel so as to ensure smooth spectrum mobility at the instance of a primary user of the network.

The Algorithm

For this improved TCP protocol to be functional, the design must capture the frame error information provided at the lower level layer protocols of a CR Network so as to assist packet level error recovery at the higher level protocol (e.g. Transport layer). This will help to avoid unnecessary packet dropping due to spectrum mobility enable the users to exploit benefits offered at the lower layers of the CR network thereby observing, reacting, learning and adapting to the environment.

The algorithm is hereby presented in Figure 6:

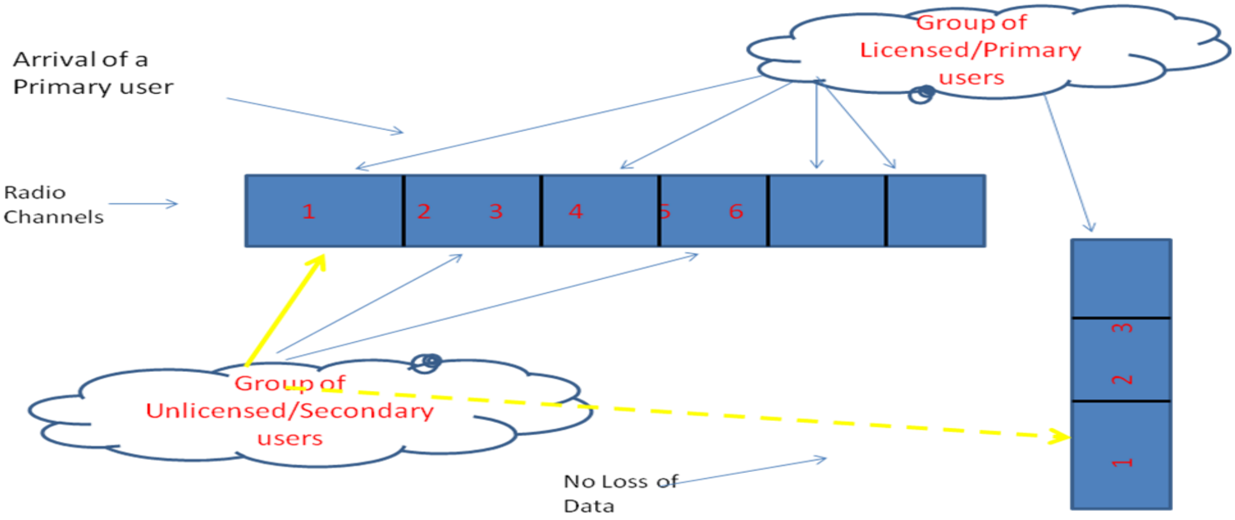
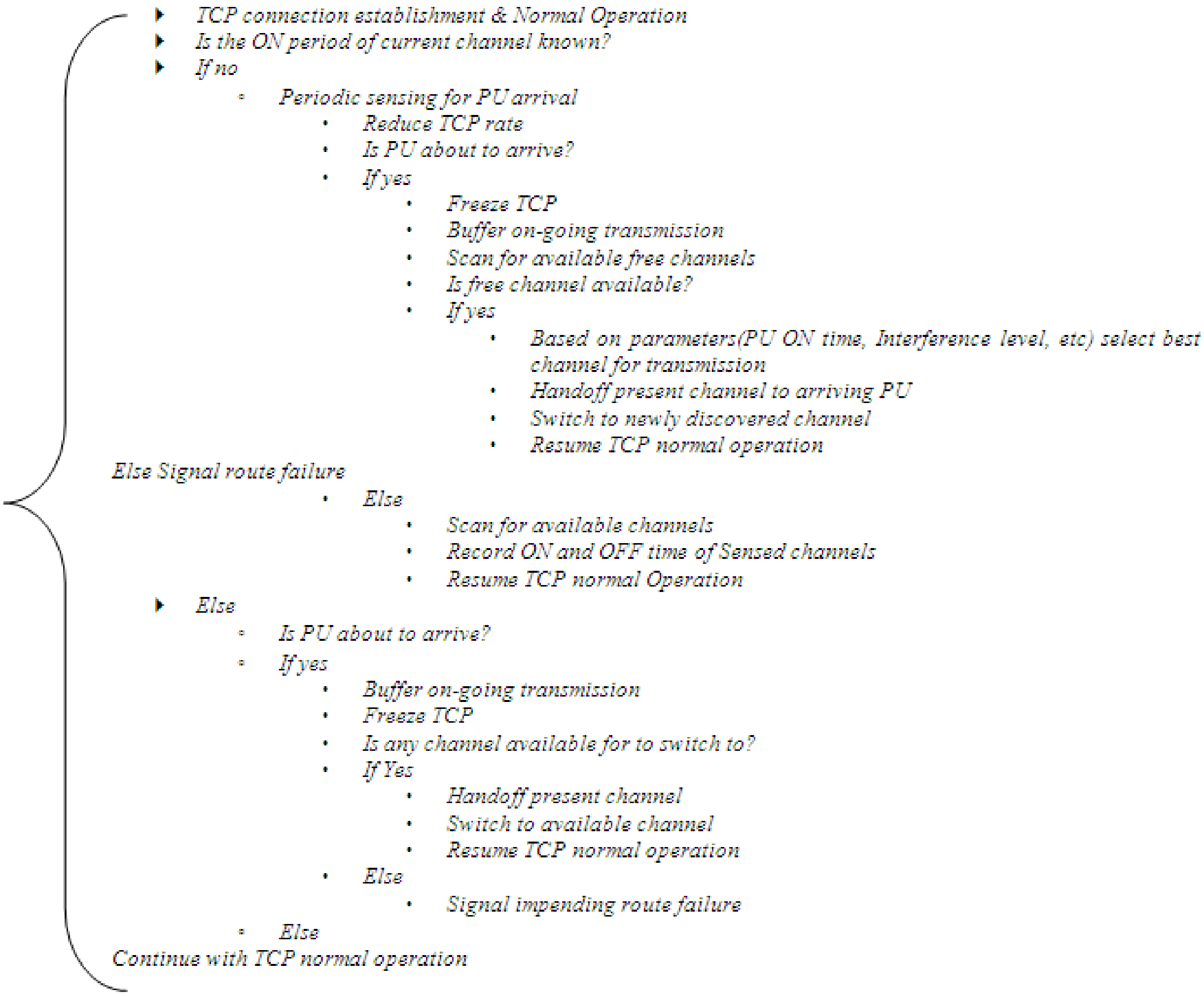


Figure 5: Proposed model for the TCP Rate Control Algorithm.



```
TCP connection establishment & Normal Operation
Is the ON period of current channel known?
If no
    Periodic sensing for PU arrival
        Reduce TCP rate
        Is PU about to arrive?
        If yes
            Freeze TCP
            Buffer on-going transmission
            Scan for available free channels
            Is free channel available?
            If yes
                Based on parameters(PU ON time, Interference level, etc) select best
                channel for transmission
                Handoff present channel to arriving PU
                Switch to newly discovered channel
                Resume TCP normal operation
Else Signal route failure
        Else
            Scan for available channels
            Record ON and OFF time of Sensed channels
            Resume TCP normal Operation
Else
    Is PU about to arrive?
    If yes
        Buffer on-going transmission
        Freeze TCP
        Is any channel available for to switch to?
        If Yes
            Handoff present channel
            Switch to available channel
            Resume TCP normal operation
        Else
            Signal impending route failure
    Else
Continue with TCP normal operation
```

Figure 6: Proposed TCP Rate Control Algorithm.

ALGORITHMIC DESIGN ISSUES AND DIRECTIONS

For the proposed TCP rate Control Algorithm to be a success, the following design issues and further work need to be considered:

- **Algorithmic Complexity:** Computationally complex algorithm that requires significantly long sensing time should be avoided.

- **Spectrum Sensing Mechanism:** While information about the network environment greatly enhances the performance in CR Networks, the messaging overhead must also be considered. The cost of collecting this information includes the link layer delay, energy consumption, and the rate of update messages to keep the state of the network current.

- **Spectrum Sensing Duration:** how to select the proper sensing and transmission periods in a distributed manner is an important issue to be considered.

- **Handoff Duration:** The protocols for different layers of the network stack must adapt to the channel parameters of the operating frequency. Moreover, they should be transparent to the spectrum handoff and the associated latency. Therefore, it is essential for the mobility management protocols to learn in advance about the duration of a spectrum handoff to ensure that the communications of a CR user undergo only minimum performance degradation.

- **Best Channel Selection Criteria:** One of the challenges faced by spectrum mobility is that many frequency bands may be available for a CR user so the algorithm must decide the best available spectrum based on the channel characteristics of the available spectrum and the QoS requirements of the CR user. These parameters could include Low ON time, Interference level to neighbouring PUs & SUs, Nearness to current channel to maintain current path, etc.

Other factors that need to be considered are:

- Investigating the TCP performance of PUs in this CR environment. The effort should not be centered only on the secondary user's TCP performance.

- To what extent should TCP rate be frozen? Should it just be reduced or frozen completely during Channel sensing and channel handoff

CONCLUSIONS

In this paper, we have elaborated on the different performance problems that engender as a result of using TCP over Cognitive Radio networks. We presented the effect of the new type of loss, called the service interruption loss, which is introduced by the concept of Dynamic Spectrum Access. TCP performance under this loss in a CR Network is different from that of conventional Network. There is a need to redesign TCP to meet with this new challenge. A TCP rate adapting Algorithm that ensures seamless spectrum handoff as PUs appear is proposed. Algorithmic design issues that need to be considered for its successful implementation were copiously analyzed.

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