An Enhanced TCP for Optimizing Channel Utilization in Dynamic Spectrum Access Networks

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ABSTRACT

Dynamic Spectrum Access (DSA) network grows rapidly in recent years. It is proposed to solve the problem of reasonable utilization of wireless spectrum resources. DSA is a new spectrum sharing paradigm which takes advantage of spectrum holes to ease the spectrum shortage problem and improve the spectrum utilization. However, due to the frequent spectrum switch, the performance of TCP will degrade greatly in the DSA network, and thus the channel is unutilized. To tackle with this problem and improve high throughput performance, this paper proposes a protocol called TCP WSP based on the assumption that there will be a Wide Stationary Process (WSP) between two spectrum switches. Then the authors propose a mechanism to predict the spectrum switch and adjust the sending rate of TCP based on the prediction to optimize channel utilization in DSA networks. They implement our mechanism on NS2 simulator, and the results show that their mechanism can achieve high throughput performance.

Keywords: Dynamic Spectrum Access, High Throughput Performance, Spectrum Switch, TCP, Wide Stationary Process

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1. INTRODUCTION

In the mobile Internet era, mobile phones and other intelligent terminals are becoming more and more popular, and the adaptation of the wireless communications business is also increasing quickly. Traditionally, Spectrum allocation policy is to provide authorized users with a fixed spectrum which is exclusive to use (FCC, 2002). While this policy has been working well in the past few decades, the proliferation of wireless services in recent years has exposed the shortcomings of this policy, such as spectrum scarcity and a large number of licensed spectrum is not fully utilized in both time and space. This is also called Spectrum Hole or Spectrum Gap, which provides a good opportunity for wireless communication. Subsequently, Dynamic Spectrum Access (DSA) is proposed to solve the problem of reasonable utilization of wireless spectrum resources. DSA is a new spectrum sharing paradigm which takes advantage of spectrum holes to ease the spectrum shortage problem and improve the spectrum utilization. Cognitive Radio (CR) technology is a promising paradigm for addressing the spectrum scarcity problem through efficient dynamic spectrum access (DSA) (Jararweh Y, 2015). In DSA networks, users are divided into two types: the Primary User (PU) and the Secondary User (SU). The Primary User can freely access the licensed spectrum band, while the Secondary Users can watch for their chances to access idle licensed bands as well as freely access the public spectrum band (IEEE, 2007). DSA network is a wireless network which has been applied to cognitive radio technology. There are three kinds of DSA models: Interweave, Underlay and Overlay. Interweave DSA model is studied in this paper. DSA network can potentially be applied to complex network environment such as the disaster scene to improve reliability and service quality. The authorized users can also rent out their licensed spectrum band for trade.

TCP is the most commonly used transport control protocol. TCP's congestion control mechanism includes four algorithms: slow start, congestion avoidance, fast retransmission and fast recovery (Jacobson V, 1990). In the slow start stage, TCP tries to find and utilize the available network bandwidth by doubling its congestion window in one RTT (Round Trip Time). When the congestion window exceeds a threshold, it will enter into congestion avoidance stage by increasing the congestion window by 1 packet in one RTT. When packet loss happens, it will fast retransmit the lost packet and reduce its rate in order to avoid congestion that is the fast retransmission stage. Packet loss is detected by duplicated ACKs or ACK time out. If an ACK times out happens, it will reduce congestion window to 1 packet and then perform a slow start. Otherwise TCP will halve its congestion window, and perform a fast retransmission.

This is called the Fast Recovery. From the above summary, we know that TCP assume every packet loss is due to congestion, and its bandwidth detection is by the aid of slow start and congestion avoidance. It works well in wired networks, but this is not true in DSA networks because the packet loss may be caused by channel switch and the available bandwidth on each channel is significantly different. While the traditional TCP design is applied in the wireless network, because of the random packet loss and spectrum switch of the wireless link, the performance of TCP will degrade greatly. As a result, people begin to put forward a lot of solutions to solve this problem. The core of the implementation of the method has two kinds, one of which needs the support of the intermediate node, such as TCP-Casablanca (S. Biaz, 2005), the intermediate nodes lose the packet intentionally to help the sender to judge the link state. The distinguishing method is that the packet loss in wireless link is random, while the packet loss of the intermediate nodes has a certain statistical law, which can be easily performed at the remote end.

The other is not required for the support of intermediate nodes, it is mainly through the detection of RTT to determine whether the occurrence of congestion, which is a relatively wide the detection of RTT to determine whether the occurrence of congestion, which is a relatively wide range of algorithms. According to the congestion control scheme, it can be divided into two categories, one is based on packet loss, and the other is based on delay to improve the TCP performance. Dynamic spectrum access network not only has all the characteristics of the wireless network, but also due to the complexity of the channel resources, it will add a lot of question. In DSA environment, the environmental change can lead to the dynamic changes of bandwidth, access, handover latency and packet loss rate. The performance of TCP will be reduced if the traditional TCP mechanism is directly placed in the DSA network. In the case of TCP, DSA network needs to solve both the problem of wireless network and DSA network, also to face the mixed problem of the operation behavior of DSA network and traditional wireless network. So the difficulty of the distinction between congestion packet loss and random packet loss will increase a lot. It should be pointed out that the frequency of channel switching is also a key factor for TCP.

In addition to the delay or packet loss caused by the channel switching itself, frequent switching may cause the TCP's congestion window to fluctuate at a lower level, which is not good to use bandwidth resources. For the research of TCP in DSA, many methods have been proposed, but it is also accompanied by a variety of problems. Moreover, we seldom see the study the effect of channel switch on TCP. In this paper, we will study a congestion control method only at the transport layer to resolve the throughput degradation problem in a dynamic spectrum switch environment. Our method will adjust the congestion window according to the spectrum switch. The method comprises two algorithms: spectrum switch detection and rata adaptation. The spectrum switch detection is based on the assumption that the measured available bandwidth sequence will be a wide stationary process (WSP). The assumption is validated through simulation results. Then the rata adaptation algorithm adjusts the congestion window according to the available bandwidth of the new channel. Our algorithm aims to optimize channel utilization and achieve high throughput performance.

2. REVIEW OF RELATED WORKS

In DSA network, the spectrum heterogeneity will aggravate the instability of wireless link, and then affect the stability of RTT. In addition, the channel switching of the DSA node will also introduce the related delay, which may induce time out at TCP layer. There have been some efforts devoted to deal with TCP's poor throughput performance in DSA. Base on the control layers of the method, we briefly classify these approaches into three types: MAC/PHY Layer, Cross-layer and TCP layer methods.

2.1. MAC/PHY Layer

There are many works focus on MAC/PHY layer (T. Chen, 2007; Y.R. Kondareddy, 2008; L. Le, 2008), which mainly try to improve the sensing functionality, channel selection algorithm, etc. These are DSA network's fundamental functionality. For multiple channels, for example, the objective of channel assignments is to reduce co-channel interference experienced by links so as to increase network capacity while maintaining network connectivity (Dai Y K, Yen L H, Su J W, 2013). Taking into account some of the sensitive issues, Zhao (2005) presents a distributed cognitive MAC protocol, and develops an analytical framework for DSA. Chowdhury (2009) takes hardware constrains into consideration, and proposes HC-MAC to identify the issue of optimal spectrum sensing decision.

Vinod Kone (2012) presents the first comprehensive study on the presence of "usable" spectrum in opportunistic spectrum access systems, and whether there is enough spectrums can be used for the secondary devices to support the traditional network applications. Wang (2012) investigates the TCP throughput performance enhancement for cognitive radio networks through lower-layer configurations. He found that there is an interaction between TCP and the lower-layer operations. Therefore, an iteration process is employed to investigate the TCP throughput under given channel condition and lower-layer configurations. In addition, they track the way how these factors considered in that paper influence the TCP throughput by using the proposed analytical method, TCP throughput enhancement can be achieved through appropriately setting lower-layer configurations.

2.2. Cross-Layer

J. Liu (2001) proposes a method to distinguish between packet loss and channel error packet loss by adding a layer between IP and transport layer to collect information of network, which to properly adapt the congestion window. The main factors that affect the performance of DSA in TCP network are analyzed by J. Jia (2008), and a reliable transport layer protocol TP-CHAHN is proposed. The main drawback is that it needs to design a new transport layer protocol, which is compatible with the existing network protocol. Luo (2010) takes a cross layer design approach that takes into account spectrum sensing, access decisions, physical layer modulation, and the encoding scheme as well as the size of the data link layer frame to improve the throughput of TCP. Kumar (2010) proposes a DSASync protocol, which can prevent TCP or UDP from the effect of spectrum switching by the third party monitoring and achieves higher performance.

2.3. Transport Layer

The performance of TCP in DSA is verified by simulation for the first time by Slingerl. Research shows that only the buffer at the AP is large enough and the receiver adopts SACK mechanism, the TCP mechanism can make full use of spectrum resources of DSA, at the same time, this article studies the effect of scanning time on the performance of TCP (Slingerl and A M R, 2007). Yogesh (2009) describes that conventional TCP is not suitable for dynamic spectrum access networks, and develops an analytical model which uses continuous-time to estimate the TCP throughput of DSA network. Luo C (2011) proposes a novel multi-channel access scheme in CR networks, where the channel access is based on the TCP throughput in the transport layer. In addition, it also exploits cross-layer design methodology to improve TCP's throughput, where modulation and coding at the physical layer and frame size at the data-link layer are considered together with TCP throughput in the transport layer to improve TCP performance. Yang H (2012) proposes an enhanced TCP protocol for CR networks called TCP FOR cognitive radio (TCP-CR) to improve the existing TCP by (1) detection of primary user (PU) interference by a remote sender without support from lower layers; (2) delayed congestion control based on PU detection when the retransmission timeout (RTO) expires, and (3) exploitation of two separate scales of the congestion window adapted for PU activity.

There are some of the relevant literatures on bandwidth estimation to improve the performance of TCP. Gerla B N M (2002) uses bandwidth estimation in congestion control. Since fair share is difficult to determine, they instead compute a Fair Share Estimate (FSE) to determine the fair share on the bottleneck, and then improve the overall network throughput. The method of Sasaki T (2004) is based on a combination of SACK and TCP-Westwood rate estimation, it applies bandwidth estimation after a slow start, thus to realize efficient communication in the wireless environment. The paper (Parvez N, 2004) presents a novel dynamic bandwidth estimation mechanism for improving TCP performance in wired-cum-wireless networks. Its idea is to measure the bandwidth used by a TCP flow via monitoring the rate of returning acknowledgements and the RTT values and achieve throughput performance improvement. Capone A (2004) first analyzes the problems faced by every bandwidth estimation algorithm implemented at the sender side of a TCP connection and proposes TIBET which is a new bandwidth estimation scheme that can be implemented within the TCP congestion control procedure, modifying only the sender-side of a connection.

RS Cheng (2007) proposes a negative acknowledgment scheme, selective negative acknowledgment (SNACK), which is applied on TCP over wireless networks. SNACK and SNACK-S which incorporates a bandwidth estimation model at the sender are proved to outperform conventional TCP implementations. From the above summaries, we can see that most papers are only focused on the MAC or physical layer to improve channel selection or reduce interference. Some papers consider cross layer method, but it is difficult to be implemented. The few TCP layer methods ignore the impact of channel switching on TCP performance. In this paper, we will propose a method only modifies the TCP layer protocols but can catch the MAC layer information form TCP layer. Our work is to measure available periodically, and through which we can judge whether channel switch happens, and then adjust TCP's congestion window based on the available bandwidth. The method can avoid the influence of channel switch and optimize channel utilization, thus improve throughput performance.

3. SYSTEM MODEL

We adopt a simple DSA scenario which comprises several different wireless channels as shown in figure 3.1.

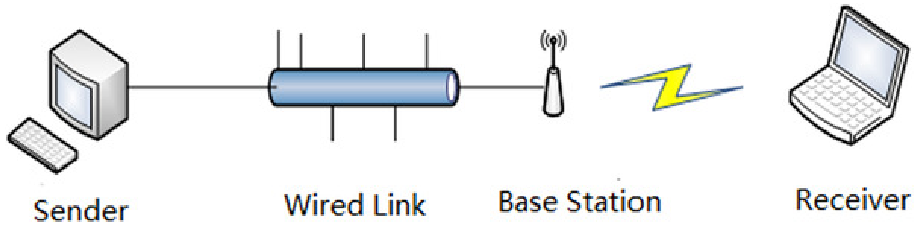

Figure 3.1. System Model

In Figure 1, the system model has a sender (SH) lying in the left, and a receiver (RH) in the right, the sender and the receiver communicate with each other through several links. The wired link has higher bandwidth and also causes some delay, the wireless link is the bottleneck with lower bandwidth, but it has several channels for use. We need to set some parameters in the model:

i) N: Number of channels in DSA network;
ii) Con_time: The time duration in one channel;
iii) bw_i: The bandwidth of each channel.

File Transportation Protocol (FTP) (Postel and J. Reynolds, 1985) is the application layer protocol for transmitting continuous data. FTP relies on TCP Reno (Jacobson V, 1990) in the transport layer below to provide a logical connection between the sender and the wireless client receiver. Further down the protocol architecture, we adopt the DSA structure. In a typical DSA network, there are two types of terminal users, the Primary User (PU) and the Secondary User (SU). There exists a number of licensed spectrum resource for the use of PU, however, SU must detect the PU's channel before using it, then monitor for its chance to access the vacant channel when a PU does not use temporarily. While the SU uses the channel, it will probe whether the PU returns, if not, the SU can continue to use this spectrum resource. When the PU arrives, the SU should immediately stop data transmission and leave the channel. In this paper, we ignore the behavior of the PUs, but focus on how to improve TCP's performance when spectrum switch occurs. In the DSA network, the spectrum switch occurs when the SU access channel and when the SU detects the arrival of PU. Due to the randomness of PU's behavior, channel switching may be quite frequently. Moreover, as different channels have different bandwidth, the sending rate at the TCP layer should be different, but the window adjustment mechanism of TCP cannot catch up with the new bandwidth environment. Thus leads to the unreasonable utilization of bandwidth. This is the subject of our new TCP's congestion control algorithm proposed in the next section to combat these issues.

4. DISCUSSION OF RESULT

The mechanism is based on the assumption that there exists a wide stationary process (WSP). And we prove it through experiments. The detection algorithm considers the network variance, so it uses five continuous values beyond the range to detect but not one. The TCP improvement mechanism is based on the widely used TCP Reno, so it is easy to be implemented and can be compatible with TCP Reno.

4.1 Performance Evaluation

In order to validate our mechanism (TCP WSP), we do simulations using the network simulator NS2 (NS2). We implement TCP WSP on NS2 and compare its performance with TCP Reno. For simplicity, the setting parameters are as follows: two different channels (N=2) are switched in a fixed interval (Con_time = 5s); the physical bandwidth of the two channels are 9Mbps and 25Mbps (bw_1 = 9Mbps, bw_2 = 25Mbps).. Every such interval a node enters a different channel (that is, the spectrum switch).We compare our TCP WSP with TCP Reno in several scenarios. Specific comparison parameters and results are as follows

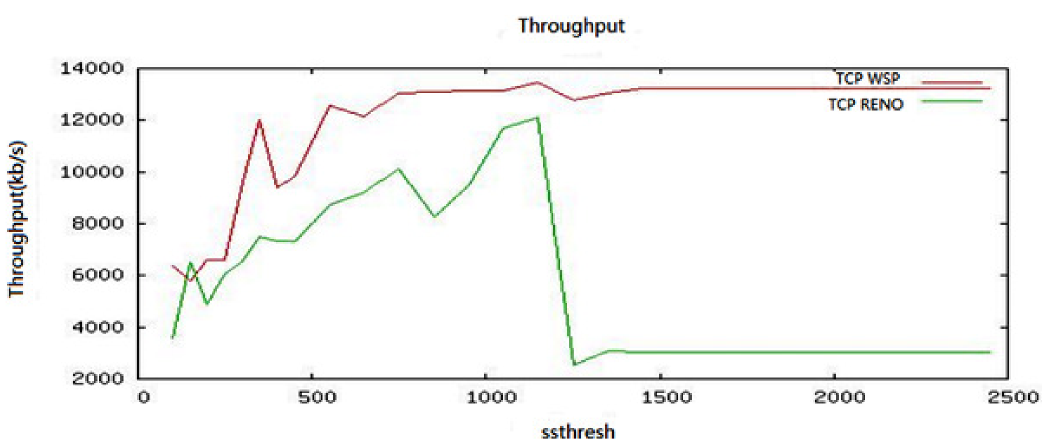

Figure 4.1. Throughput comparison with different ssthresh

4.2. Throughput under Different Bit Error Rate

Figure 4.2 compares the throughput under different bit error rate of wireless network. The parameters are the same in last scenario except we employ different bit error rates. Through the figure, TCP WSP achieves better performance, and at the same time, behaves more steady that TCP-Reno. As we can see in the figure, TCP WSP remains high throughput, under most of the circumstance.

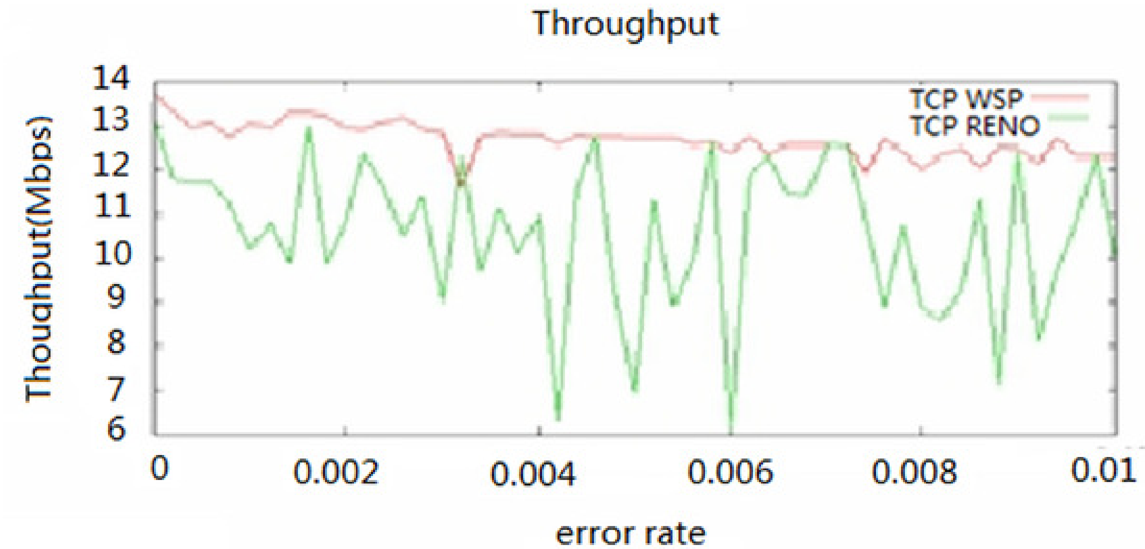

Figure 4.2. Throughput comparison with different bit error rate

4.3 Throughput under Different Switching Period

Figure 4.3 describes the comparison of throughput under different switching period of wireless network. The parameters are the same as the above scenario except we vary different switching periods. Through the figure, we can see that compared with TCP-RENO, when the switching period is relatively small, DSA TCP can also get a larger throughput, and performance is very stable. The reason may be that DSA TCP can quickly adjust the window when the channel switch is detected.

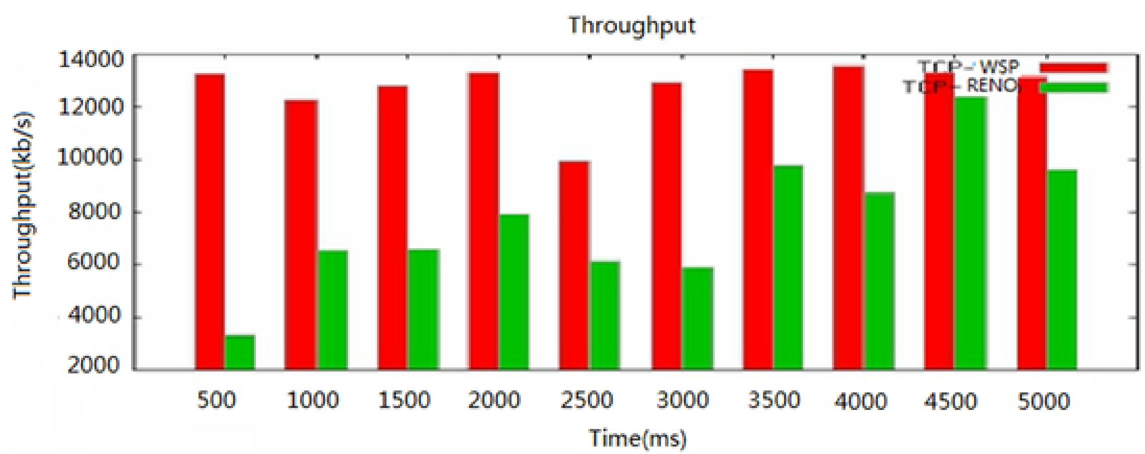

Figure 4.3. Throughput comparison with different switching period

4.4. Fairness Analysis: TCP Reno is the most commonly used transport layer protocol, so a new TCP protocol should be friendly with TCP Reno. At last, we study the coexistence of TCP WSP and TCP Reno. We add a pair of transmission nodes as shown in Figure 4.4. There are two TCP Reno flows (W0 to N0, W1 to N1) and two TCP WSP flows (W0 to N0, W1 to N1) in the scenario.

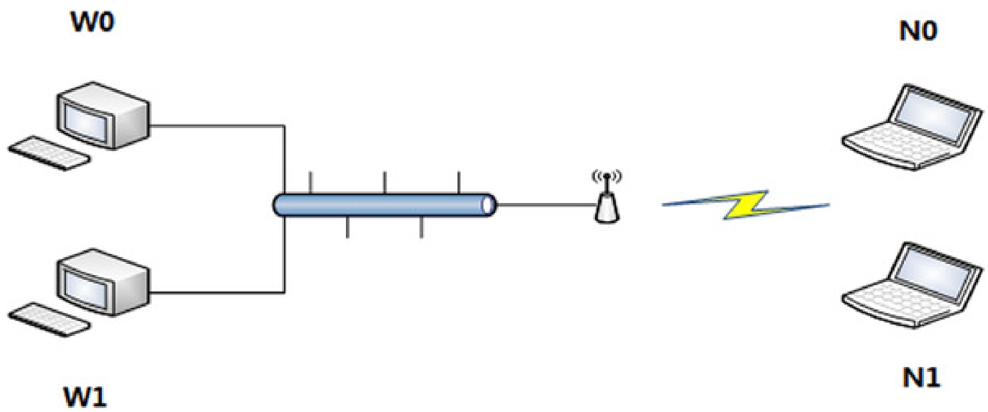

Figure 4.4. Scenario for fairness comparison

From the Figure 4.4 we can see that both the two Reno flows and TCP WSP flows has a certain fairness performance. This means the window adjust strategy of TCP WSP is moderate, has no impact on other flows. The throughput performance of TCP WSP outperform than TCP Reno as it can be fit to the DSA environment.

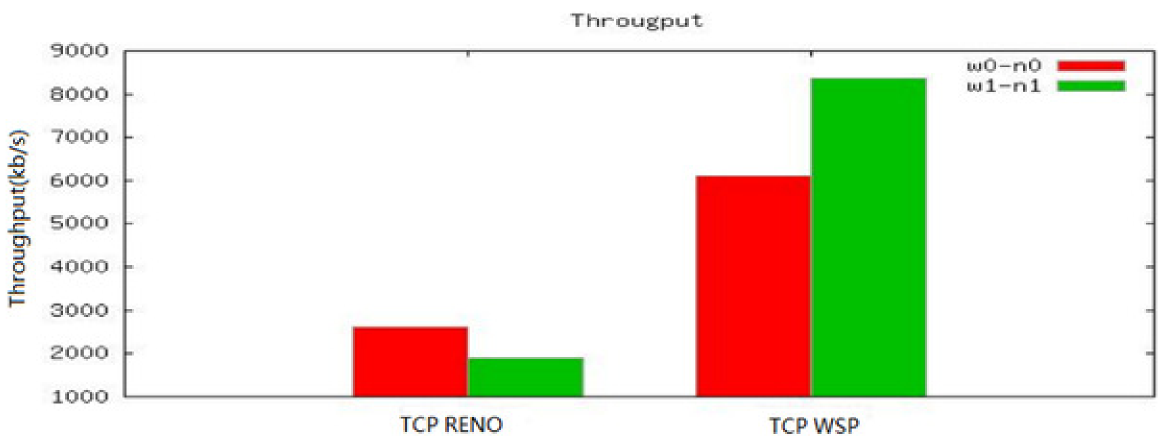

Figure 4.5. Fairness comparison

5. CONCLUSION

In this paper we have studied the impact of spectrum switches in a typical DSA network on TCP throughput performance. The bandwidth utilization ratio of the traditional TCP in DSA network is insufficient. So we propose a transmission control protocol called TCP WSP. By measuring the available bandwidth, TCP WSP estimates the distribution of measurement bandwidth, and then uses the means and variance to judge whether the channel switch occurs, and then controls the reasonable congestion window value, and finally achieves the purpose of maximizing the utilization of the channel bandwidth. In the future, we will study the impact of PU's behavior on TCP's performance in a more complex spectrum environment.

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