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A New Architecture for Application-Aware Cognitive Multihop Wireless Networks

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Abstract

In this paper, we propose a new architecture for application-aware cognitive multihop wireless networks (AC-MWN). Cognitive radio is a technique to adaptively use the spectrum so that the resource can be used more efficiently in a low cost way. Multihop wireless network can be deployed quickly and flexibly without a fixed infrastructure. In our proposed new architecture, we study backbone routing schemes with network cognition, routing scheme with network coding and spectrum adaptation. A testbed is implemented to test the proposed schemes for AC-MWN. In addition to basic measurements, we implement a video streaming application based on the proposed AC-MWN architecture using cognitive radios. Preliminary results demonstrate that the proposed AC-MWN is applicable and is valuable for future low-cost and flexible communication networks.

Index Terms

cognitive radio; multi-hop; backbone; routing; testbed

I. INTRODUCTION

In multihop wireless networks (MWN), there are one or more intermediate nodes along the path (route) that receive and forward packets via wireless links. In cellular and wireless local area networks, wireless communications only occurs on the last link between a base station and

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the wireless end system. Multihop wireless networks have several benefits: (1) Compared with networks with a single wireless link, multihop wireless networks can extend the coverage of a network and improve connectivity; (2) Transmission over multiple short links might require less transmission power and energy than that required over long links; (3) Multihop wireless networks can be quickly deployed without the support (or with limited support) from wired infrastructure. Due to such salient features, multihop wireless networks are expected to play a key role in modern society, helping to improve quality of life and to solve problems related to homeland security, protection of critical infrastructure, and the diagnosis and treatment of illnesses. In the past two decades, we have witnessed a dramatic growth in wireless communications and networks, with mobile devices such as cell phones, personal digital assistants (PDAs), and laptop computers becoming essential to everyday life. Such a trend has been accelerated in the past three years, driven by the popularity of a new generation of mobile devices like netbooks, smart phones (iPhone, Android Phones, etc.), and other new gadgets (Kindle reader, iPad, etc.). Our society has been rapidly evolving toward the pervasive computing age, in which the network infrastructure shall support not only traditional communication patterns (i.e., human-to-human, human-to-computer, and computer-to-computer) but also the communication needs from devices such as mobile phones, PDAs, sensors, and radio frequency identification (RFID) devices. To support the so-called Internet-of-things, it becomes a major challenge to fully explore multihop wireless networks. Given the recent upward trend in wireless traffic, capacity demand increases faster than spectral efficiency and availability (in particular at hot spots/areas). On the other hand, it has been well-known that in wireless communications most of the spectrum is significantly under-utilized in most of the time. This simple fact has attracted researchers from academia and industry who are interested in the next generation cognitive and radio communication systems. Despite the importance of such ongoing efforts, we have observed a huge gap between the research on cognitive radios and the network applications. For instance, most researchers on cognitive radios focus on the spectrum sensing and dynamic spectrum allocation, but few of them have considered to interact with the network layer so that the network can accommodate the requirements of applications from the upper layer. In spite of many recent research activities on the topics related to multihop wireless networks, including cognitive radios, capacity analysis and improvement, and wireless applications, there is still a critical gap in the knowledge base to understand the network design principles to meet the requirements of different applications

for multihop wireless networks with the constraints of spectrum availability.

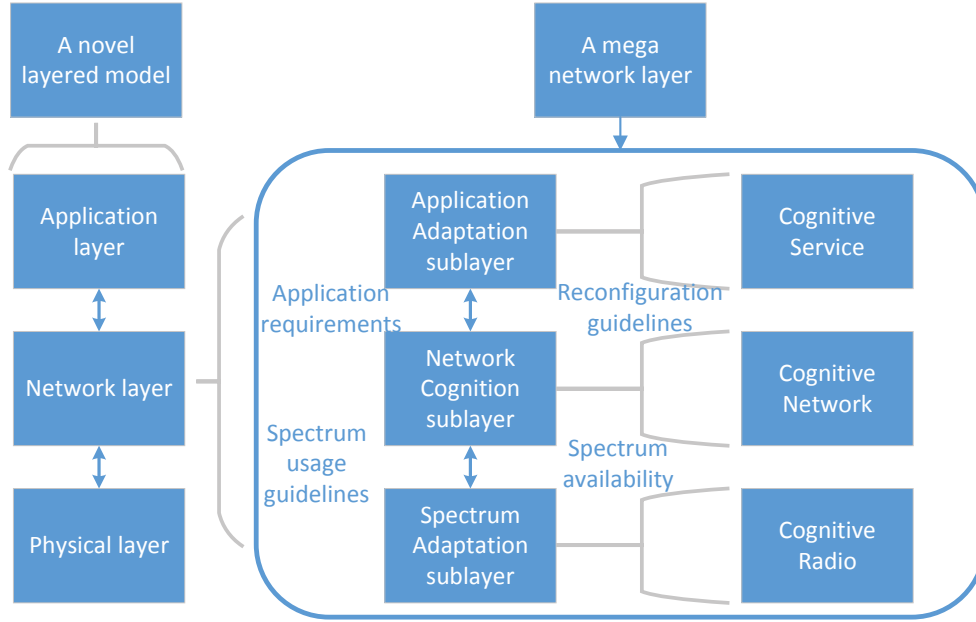


Fig. 1. A new model and a mega network layer for the proposed AC-MWN architecture

In this paper, we propose and study a new wireless networking architecture, AC-MWN, or Application-Aware Cognitive Multihop Wireless Networks. In AC-MWN, we apply a new layered model that has three layers (application layer, network layer and physical layer), as shown in Fig. 1. We propose to design a mega network layer for multihop wireless networks that will combine the major functionalities of medium access control layer, network layer and transport layer in the traditional layered model of wireless networks. The proposed mega network layer will have cognition related to the spectrum availability in the network and the requirements of applications of the network. Moreover, the new design not only can efficiently utilize the spectrum resources, but also can effectively adjust the application resources, such as storage and computational capabilities, etc. Since each MWN will be deployed as an autonomous domain even if it is interconnected with the Internet, we envision that our novel layered model and the mega network layer for the proposed AC-MWN architecture can be implemented and deployed in the MWN domain regardless of the standard 7-layer ISO/OSI model or the standard TCP/IP layer model, in a manner similar to most wireless sensor networks. AC-MWN can push the capacity limit for MWNs and at the same time to accommodate the requirements of different

applications in MWNs; thus, it achieves application-aware cognitive multihop wireless network design.

At the center of the proposed AC-MWN architecture is a mega network layer model as shown in Fig. 1, which consists of three sublayers: application adaptation sublayer, network cognition sublayer, and spectrum adaption sublayer. The application adaptation sublayer is the interface in the network layer that interacts with the application layer; it passes the application requirements from the application layer to the network cognition sublayer, and it receives reconfiguration guidelines from the network cognition sublayer. The network cognition sublayer is the central part of the AC-MWN for cognitive networking. This layer takes the application requirements from the application adaptation sublayer, and it also receives the spectrum availability information from the spectrum adaptation sublayer. Both the application requirements and the spectrum availability information will be used to generate the best fitting routing strategies in the network layer (for the required applications with the spectrum constraints); then, the best fitting routing strategies will be mapped into spectrum usage guidelines to be passed to spectrum adaptation sublayer below. The best fitting routing strategies will also be translated into reconfiguration guidelines and then sent to the application adaptation sublayer above. The spectrum adaptation sublayer is the interface in the network layer that interacts with the physical layer for cognitive radio functions like spectrum sensing and dynamic spectrum allocations. The proposed AC-MWN architecture will be focused on the mega network layer, which including application adaption sublayer, network cognition sublayer, and spectrum adaption sublayer, will be discussed in the three sections following.

In Section II., we describe the application adaptation for AC-MWN. In Section III., we discuss the design of network cognition for AC-MWN, including backbone network construction, routing with channel bonding, and routing with network coding. In Section III, we elaborate the spectrum adaptation for AC-MWN, including channel-aware routing for both unicast and multicast transmissions. In Section IV, we set up a testbed, and show preliminary results of sensing, channel switching, as well as a video streaming application based on proposed AC-MWN. In Section V, we conclude this project.

II. APPLICATION ADAPTATION FOR AC-MWN

In this section, we describe the design of the application adaptation sublayer for AC-MWN, and the interactions with the application layer above and the network cognition sublayer below. In this way, the application adaptation sublayer will achieve “application-aware” design in AC-MWN. In future MWNs, each type of applications can be characterized by communication patterns and service requirements [1].

Communication patterns: A network application can have one of the specific communication patterns [1]: (1) one-to-one (unicast), (2) one-to-many (multicast), (3) one-to-all (broadcast), (4) many-to-one, and (5) many-to-many.

Service requirements: A network application can also be associated with a variety of service requirements, including data rate type (fixed or variable), delay type (real-time, non-real-time, and delay-tolerant), and security and reliability requirements [1].

In the application adaptation sublayer design for AC-MWN, we specifically focus on the application characteristics of communication patterns and service requirements with data rate type and delay type, which are the major characteristics of network applications that could affect the design and operation of MWNs. The work in [1] shows that WiMAX networks can be properly complemented through advance connection management and scheduling in the network layer with the consideration of application characteristics from the application layer above. In this AC-MWN we consider different combinations of communication patterns and service requirements for future applications of MWNs, and the impact of the network application characteristics on MWN network layer design including routing schemes.

We define a simple interface between the application layer above and the application adaption sublayer, so that a network application can be abstracted in the application adaption sublayer in terms of the communication patterns and service requirements discussed early, to be used by the network cognition sublayer below. We also define a simple interface between the application adaption sublayer and the network cognition sublayer below, so that the abstracted application requirements can be passed to the network cognition sublayer for routing and scheduling, and it will also receive the reconfiguration guidelines from the routing and scheduling functions of the network cognition sublayer, so that different applications will be accommodated in MWNs.

III. NETWORK COGNITION FOR AC-MWN

For the design of the network cognition sublayer for AC-MWN, we first summarize the recent advances in cooperative wireless networks, including network coding and physical-layer network coding, and wireless backbone construction schemes, and then we propose algorithms and protocols to best fit in the network cognition sublayer for AC-MWN. Specifically, we design and evaluate effective backbone routing algorithms, which will be suitable for applying network coding to multihop wireless networks.

Although wireless backbone routing schemes have already been studied for years (e.g., [2] [3]), our AC-MWN design is significantly different from prior work. In particular, we propose to explore network coding aware backbone construction and optimal backbone routing in terms of node characteristics, transmission schemes, communication patterns and service requirements, and spectrum availability constraints. The spectrum availability constraints will be passed from the spectrum adaption sublayer below, and the communication patterns and service requirements will be passed from the application adaption sublayer above.

Node characteristics: We design practical wireless backbone construction schemes with the considerations of heterogeneous wireless nodes, in terms of communication capability, storage capability, computational capability, energy resource, etc., or any combination of them.

Transmission schemes: We consider three types of transmission schemes: (1) traditional flow-based scheme, (2) network coding scheme, and (3) physical-layer network coding (PLNC) scheme. Communication patterns and service requirements: As discussed in the last section, future multihop wireless networks will be able to support a variety of traffic patterns, including one-to-one (unicast), one-to-many (multicast), one-to-all (broadcast), many-to-one, and many-to-many [1]. For each category, there can be multiple flows in the network and each of them can have a different data rate type and delay type requirements. Overall, we have an application traffic matrix as the input for the backbone construction. With our definitions above, existing studies can be readily classified. For instance, most existing studies on backbone construction assume a single broadcast flow. With such an assumption, it is reasonable to develop backbone topology with techniques such as the minimum connected dominating set (MCDS) [4], whose objective is to minimize the backbone size.

In our AC-MWN, nodes are equipped with multiple interfaces so that richer spectrum resource

can be utilized. In [5], we study the backbone network construction with the introduction of channel bonding technique [6]. Channel bonding technique utilizes multiple consecutive channels as one so that the bandwidth is increased. With multiple antennas and multiple interfaces, channel bonding technique is getting more popular in wireless communication. Considering the under-utilized TV band where nearly 70% of the spectrum is available, the throughput of the backbone network of AC-MWN can be dramatically increased. As shown in Fig. 2, even when the channel availability for cognitive users is only 30%, the average bandwidth of the backbone network is doubled compared with the one without channel bonding. However, due to limited spectrum resources and the interference of wireless transmission in the same spectrum, bonding more channels may not yield to the maximum throughput of the backbone network.

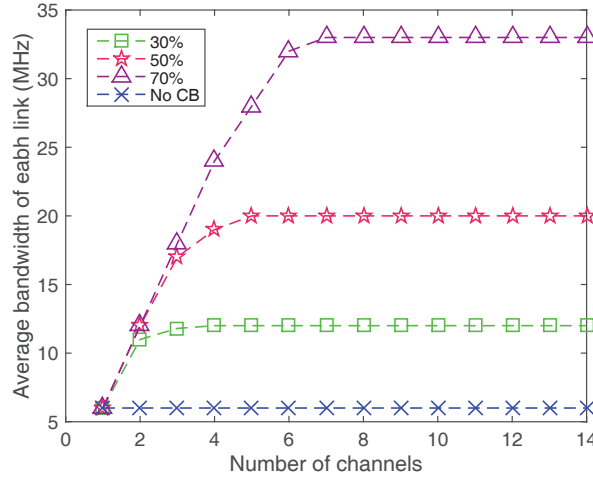


Fig. 2. Average bandwidth of each link.

After a backbone network is established, we further apply multi-interface and channel bonding technique into application-aware routing for origin-destination applications in AC-MWN [7]. As shown in Fig. 3(a), our proposed application-aware routing scheme utilizes the spectrum resource and provide O-D (origin to destination) pair service through multi-path and multi-link transmission. On one hand, the achievable service request multiple times higher than traditional schemes without channel bonding even when spectrum availability is only 30%. On the other hand, fewer links are needed to fulfill O-D pair service and thus the network performance is further enhanced, as indicated in Fig. 3(b).

Network coding [8] has been proven an effective technique to increase throughput in many

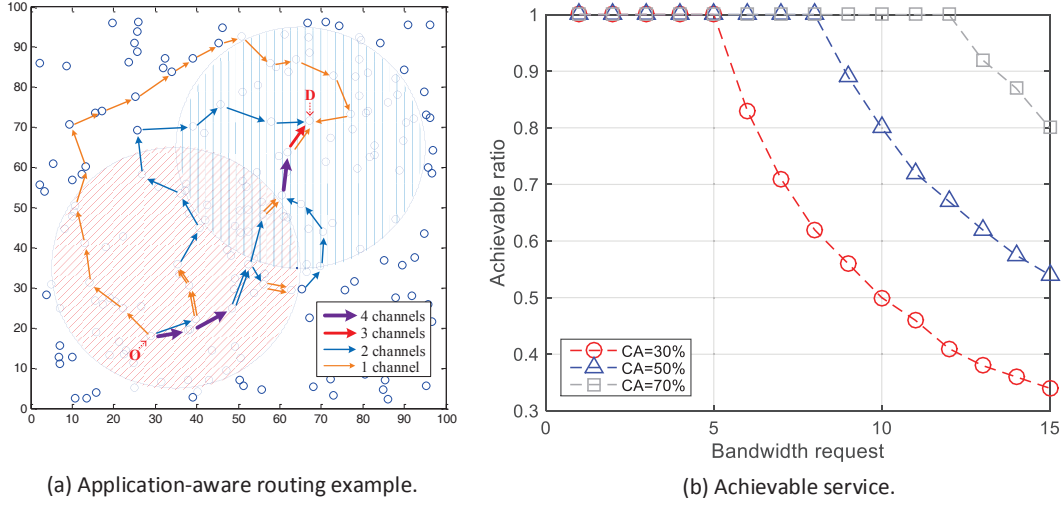


Fig. 3. Application-aware routing scheme with channel bonding

types of networks. For example, without network coding, four channels are needed for two nodes to exchange information through an intermediate node within two time slots. With network coding, one channel is saved because the intermediate node is able to broadcast the coded information to the two nodes. In [9], we propose a network coding aware routing scheme which is intended to maximize the throughput for AC-MWN. As shown in Fig. 4, network coding-aware routing scheme has a better network performance when channel availability is relatively low (i.e., 20% to 60%), which is exactly the case in AC-MWN.

(a) Throughput of network coding-aware routing v.s. shortest path routing.

IV. SPECTRUM ADAPTATION FOR AC-MWN

In this section we present the design of the spectrum adaptation sublayer for AC-MWN, and the interactions with the network cognition sublayer above and the physical layer below. The spectrum adaptation sublayer will obtain the spectrum availability information from the spectrum sensing function in the physical layer below, and pass it to the network cognition sublayer above for the network layer function (routing) design. At the same time, it will receive the spectrum usage guidelines from the network cognition sublayer above, and the spectrum usage guidelines will be used for dynamic spectrum allocation in the physical layer below.

Here, we investigate how the spectrum availability information can be abstracted and be used

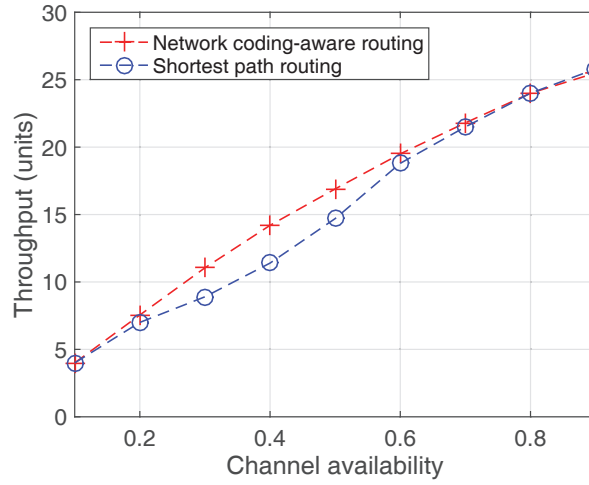


Fig. 4. Throughput of network coding-aware routing v.s. shortest path routing.

by the algorithms in the network cognition sublayer. Spectrum sensing has been comprehensively studied for the past ten years. In order to achieve the cognitive network design in AC-MWN, it is necessary to implement the basic spectrum sensing schemes and provide the realistic spectrum availability information to the network layer. We consider the spectrum occupancy as random variables over frequency and time domain. Based on the stochastic properties and asymptotic performance of eigenvalues of random matrices, we can apply these properties for the spectrum sensing in cognitive radios. We can capture the channel state information by exploring the following schemes.

Scheme 1 - Energy detection for wideband spectrum sensing. In wideband cognitive radio, wideband (i.e. from 0 to 3 GHz) spectrum sensor scanning multiple licensed bands may not be practical for all feature detection algorithms to identify the primary users (PUs) operating in the measured frequency band. In this case, it may be preferred to use energy detection. As a secondary user (SU) or cognitive user, this sensing and transmission function is performed over the wider bandwidth to give the highest probability of detecting unused spectra - opportunistic transmission. The unique sensing function requires quality hardware such that the front-ends have several GHz sampling rate with high resolution (at least 12 bits), if GHz bandwidth need to be searched. Therefore, we can use energy-based sensing which does not require a priori knowledge of the signals.

Scheme 2 - Spectrum sensing using cyclostationarity. The inherent spectral redundancy caused by the use of a cyclic prefix in orthogonal frequency division multiplexing (OFDM) signals has been exploited in several literature, e.g., [10, 11]. A unified approach to the recognition of signals belongs to the three basic air interfaces categories: single carrier TDMA, OFDM systems, and single carrier CDMA systems. It is also used to wideband CDMA. It has been used in a framework of overlay/underlay cognitive radio. This unified approach may be the most promising from the view point of stochastic performance, if there is a priori information about the communications such as modulation format [11]. Therefore higher-order statistics of the cyclostationary signals are explored for spectrum sensing.

Scheme 3 - Sensing dynamic range of front-end. A major limitation in a radio front-ends ability to detect weak signals is its dynamic range, which dictates the requirement for number of bits in A/D converter. Since it is difficult to design high-resolution A/D converters - the pricing will not follow Moores law, it is highly desirable to relax the A/D requirement. In addition, the power consumption and complexity of ADC increases nearly exponentially with the resolution or the number of bits. For example, TV broadcasters have set a stringent limit for the digital TV signals to be reliably detected (probability of detection greater than 90% with probability of false alarm less than 10%) at a signal strength of -116 dBm translating to roughly -21 dB of signal-to-noise ratio (SNR) based on the receiver noise figure (NF) of around 11 dB and the use of omnidirectional antenna for spectrum sensing. Based on the traditional estimation and detection framework, FCC determined a detection sensitivity of -114 dBm. Measurements suggest that using this threshold will result in limited white space availability, especially in metropolitan area where spectrum demand is high. The research community has developed cooperative approaches to spectrum sensing that do not require the same fading margins because they can exploit cooperative diversity. However, these approaches are impractical because the current regulatory model is based on certification of individual devices, and there is no notion of certifying the cooperative performance of devices. Therefore, we plan to develop fast algorithms insensitive to the dynamic range.

In the design of spectrum adaptation sublayer for AC-MWN, we first study how the spectrum availability information can be abstracted and be used by the algorithms in the network cognition sublayer, i.e., how to capture the channel state information by exploring the three schemes described above, Scheme 1 - Energy detection for wideband spectrum sensing; Scheme 2 -

Spectrum sensing using cyclostationarity; and Scheme 3 - Sensing dynamic range of front-end. We define a simple interface between the network cognition sublayer above and the spectrum adaption sublayer, so that the spectrum availability information obtained above can be used by the network cognition sublayer above to make the routing and transmission decisions. We further define a simple interface between the spectrum adaption sublayer and the physical layer below, so that the spectrum usage guidelines can be passed to the physical layer for dynamic spectrum access, thus a cognitive MWN.

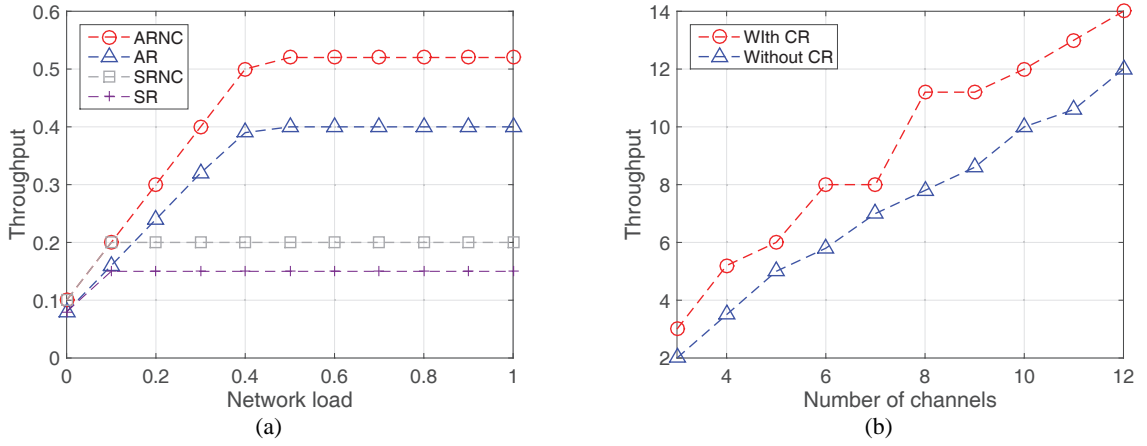


Fig. 5. (a) Network load v.s. throughput in uni-cast. (b) Number of channels v.s. throughput in multicast transmission.

Because of the dynamic activities of PUs, SUs need to allocate their resources and route accordingly so that the multi-hop transmission can remain connected with high throughput. In [12], we apply network coding with backpressure algorithm and dynamic channel allocation scheme into unicast routing in AC-MWN. Our objective is to maximize the aggregated throughput of all time slots while ensuring the stability of all the queues from the backpressure algorithm. As shown in Fig. 5(a), our proposed schemes (i.e., AR for adaptive routing and ARNC for adaptive routing with network coding) achieve higher throughput than both shortest path routing (SR) and shortest path routing with network coding. Moreover, we once again prove that network coding improves network performance.

In addition to unicast, we further study channel allocation and routing in multicast transmission in AC-MWN [13]. Multicast has its advantage of saving spectrum resources by broadcasting. Due to the dynamic activities of PUs, tree-based routing schemes may not work well for multicast

transmission in AC-MWN. In our proposed schemes, we maximize the transmission rate of the network with several multicast sessions. As shown in Fig. 5(b), our proposed scheme achieves higher throughput.

V. TESTBED IMPLEMENTATION AND MEASUREMENTS

In this section, we set up a testbed for the proposed AC-MWN to implement the basic functions of cognitive radio and the proposed schemes. Moreover, we implement a video stream application in AC-MWN based on the testbed setup. The testbed consists of three laptops, two USRP2-N210 software defined radios (SDR) [14], and one USRP2 SDR. The SDRs are capable of transmitting in both 824-960 MHz and 1710-1990 MHz spectrum. Most of the work done was in the lower band. Each laptop operates as signal generator and processor. The laptops are identically configured, running Ubuntu [15] version 13.10 64-bit operating system with GNU Radio and GStreamer software packages.

A. Basic Measurements for Benchmark

When a channel is busy, SUs should sense a much higher power compared with an idle channel. In order to establish a benchmark for further implementations, we first set one SDR as a PU, and set the other two as SUs. When the PU is transmitting on a specific channel, we tune the SUs to measure the receiving power of that channel. The measurement is done for the spectrum from 824 MHz to 960 MHz with/without PU activity for 1,000 times. The average results are shown in Fig. 6(a). As we can see, receiving power is much higher with PU activity compared with the one without PU activity. The average values are used as benchmark for channel switching.

In the second step, we measure the receiving power on the adjacent channel of a channel with PU activity. The channels chosen for sensing started at 820 MHz and finished at 960 MHz incremented by 35 MHz. The channels used for primaries were 830 MHz, 900 MHz, and 960 MHz. The results in Fig. 6(b) are the average values of 1000 samples of each aforementioned channel. As we can see, adjacent channels within 25 MHz of 900 MHz are significantly affected. However, it is not the case even within 10 MHz when the PU transmits on 830 MHz. This information can be used to establish a minimum band gap between the current channel and the

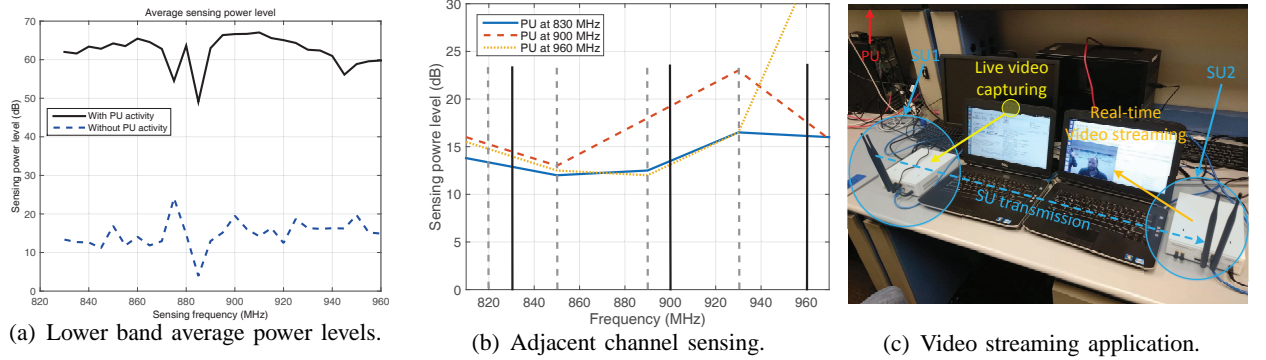


Fig. 6. Upper and lower band average sensing power levels.

new channel chosen. More channel efficiency can be achieved if adaptive channel gap is adopted based on real-time channel quality.

B. Video Streaming Application

In this preliminary implementation, a one-way video streaming service between two SUs is provided based on the proposed AC-MWN architecture using 900 MHz spectrum. The third SDR functions as a PU with arbitrary activities. For better service, channel sensing/switching need to be transparent to users. Therefore, a maximum of approximately 150 *ms* delay can be noticed between the transmitter and the receiver. However, neither the transmitter nor the receiver notices any interruption due to background channel sensing/switching. In the application, we adopt GStreamer as the application programming interface (API) to capture, encode and pipe Audio/Video (AV) to GRC. Fig. 6(c) shows the video stream application. The computer on the left captures live video through webcam. Signal is transmitted from SU_1 to SU_2 . Live video streaming is shown on the right-hand-side computer.

VI. CONCLUSION

In this paper, we proposed a new architecture for application-aware cognitive multihop wireless networks. With cognitive radio technique implemented in AC-MWN, it is a visionary architecture for future low cost and flexible wireless communication networks. We studied the proposed AC-MWN from different aspects, including mainly backbone construction and routing. Several techniques such as channel bonding, network coding and spectrum adaptation were considered in

the study to enhance the performance of AC-MWN. Moreover, a testbed was implemented to test the proposed schemes for AC-MWN. Besides basic functions (i.e., channel sensing/switching) of cognitive radio, a video streaming application was implemented as a preliminary demonstration of the AC-MWN architecture. In the future work, more SDRs will be applied to establish a larger network. Video conference will be the application implemented on the improved testbed.

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REFERENCES

- [1] K. Lu, Y. Qian, H.-H. Chen, and S. Fu, "WiMAX networks: From access to service platform," *IEEE Network*, vol.22, issue 3, pp.38-45, May/June 2008.
- [2] A. Srinivas, G. Zussman, and E. Modiano, "Construction and maintenance of wireless mobile backbone networks," *IEEE/ACM Transactions on Networking*, vol. 17, no. 1, pp. 239C252, 2009.
- [3] H. Guo, Y. Qian, K. Lu, and N. Moayeri, "Backbone Routing over Multihop Wireless Networks: Increased Network Coding Opportunity", in Proceedings of *EEE ICC'10*, Cape Town, South Africa, May 23-27, 2010.
- [4] D. B. West, "Introduction to Graph Theory", 2nd ed., Prentice Hall, 2000.
- [5] F. Ye, J. Zhou, Y. Yang, H. Sharif, Y. Qian, "Constructing Backbone of a Multi-hop Cognitive Radio Network with Channel Bonding," in Proceedings of *IEEE GLOBECOM'2012*, Anaheim, CA, USA, December 3-7, 2012.
- [6] S. Aleksic, "Optical burst-switched WDM networks with channel bonding," *IEEE CNSDSP'08*, pp.405-409, July 2008.
- [7] F. Ye, J. Zhou, Y. Qian, and R.Q. Hu, "Application-Aware Routing for Multi-hop Cognitive Radio Networks with Channel Bonding," in Proceedings of *IEEE GLOBECOM'13*, pp.4372-4377, Atlanta, Dec. 2013.
- [8] R. Ahlswede, N. Cai, S. Li, and R. Yeung, "Network information flow," *IEEE Transaction on Information Theory*, Vol.46, No.4, pp.1204-1216, 2000.
- [9] Z. Shu, J. Zhou, Y. Yang, H. Sharif, and Y. Qian, "Network Coding-aware Channel Allocation and Routing in Cognitive Radio Networks," in Proceedings of *IEEE GLOBECOM'12*, Anaheim, Dec. 2012.
- [10] Z. Tian, G. B. Giannakis, "A Wavelet Approach to Wideband Spectrum Sensing for Cognitive Radios," in Proceedings of *CROWNCOM'06*, Mykonos Island, Greece, June 2006, pp. 1C5.
- [11] J. A. Bazerque and G. B. Giannakis, "Distributed Spectrum Sensing for Cognitive Radio Networks by Exploiting Sparsity," *IEEE Transactions on Signal Processing*, vol.58, issue 3, pp.1847-1862, 2010.
- [12] Z. Shu, J. Zhou, Y. Qian, and R. Q. Hu, "Adaptive Channel Allocation and Routing in Cognitive Radio Networks," in Proceedings of *IEEE GLOBECOM'13*, Atlanta, Dec. 2013.
- [13] Z. Shu, J. Zhou, Y. Qian, and R. Q. Hu, "Channel Allocation and Multicast Routing in Cognitive Radio Networks," in Proceedings of *IEEE WCNC'13*, Shanghai, China, Apr. 2013.
- [14] <http://www.ettus.com>
- [15] <http://www.ubuntu.com>

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