ROSALNet: A Spectrum Aware TDMA Mesh Network for Rural Internet Connectivity

Nitin Rakheja*, Prerna Bhatia†, Vishal Sevani‡ and Vinay J. Ribeiro§
Department of Computer Science and Engineering, Indian Institute of Technology Delhi*†§, India
Department of Computer Science and Engineering, Indian Institute of Technology Bombay‡, India
Amarnath and Shashi Khosla School of Information Technology§, Indian Institute of Technology Delhi, India
nitin.rakheja@gmail.com*, bhatia.prerna12@gmail.com†, vsevani@iitb.ac.in‡, vinay@iitd.ac.in§

***Abstract*—In this paper, we present ROSALNet, a low-cost TDM mesh network which is designed to opportunistically exploit TV white spaces (TVWS) to provide broadband Internet connectivity to remote rural areas. Recent research has proposed WiFi-based wireless networks as cost-effective solutions to bridge the last-mile problem. However, WiFi normally operates in the 2.4 GHz band and above, where signal propagation is not as good as in sub-GHz bands such as terrestrial TV bands. Exploiting TV white spaces for broadband connectivity can potentially further bring down the cost of such wireless networks to a more affordable level.**

ROSALNet is implemented on commodity hardware using the open-source OpenWrt operating system. A single mesh node currently costs US$330, which is significantly cheaper than competing TVWS commercial solutions. ROSALNet can opportunistically use spectrum by looking up a white space database and by performing spectrum sensing. Our experiments with ROSALNet on a university campus demonstrates the superior coverage possible with TVWS compared to 2.4GHz. ROSALNet exploits an existing TDM mesh implementation originally designed to use WiFi bands, called FRACTEL, thereby inheriting its attractive features of low-latency and low jitter. Results from a lab testbed consisting of 4 nodes show that ROSALNet can provide an aggregate throughput of 11Mbps, which is sufficient to support triple play services.

Keywords*—*Spectrum Sensing, Cognitive Radio, Dynamic Spectrum Access, Opportunistic Spectrum Sharing, Rural Broadband, TV white spaces.

I. Introduction

Providing broadband Internet connectivity to the masses is a key technological goal in several developing nations. In several of these countries, a large percentage of the population resides in far flung rural areas. Because the density of population and purchasing power in such rural areas is low, laying fiber or other cables to these locations is financially unviable. As a result, the digital divide continues, with broadband penetration being as low as 1% in some nations [7].

Wireless networks have been proposed by several researchers to overcome the last-mile problem [9], [10], [13]. To reduce cost to meet the price point of developing countries, several of the proposed solutions use (i) unlicensed frequency bands, which are free, unlike expensive licensed spectrum, and (ii) commodity hardware, such as WiFi cards which sport advanced physical layer technology like OFDM and are yet inexpensive due to economies of scale.

978-1-4799-2361-8/14/$31.00 © 2014 IEEE

Recently, the opening up of TV white spaces (underutilized TV bands) for unlicensed use by regulators (FCC, OFCOM etc.) has provided an opportunity to develop wireless networks with better reach and/or lower cost than the existing wireless rural networks [6]. In case a TV band is not used in a particular geographical region by the incumbent licensed user (termed a *primary user*), then other unlicensed (*secondary*) users are permitted to transmit in that band, under certain limits on the emitted power.

Terrestrial TV bands are roughly in the 400 - 800 MHz spectrum (in many countries) where signals have much better propagation and penetration characteristics than the 2.4GHz or 5GHz WiFi bands. This implies that TVWS networks can reach distant locations using fewer wireless hops or lower transmit power than WiFi networks. In addition, they may not require line-of-sight to function well in contrast to long-distance WiFi connections that do, and hence can potentially use shorter towers for hoisting antennas. In addition, sub-GHz electronics is generally known to be easier to develop and components less expensive than those for higher frequencies.[1]

ROSALNet is designed to query a TVWS database and vacate a white space whenever a TV transmission is scheduled to begin in that band. The task of making all mesh nodes vacate a particular band requires all nodes to be time-synchronized as well as aware of back-up channels to hop to. Implementing channel switching turned out to be non-trivial using the hardware and suite of software we used to build ROSALNet with, as described in later sections.

ROSALNet has the additional capability of sensing spectrum which can be used to complement or replace the TV database querying. Spectrum sensing also helps determining the presence of other secondary transmitters in the vicinity. We hence decide to include a spectrum sensing capability in ROSALNet.

A single mesh node of ROSALNet consists of a Microtik router board 433AH with a mounted XR2 card, a Doodle Labs DL550-80 card and an RF Explorer model WSUB1G that together cost less than $460 to setup which is far less expensive than competing commercial TVWS solutions [4]. Without the need for spectrum sensing, the RF explorer can be eliminated, which brings the cost down further to $330.

[1] The initial lack of economies of scale for TVWS equipment may make them expensive. We expect prices to drop as the popularity of these devices increases.

This price will likely come down with time as economies of scale kick in for the TVWS cards.

We decided to modify the MAC and routing protocols of FRACTEL, which employs a TDM MAC to ensure low latency and jitter, avoids hidden terminal problems and supports sustained throughput of greater than 11Mbps [9]. For details about FRACTEL we refer the interested reader to the original paper describing the design [10]. Our focus in this paper will be on the TVWS aspects of ROSALNet.

The two-tiered topology of a typical ROSALNet deployment is depicted in Figure 1. ROSALNet extends Internet connectivity from a root node to remote areas through a tree-structured mesh network which forms the first tier. The links along this tree are intended to cover long distances (of the order of several kilometers) and all employ TV white space frequencies. Each mesh node in this tree has an additional WiFi radio that enables it to act as a WiFi access point to which client devices can connect. These form tier-2 of the network. We deliberately choose not to use TV white spaces in the second tier keeping cost in mind because TVWS equipment is currently more expensive than WiFi hardware. Ideally, however, TV white spaces are well suited for access too, in addition to long-distance backhaul, and have been suggested for use in "Super WiFi" networks [5].

Through experiments on a university campus with ROSALNet we demonstrate the efficacy of using sub-GHz bands versus 2.4GHz bands. We also perform experiments in a 4 node testbed to evaluate the throughput possible with ROSALNet. We summarize the main contributions of the paper below.

Main Contributions

- We present the design of ROSALNet, a low-cost mesh network which opportunistically uses TVWS for communication. ROSALNet can leverage TVWS databases and vacate a TV channel if the incumbent begins transmission in it.
- We present implementation details of ROSALNet and develop a prototype mesh node consisting of commodity hardware and an open source operating system.
- Through experiments on a university campus we show that sub-GHz frequencies can give better ranges than ISM bands and even work in non-line-of-sight (NLOS) scenarios. We also evaluate the performance of ROSALNet in terms of throughput and jitter in a 4 node testbed.

The rest of the paper is organized as follows. Section II describes related work and Section III describes the design and implementation aspects of ROSALNet. We present experimental results from a university campus in Section IV and conclude in Section V.

II. Related Work

We discuss related work for (i) broadband rural connectivity using WiFi-based cards, and (ii) TVWS networks in this section.

A. WiFi for long-distance rural connectivity

In order to provide long-distance rural connectivity, several works have been proposed to use WiFi-based networks because of the low-cost of WiFi equipment as well as its advanced physical OFDM layer. WiFi was not designed for long-distance transmission, however, and hence its MAC layer was modified to improve performance. For example, Raman et al. [14] replaced CSMA with TDMA and Patra et al. [13] improved robustness through an adaptive error recovery mechanism which used bulk acknowledgements and FEC. FRACTEL improved scalability with the use of hierarchy in the network, centralized scheduling, a multi-hop connection-oriented link layer, and a multi-hop framing structure [9]. Our work differs from these solutions in that it uses TV white spaces and so needs additional mechanisms such as channel switching, TVWS database lookup capability, spectrum sensing etc.

B. TV White space networks

Recently, few prototypes of TVWS networks have been developed and proposed in the literature. P. Bahl et al. present *WhiteFi*, a UHF white space wireless network that adaptively configures itself to operate in the most efficient part of the available white spaces [8]. Their focus lies primarily on setting up a WiFi like network consisting of an Access Point (AP) with multiple associated clients. Rohan Murty et al. came up with a database-driven white spaces network called "SenseLess" [12]. In SenseLess, white space devices do not sense the spectrum but rely on a database service to determine white spaces availability. In contrast to these works, our focus was on long-distance and low-cost rural connectivity using TVWS.

A few point-to-multipoint commercial solutions have been developed which conform to FCC TVWS regulations [2], [4]. Through recent personal communications we learned that a Carlson base-station costs $4,000 and a client $600. A Neul trial system consisting of a single base-station and one client costs $12,000 with every subsequent client costing $850. The exact protocols used by these networks are proprietary. In contrast, a ROSALNet node is built from commodity hardware, currently costs $330 to put together, and allows for a multi-hop mesh network to be setup. The Doodle Labs cards used in ROSALNet are essentially Atheros based WiFi cards made to operate in TV bands. They hence do not meet the stringent emission masks mandated by the FCC for TVWS operation. We note, however, that ROSALNet is designed for developing nations, most of which have not passed TVWS regulations. Some of these countries have more than 90% of TV bands unused at all times [11].

III. Implementing a Spectrum Aware White Space Network

In this section we begin with a taxonomy of different nodes in ROSALNet, and then describe the hardware used to build ROSALNet, the protocols used by the nodes to switch channels when a primary user comes on, and details about the software implementation of this algorithm.

A. Taxonomy of network nodes

The tier-1 of ROSALNet uses FRACTEL as the underlying MAC layer [9]. FRACTEL forms a tree for communication.

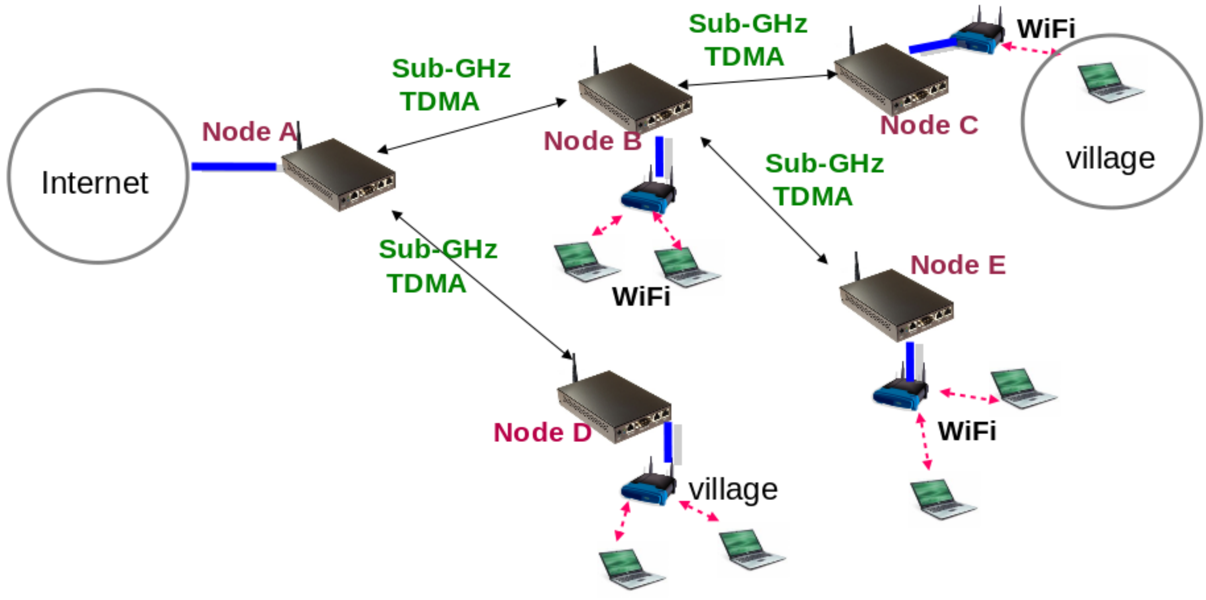

Fig. 1. Topology of ROSALNet two-tier network. The first tier provides long-distance connectivity using TVWS and the second provides local access using WiFi.

We term each node in the tree a *mesh node* and term the root of the tree the *root node*. The root node has Internet access and is responsible for obtaining TV channel occupancy from an online database. It thus acts as a *server* of this information which must be obtained by all the other mesh nodes which act as *clients*. Each mesh node is part of both tier-1 and tier-2. It connects to its parent and children over a TV white space and also acts as a local AP for tier-2. Users who want Internet access through ROSALNet can use any WiFi enabled device to connect to a local AP. They obtain an IP address from the AP which is subsequently used for routing.

B. Mesh node hardware

Each mesh node is designed to operate on a TV band for the tier-1 backhaul and also a WiFi ISM band to act as an AP for tier-2 (see Figure 1). A bare bones mesh node (without the optional RF sensing capability) consists of a Mikrotik Board 433AH (base router platform), a DL550 (sub-GHz Card for tier-1 backhaul), and an XR2 (WiFi card for tier-2 WiFi AP).

1) Microtik Router Board 433AH: For our implementation we chose Mikrotik Router Board 433AH to form the base platform for the mesh node. Each of these Microtik boards has three MiniPCI Type IIIA slots with 3.3V power signaling in which WiFi cards can be inserted. One slot houses a DoodleLabs DL550 card which operates in the 510 - 590 MHz band. This card is used to communicate over the tier-1 multihop backhaul. We fit the second slot with an off-the-shelf Atheros based XR2 2.4GHz WiFi card which makes the node act as a WiFi AP. The Mikrotik Board is re-flashed to run the OpenWRT OS replacing the proprietary Mikrotik Router OS which comes with it. We do so to exploit the MAC modifications possible with OpenWRT.

2) Doodle Labs DL550: Doodle Labs DL-550 is a high performance embedded OFDM radio transceiver for operations between 510MHz-590MHz. It supports Software configurable high Tx power up to +30 dBm (1W) for long-range coverage. The design uses a highly linear power amplifier and supports OFDM with 64 QAM, 16 QAM, QPSK, and BPSK. The radio transceiver is supported by open source MadWiFi Linux kernel drivers. The device is available off the shelf. More details can be obtained by contacting Doodle Labs [1]. The total cost of a Microtik RB433AH board along with a DL550 and an off-the-shelf WiFi miniPCI card roughly comes to $330.

3) RF Explorer: spectrum sensing hardware: A ROSALNet mesh node can also be optionally interfaced to a separate spectrum sensing hardware unit which can give it information about whether a channel is currently being used or not. We have used an RF Explorer model WSUB1G to perform spectrum sensing in our testbed [3]. This device is a handheld digital spectrum analyzer based on a highly integrated frequency synthesizer. The model comes with a Nagoya NA-773 wideband telescopic antenna. More details can be found from the RF Explorer technical specifications [3]. The device currently costs nearly $130. This expense could potentially be removed by using the carrier sensing capabilities of DL550 cards thereby further lowering the cost of ROSALNet nodes.

C. Synchronization

In ROSALNet all mesh nodes obtain information about availability of TV spectrum periodically from the root node. In addition, all mesh nodes are synchronized with an NTP server on the root. As a result, all the mesh nodes know well in advance when to vacate a particular channel. This allows all nodes to switch channels simultaneously.

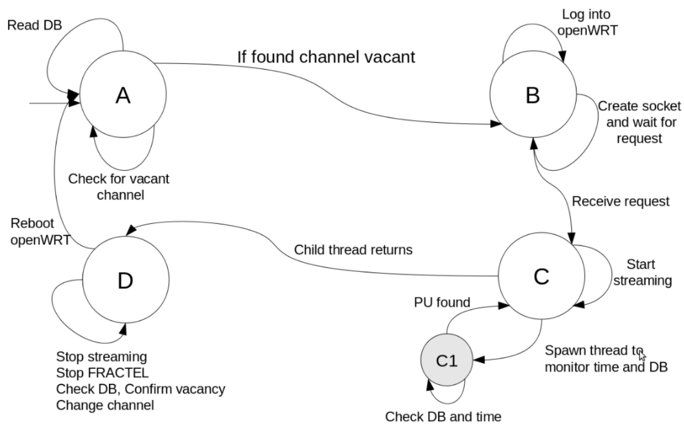

Fig. 2. State Diagram of Server

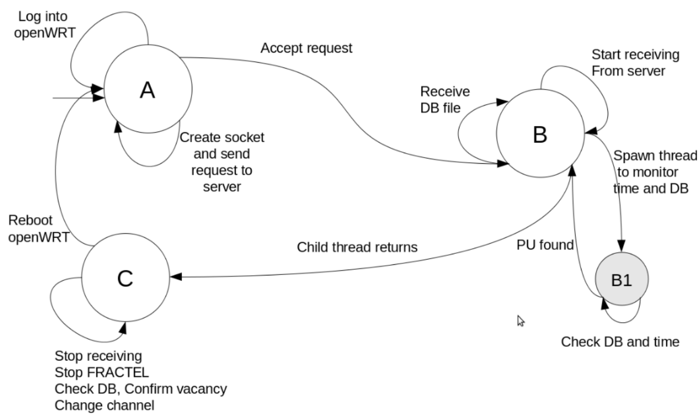

Fig. 3. State Diagram of Client

D. Channels of communication

The channel on which tier-1 is operating is termed as the "Main channel". All mesh nodes identify a Backup channel to be used for communication on tier-1 in the event a primary user starts using the Main channel. Both the channels in our current implementation are 20MHz wide. This bandwidth can easily be reduced to 10MHz or 5MHz using the DL-550 cards. The Main Channel and the Backup Channel on bootup are manually configured before the mesh nodes boot up. Subsequently, the Backup Channels are modified based on the spectrum availability information learned from the root.

E. Implementation details

We now present fine details of the implementation of server and client.

1) Server details: The root node runs the server and is connected to the Internet as the gateway. When the root boots up, it first reads the TVWS database from the Internet and prepares a Spectrum Availability Table containing the schedule for the next 24hours. This table is transmitted to each child as soon as it boots up and establishes a connection with the root. Once the table is ready, the root senses the surroundings to ensure that unused channels specified by the database are indeed unoccupied.

The states that the root goes through are shown in Figure 2. Once the root has booted it searches for a TVWS. Upon finding a White Space from the database, it performs spectrum sensing with an RF Explorer to verify that the White Space is unoccupied. The root then creates sockets for allowing the clients to establish connections and goes into a wait state wherein it expects requests from the clients to connect.

Once such a request is received from a client, the root establishes a connection and upon confirmation from the client, commences data exchange. Simultaneously, the root also spawns a thread that continuously checks the Spectrum Availability Table and tallies it with the current system time. Time is kept synchronized on the root to a global atomic clock through NTP. The root keeps an NTP server running on it and all clients synchronize their clocks with the root. A parallel thread responsible for checking the database and the time returns control to the main program as soon as it detects that the system time corresponds to a time in the Spectrum Availability Table when the band in question is occupied by a primary user. Once this interrupt is received at the root it stops data transmission and suspends all communications at the MAC layer. It then goes into the waiting state wherein it continuously checks the Spectrum Availability Table and looks for a free spectrum band. At this stage, if the spectrum corresponding to the backup channel is found to be available, the root changes the channel in the configuration file and performs the procedure for reconnection.

2) Client: The states that the client goes through are shown in Figure 3. When the client boots up, it sends a request to the server for establishing a connection. This request is replied to by the open socket at the root node. The root then sends the slot information and the Spectrum Availability Table to the client. Upon receiving this information, the client now behaves completely autonomously.

The client starts its reception of the data from the server. It also spawns a thread that continuously checks the Spectrum Availability Table to make sure that the channel being used is vacant. If the spectrum being used for communication is found to be unavailable (according to the table), the thread returns to the parent. The parent thread then stops the data exchange and suspends all communications at the MAC layer as well. It goes into a wait state wherein it continuously checks if any vacant band is available. If a backup channel exists, the client senses that band to ensure that it is unoccupied. It then changes the channel information in the configuration file by rewriting it and performs the procedure for reconnection. A condition could arise that the root and the client face different spectrum environments wherein the same channel may not be vacant for both the nodes. This occurrence can be circumvented if the root selects a backup channel only from among channels free at all mesh nodes based on the knowledge of the geographical location of all mesh nodes.

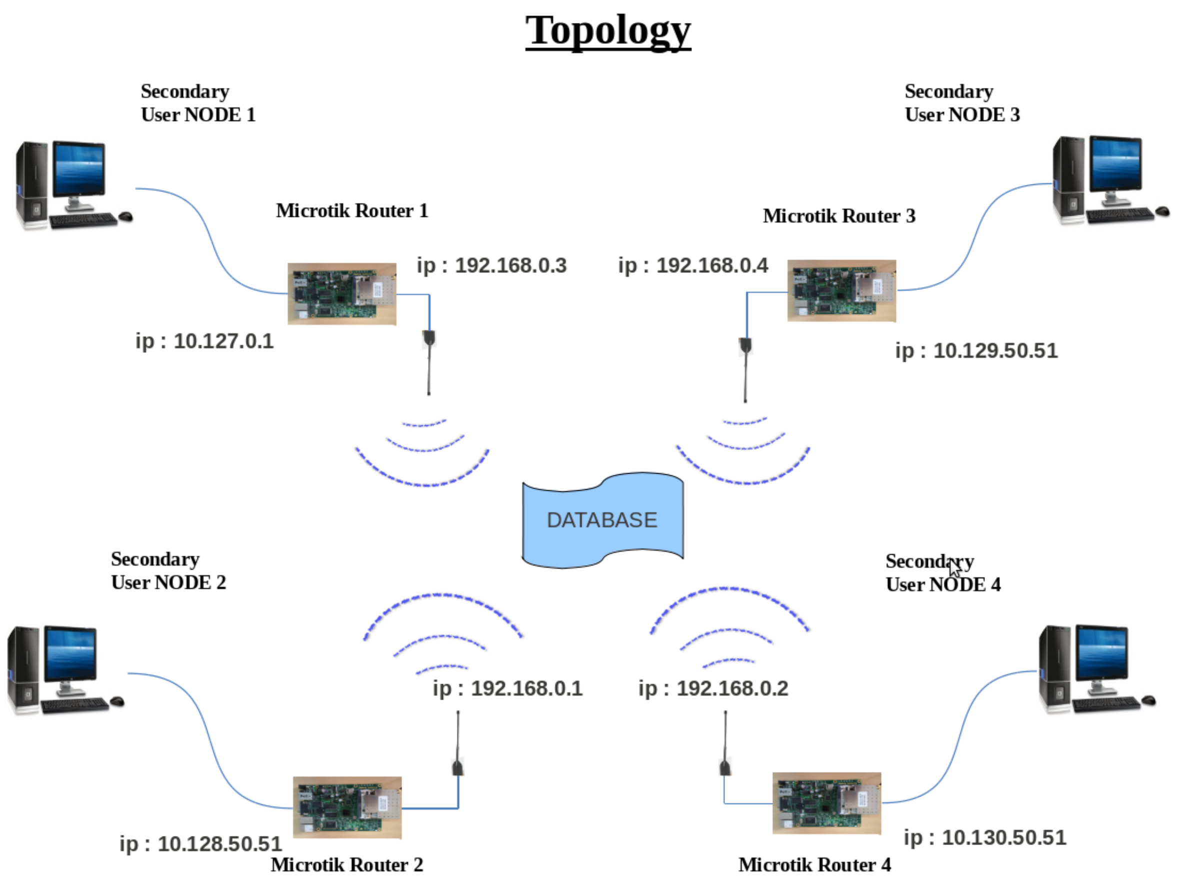

Fig. 4. Testbed Topology

IV. Experimental Results

In this section we describe results from a lab testbed as well as field experiments. We set up a testbed and exchanged data over a TCP connection between node 1 and node 3 with no intermediate hops. We also tested the network for throughput when node 1 was connected to node 3 with node 2 as an intermediate hop. The experiments were conducted for ten iterations of 3 minutes each. The maximum throughput achieved on ROSALNet was measured at 3.85Mbps by Iperf in both cases. This when aggregated for all nodes in the testbed gives 11Mbps which is the expected throughput for FRACTEL.

A. Spectrum Map : Coverage of WiFi versus ROSALNet

We plotted an Area Coverage Map for area covered by WiFi compared to area covered by ROSALNet. The experiments were conducted within the university campus. Each node in the experiment used two wireless cards, one DL550 card to operate in a TVWS and one to operate in a 2.4GHz band. Transmit powers of both radios were kept the same.

One node was placed atop a building of height of 50 ft. A second node was setup as a mobile node. We then made measurements of signal strength at 30 different locations around the university campus and recorded corresponding GPS positions. It was observed that in areas where signal strength was better than -90dBm, ROSALNET had nearly 100% reliability with zero packet loss during tests within the university campus.

We plot the coverage of WiFi Network (2.4GHz) and ROSALNET (540MHz) in Figures 5 and 6. The Figure 5 shows coverage by a WiFi network whereas Figure 6 shows the coverage using a TV band.

- Yellow colour corresponds to the areas that have coverage by a Signal Strength of less than -90dBm.
- The light orange shade depicts the areas within the campus that have coverage ranging from Signal Strength between -80dBm and -90dBm.
- The orange colour depicts the areas that have coverage of Signal Strength greater than -70 dBm.
- Similarly shades of blue from darkest to lightest depict the decreasing signal strength and datarate for WiFi.

A comparison of the coverage by WiFi with that by a White Space Network like ROSALNet reveals that the geographical area covered by ROSALNet is on an average greater than 3 times the area covered by WiFi given the same transmission and power output parameters. Additionally, ROSALNet achieves a signal strength between -80dBm to -90dBm for more than 80% of its covered area whereas for WiFi the same quantity was just 50%.

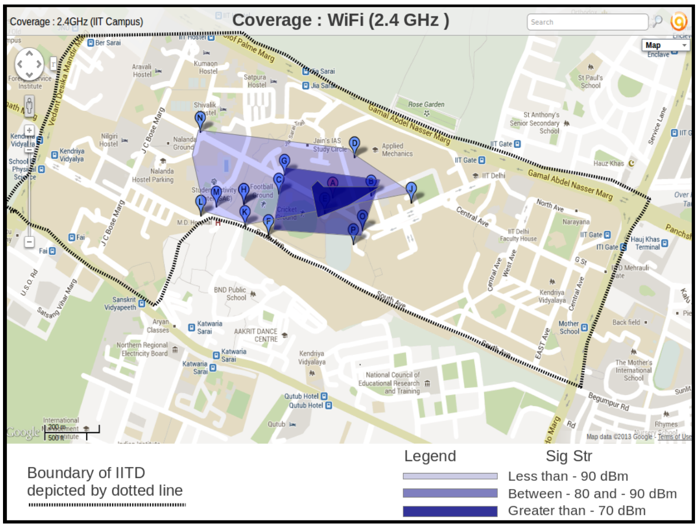

Fig. 5. Coverage by WiFi.

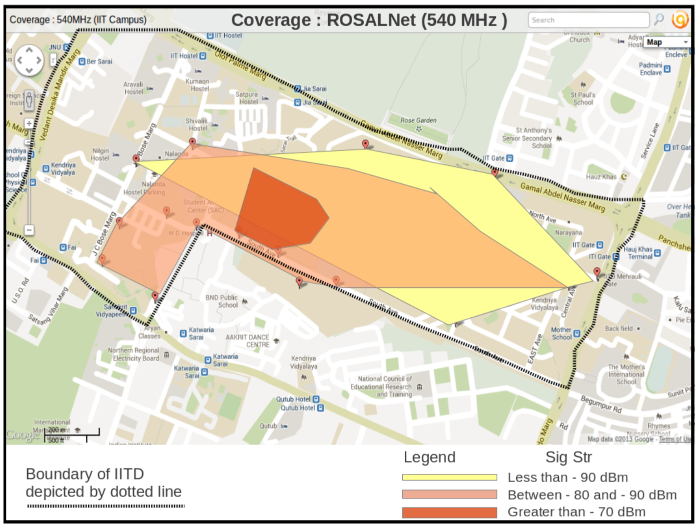

Fig. 6. Coverage by ROSALNet

ROSALNet had good NLOS coverage and could communicate even when the two nodes were sometimes separated by a building. Our experiments thus confirm the advantages of using TVWS over 2.4GHz ISM bands for long-distance communication.

V. Conclusion

We have presented ROSALNet, a low-cost TVWS network which is built atop off-the-shelf hardware and an open source operating system. Experimental results show throughput sufficient to support a few Mbps which is along expected theoretical lines. The network exploits White Spaces in the Spectrum by making use of any online available Spectrum Database and then reconfirms the vacancies by carrying out Spectrum Sensing using a low cost Spectrum Analyzer called RF Explorer. In addition, it shifts out of a TV band before any primary usage is scheduled to begin.

The most important advantage of this network is its economical viability. The hardware comprises inexpensive router boards and Sub-GHz Atheros based radio cards. The total cost of building a single White Space Network node is less than \$330 (the cost is \$460 including the optional R F explorer). The second major advantage of this network over similar networks using WiFi bands is its coverage and range. The network covers multiple times the area covered by a WiFi network with similar transmission and reception parameters. The third advantage of this network is its robustness. It is well known that lower sub-GHz frequencies have much lesser attenuation and easily bend around obstacles. This will allow the network to remain connected without having direct Line-Of-Sight between intermediate nodes, an aspect demonstrated in the experiments on a university campus.

Acknowledgments

This work was supported by the project “SPARC: Spectrum-Aware Rural Connectivity”, funded by the Department of Electronics and Information Technology (DeitY), Government of India.

References

[1] Doodle labs. http://doodlelabs.com.

[2] Neul. http://www.neul.com.

[3] R F explorer website. http://rfexplorer.com/product/model-wsub1g.

[4] Ruralconnect by carlson wireless. http://www.carlsonwireless.com/products/ruralconnect-ip.html.

[5] Super WiFi. http://en.wikipedia.org/wiki/Super_Wi-Fi.

[6] In the matter of unlicensed operation in the TV broadcast bands: Second report. *Federal Communications Commision, FCC 10-174*, 2010.

[7] The Indian Telecom Services Performance Indicators October- December 2012. *Telecom Regulatory Authority of India*, May 2013.

[8] P. Bahl, R. Chandra, T. Moscibroda, R. Murty, and M. Welsh. White space networking with Wi-Fi like connectivity. *ACM SIGCOMM Computer Communication Review*, 39(4):27–38, 2009.

[9] K. Chebrolu and B. Raman. Fractel: a fresh perspective on (rural) mesh networks. In *Proceedings of the 2007 workshop on Networked systems for developing regions*, page 8. ACM, 2007.

[10] V. Gabale, B. Raman, K. Chebrolu, and P. Kulkarni. LIT MAC: Addressing the challenges of effective voice communication in a low cost, low power wireless mesh network. In *Proceedings of the First ACM Symposium on Computing for Development*, page 5. ACM, 2010.

[11] P. Kumar, N. Rakheja, Aparna, Himanshu, Prerna, Sandeep, and V. Ribeiro. White Space Detection and Spectrum Characterization in Urban and Rural India. In *Second IEEE Workshop on Emerging COgnitive Radio Applications and aLgorithms*, page 10. IEEE, 2013.

[12] R. Murty, R. Chandra, T. Moscibroda, and P. Bahl. Senseless: A database-driven white spaces network. *Mobile Computing, IEEE Transactions on*, 11(2):189–203, 2012.

[13] R. K. Patra, S. Nedevschi, S. Surana, A. Sheth, L. Subramanian, and E. A. Brewer. WiLDNet: Design and implementation of high performance WiFi based long distance networks. In *NSDI*, volume 1, 2007.

[14] B. Raman and K. Chebrolu. Design and evaluation of a new MAC protocol for long-distance 802.11 mesh networks. In *11th annual international conference on Mobile computing and networking*, pages 156–169. ACM, 2005.