

## Network Throughput Improvement in Cognitive Networks by Joint Optimization of Spectrum Allocation and Cross-layer Routing

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### **ABSTRACT**

*This paper introduces innovative technology development that will improve performance of next-generation cognitive wireless networking among space, air, and ground assets. The paper describes methods to develop a system where cognitive users transmit wideband spread-spectrum signals that are designed to adaptively avoid the interference dynamics of the available spectrum at the receiver. These technological advances can achieve improvement in network throughput, delay, and reliability. Theoretical performance expectations are given. The theoretical approach is translated to the construction of specific software techniques and their implementation within the cross-layer wireless communications architecture. The hardware/software testbed that simulates a dynamic Ad Hoc Software Defined Radio (SDR) network is described, and a series of tests to measure the value of the optimization techniques is given. Preliminary test results and the total expected performance improvements are shown.*

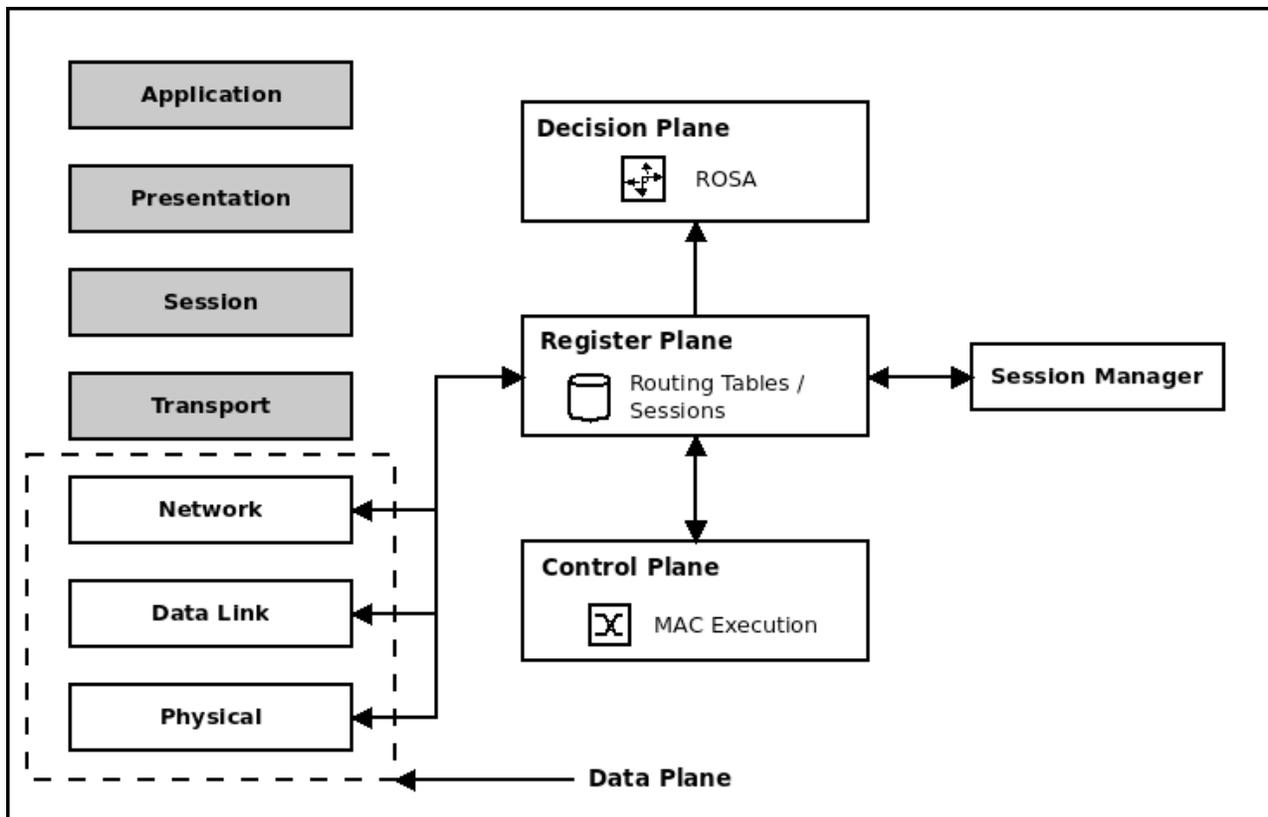
### **1.0 INTRODUCTION**

Cognitive radio networks have emerged as a promising technology to improve the utilization efficiency of the existing radio spectrum. However, in a radio network consisting of a number of primary and secondary users, primary users hold licenses for specific spectrum bands, and can only occupy their assigned portion of the spectrum. Secondary users do not have any licensed spectrum and opportunistically send their data by utilizing idle portions of the primary spectrum. In unlicensed spectrum bands there are potentially many uncoordinated devices. And in a multi-hop network the spectrum environment varies in time and space depending on the activities of primary users, interference, and fading, so the optimal spectrum-spreading channelization may therefore be different at each hop in a multi-hop path. Also as new secondary links are formed and others vanish, routing of data flows from one secondary node to another may frequently change. Therefore, controlling the interaction between routing and spectrum allocation is of fundamental importance.

The focus of the research is on developing software enhancements in multi-hop routing and spread spectrum channelization that allow for secondary and primary users to co-exist on a non-interfering basis. The authors are

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implementing optimization technique software that runs in Physical (PHY), Medium Access Control (MAC) and Network layers (i.e., “cross-layer”). Figure 7-1 shows the major components of the new development software alongside the customary seven layers of the Open Source Interconnection (OSI) Model.



**Figure 7-1: Optimization software implemented in planes that complement the lower three OSI layers.**

The software techniques are instantiated in each network node; a decentralized joint routing and code-division channelization solution that maximizes throughput by jointly optimizing the following parameters: opportunistic routing, spectrum allocation, and transmit power control. The joint optimization algorithms will be extended to include dynamic code sequence optimization. The result of this joint optimization is improved throughput and reliability. With nodes constrained to maintain constant Signal-to-Interference-plus-Noise-Ratio (SINR), network performance improvement is measured in terms of Quality of Service (QoS) metrics including throughput (Mbits/sec), and packet loss when undergoing network traffic reshaping.

**2.0 TESTBED ORGANIZATION**

The network control technology is being implemented and demonstrated in a programmable and reconfigurable testbed consisting of a grid of up to six network nodes based on the Universal Software Radio Peripheral (USRP) 2 hardware and GNU Radio software.

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Software development in the ANDRO SDR lab is aligned with companion and complementary research at testbed facilities of academic partners at the University of Buffalo and the government sponsor at the US Air Force Research Laboratory in Rome NY. Each of the three program partners has very similar SDR lab environments; thus, collaborative software development and innovations can be easily shared.

### 3.0 ALGORITHM DEVELOPMENT AND EXPERIMENTAL PROCEDURE

#### 3.1 Research Goals and Results

The research effort succeeded in demonstrating the feasibility of the approach to enable cognitive radio frequency (RF) users to implicitly cooperate with existing narrowband or wideband users of the spectrum without effectively limiting each individual device's throughput, operating distance, or both. Methods were introduced to achieve cooperative spread-spectrum access that can be measured in terms of enhanced throughput, reliability, and reduced delay. A new theoretical framework was developed based on nonlinear optimization to rigorously derive efficient distributed algorithms for joint adaptive cognitive routing and spread-spectrum allocation using waveforms compatible with existing military defense applications.

A new spread-spectrum management paradigm has been proposed in which digital waveforms are designed to occupy the entire available spectrum, and to adaptively track the interference profile at the receiver to maximize the link capacity while avoiding interference to primary users. Specifically, power and spreading code are jointly selected to maximize the pre-detection secondary SINR while providing QoS guarantees to on-going primary and secondary transmissions, and while the routing algorithm dynamically selects relays based on the network traffic dynamics and on the achievable data rates on different secondary links. Throughput and delay performance were characterized by conducting extensive simulation experiments. The simulations demonstrated the appeal of the proposed framework by indicating significant performance gains compared to baseline solutions.

#### 3.2 Routing and Spectrum Allocation (ROSA) Algorithm Development

The ROSA algorithm [1] [2] is the enabler for the SDR adaptation in response to network conditions such as events in the RF channel preventing packets reaching a destination node or slowing down such a transfer, or corrupting the data. ROSA instructs the SDR to adapt its PHY, MAC, and routing behavior according to time-varying traffic demands, network topology, and interference profile. Based on the feedback from the relay nodes and the destination node, ROSA generates real-time decisions and reconfigurations finding several possible routes and the best current route.

Data packet delivery management (transmission, reception and temporary storage) is achieved using a novel application of the backflow-pressure algorithm based on hydro-flow principles. ROSA pulses each network node for a utility value that describes the node's usage. If a relay node has many backlogged packets, then this would provide a low utility value for that particular link, and thus trigger the decision algorithm to avoid routing through that path if an alternative is available. Specifically, the routing protocol Finite State Machine (FSM) pulls routing information contained in the routing table and initiates the decision algorithms to form new network layer headers, in coordination with the MAC-layer FSM. Therefore, the routing FSM prepares packets to be sent to the MAC layer or identifies received packets from the MAC layer.

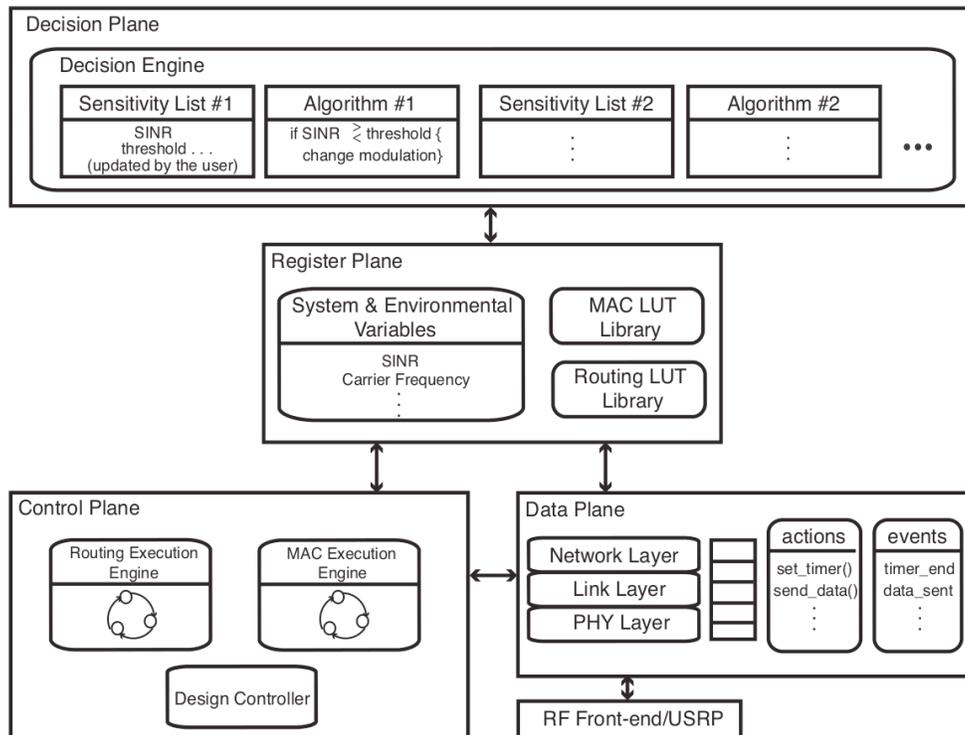
ROSA decision algorithms decide the next hop, spectrum band to be occupied, waveform and size of the contention window. After execution of the decision algorithm, the updated, optimized parameters are written to

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and made accessible from the register plane. Dynamic routing updates endure an insignificant time lag due to time spent on the decision and updating the routing tables so that the route reconfigurations are still optimized in real time.

Advanced testing and development of SDR networking protocols necessitates a relatively stable system architecture that defines interactions between components such as the OSI network layers and device Input/Output (I/O). An abstracted system architecture can be used to test a variety of protocols and programs on a common platform. Cross-layer routing algorithms such as ROSA could also benefit from such a modular architecture.

To build upon the preliminary simulation results, a new cross-layer SDR architecture was developed called RcUBe (Realtime Reconfigurable Radio). RcUBe abstracts the SDR node into four distinct planes: decision, control, register and data as illustrated in Figure 7-2. The decision plane implements routing algorithm logic; the control plane implements access-control between the layers; and the data plane implements the network, link, and physical layers of the protocol stack. All three of these layers communicate through the register plane which instantiates a shared memory model.

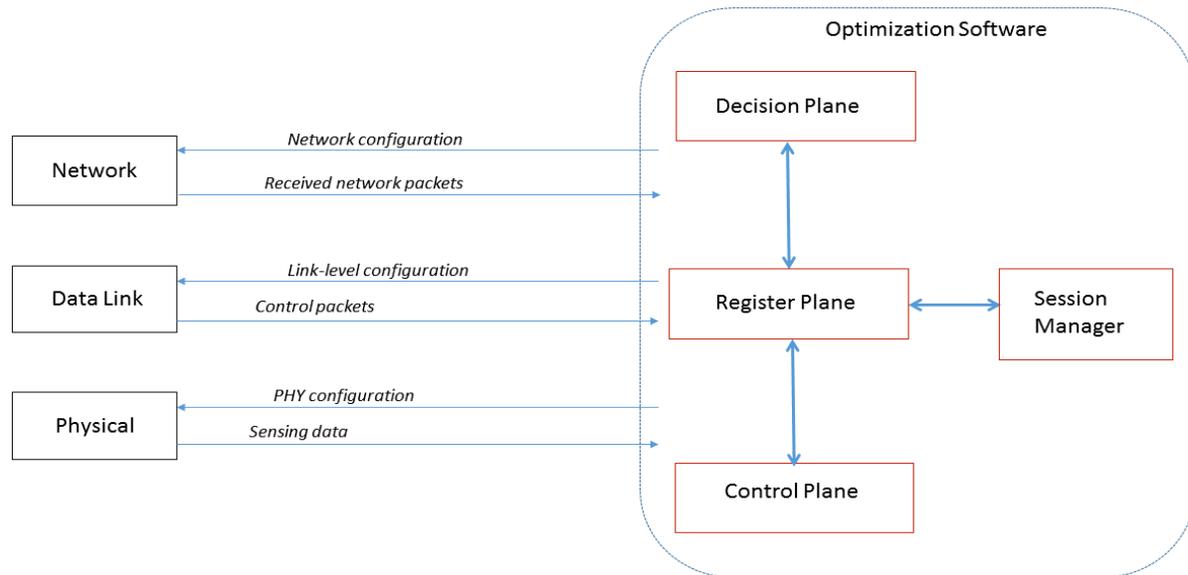


**Figure 7-2: RcUBe architecture.**

The RcUBe architecture was successfully demonstrated on a six-node USRP test bed at the University of Buffalo’s electrical engineering laboratory. It was implemented in Python and also demonstrated key concepts of the ROSA routing algorithm as a test case. After the initial RcUBe prototype was demonstrated, an expanded architecture was investigated in order to help transition the technology to other radios beyond GNU Radio and USRP platforms. ANDRO’s Cross Layer (AXL) architecture, shown in Figure 7-3, is fundamentally identical to

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RcUBE at a high-level, but it is being developed for transition into more robust testing environments. The diagram below shows how the AXL separates each of the network, link, and physical layers as abstract modules in the system. This simply is a lower level view of the interface provided by RcUBE, and more closely resembles the actual implementation. It also shows how each network layer is independently and cooperatively accessed by the optimization software.



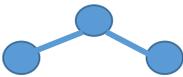
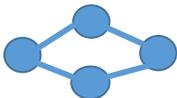
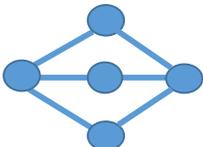
**Figure 7-3: AXL architecture representation.**

The authors are further developing an implementation of the ROSA algorithm in the AXL architecture that includes sensing using GNU Radio primitives. Under AXL, the ROSA algorithm will be able to exchange relatively up-to-date SINR estimates with each node in the network in order to jointly optimize routing operations and spectrum allocation. AXL is currently being prototyped in the Python programming language using a multithreaded architecture. Python was chosen to quickly start the testing process and to evaluate the initial design. The ROSA algorithm was developed with the assumption of a second transceiver that could be used to communicate over a Common Control Channel (CCC). Further studies are being done to implement a CCC using a time-slotted algorithm and a single transceiver. This research has assumed the presence of a second transceiver, and simulated the link using an Ethernet Local Area Network (LAN). Separate work on a wireless control channel using USRPs is being done in parallel and there are plans to integrate the work in the future.

A detailed test plan has been developed to coordinate testing of live demonstrations showcasing AXL and ROSA's functionality, starting with tests at the unit level all the way to high-level systems testing. To use AXL as an ongoing test platform it must be continuously tested, including integration and regression testing. A four-case test sequence is underway as summarized in Table 7-1. Initial testing was limited to just a pair of USRP nodes, each with a connected laptop running the AXL software. At first, MAC layer functionality must be verified including RTS/CTS/DTS (Request-to-Send, Clear-to-Send, Data Transmission reServation) protocols. Test cases monitored the performance of Link-layer handshakes and simultaneously measured throughput to make sure physical layer performance was not adversely effected.

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**Table 7-1: Test Cases toward verification of routing optimization methods.**

Test Case		Description	
2 node: Transmit / Receive			
1		1A	Successfully transmit data packets from transmitter to receiver using RTS/CTS/DTS handshake implemented in AXL's control layer using a protocol derived from 802.11.
		1B	Include spectrum allocation with ROSA. Transmitter is able to select the best channel for the data link before the transmission and avoid unusable frequency bands by detecting the interference. Also include collaborative virtual sensing information exchanged via control packets on the CCC
3 node: T/R + Relay node			
2		2A	Successfully transmit data packets from source to destination node using the relay node as a pre-defined hop point. The channel will also be pre-selected.
		2B	Spectrum allocation and collaborative sensing. The relay node will still be a pre-defined hop point, but spectrum allocation will now be used to compare with previous tests.
4 node: T/R + 2 relay nodes			
3		3A	"Best route" decision making. ROSA algorithm selects among alternatives routes to maximize throughput.
		3B	Subject one relay node to interference. Also increase network packet traffic and measure throughput and latency.
		3C	Multiple separate sessions with common transmitter-receiver pair, measure throughput and latency.
5 node: T/R + 3 alternate nodes			
4		4A	Successfully route data packets by using the ROSA algorithm to jointly optimize the best route among three distinct relay nodes while also selecting the optimal spectrum band. Test a variety of different network conditions.
		4B	Include network initialization packets, test the network under situations where nodes are entering and leaving the network.

After successfully transmitting data packets with MAC layer RTS/CTS handshakes, a third USRP node is added to act as a relay point. This represents an isolated network hopping scenario in order to test the packet inspection capabilities of AXL and verify that header information was being correctly parsed.

As basic MAC and PHY layer functionality has been verified test cases progressed into more complex scenarios, culminating in a six node test with three intermediate hop points. The six-node setup includes a dedicated source and receiver pair, with three intermediate hop points. The sixth USRP node will be used to run the AXL dashboard application which can be used to monitor network performance and operations.

The final test scenario includes nearly all of the ROSA functionality that is capable on the USRPs, except for transmit power allocation. Following completion of the planned testing program a distributed, cross-layer SDR architecture will be demonstrated with a computationally efficient jointly optimized routing and spectrum allocation algorithm. Subsequent testing will help verify the AXL architecture and lead into transition efforts onto more commercially available radio hardware.

**3.3 ROSA and AXL Experimental Results**

At the time of the writing of this paper, the first test case was completed and preliminary results have been obtained. A new PHY layer sensing module has also been demonstrated in parallel with the ROSA

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implementation. Tests have been run with the current ROSA implementation using sensing information from new GNU Radio PHY layer modules. Upon selecting a channel for transmission, AXL was able to successfully transmit packets with a bit-error-rate (BER) comparable with what had been achieved using GNU Radios benchmark programs and a manually selected channel. In other words, the ROSA spectrum allocation method achieves throughput equal to that of a manually selected channel with GNU Radio.

As stated previously, the ROSA algorithm has been initially implemented in Python to ease merging with the other modules that are being developed for the AXL framework. The algorithm reads the required input variables such as current session size, SINR at its neighboring nodes, and received signal strength at the neighboring nodes of all ongoing transmissions. This information has been gathered and updated through collaborative sensing performed with the help of control packets. Through iteration among all active session and corresponding next hops, ROSA chooses the best session, next hop, and frequency range that correspond to maximum utility [1].

An example of decision making by the implemented ROSA algorithm is illustrated next. Node A is surrounded by five neighboring nodes (B, C, D, E and F) as shown in Figure 7-4. Consider Node A having an active session to be transmitted. According to the forward progress rule assume that the suitable nodes for the next hops are Nodes B, C and D. The other two neighboring Nodes E and F are not suitable next hop nodes, but are assumed to be active receivers for two different ongoing transmissions.

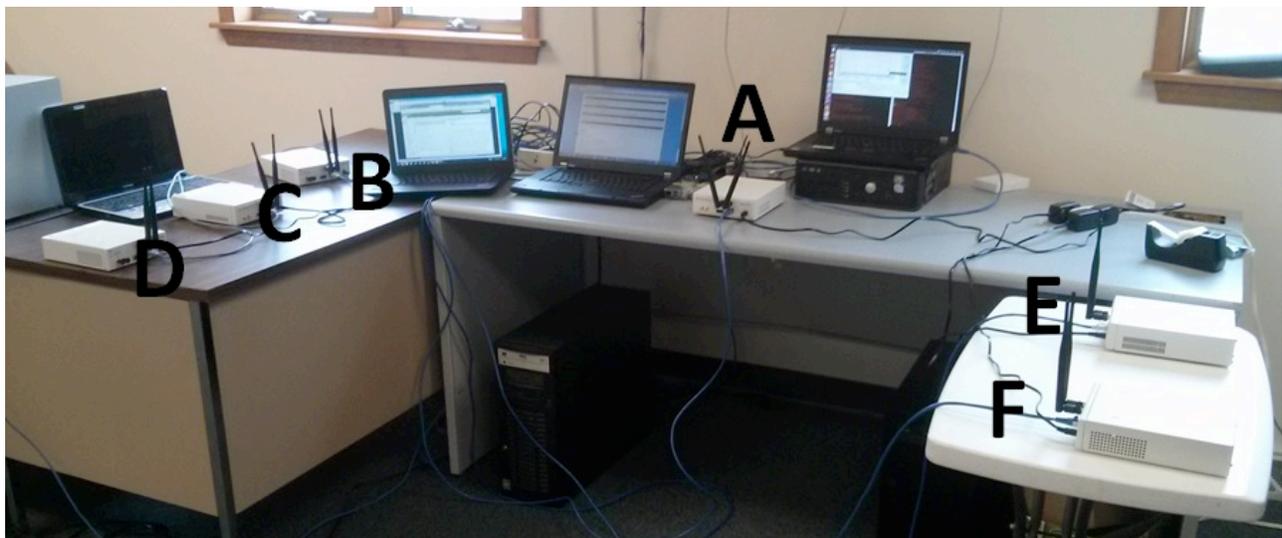


Figure 7-4: USRP six-node network.

Also assume a primary user is receiving at a set frequency. Ten sub-bands form the entire spectrum under consideration, with each sub-band having a bandwidth of 1 MHz so that the total spectrum bandwidth is 10 MHz. An interferer is placed in the network which is transmitting at a set frequency. The maximum transmit power of the USRP is 50 mW. Using sensed data gathered at Nodes B, C and D, ROSA chooses the optimal frequency and transmit power as shown in Figure 7-5. Figure 7-6 shows the sensing data gathered at Nodes B, C and D, respectively. This information is collected at Node A through collaborative sensing which is achieved through the exchange of control packets. This selection ensures that the ongoing transmissions at Nodes E, F and the primary user are unaffected, while maintaining the SINR threshold at the intended receiver node.

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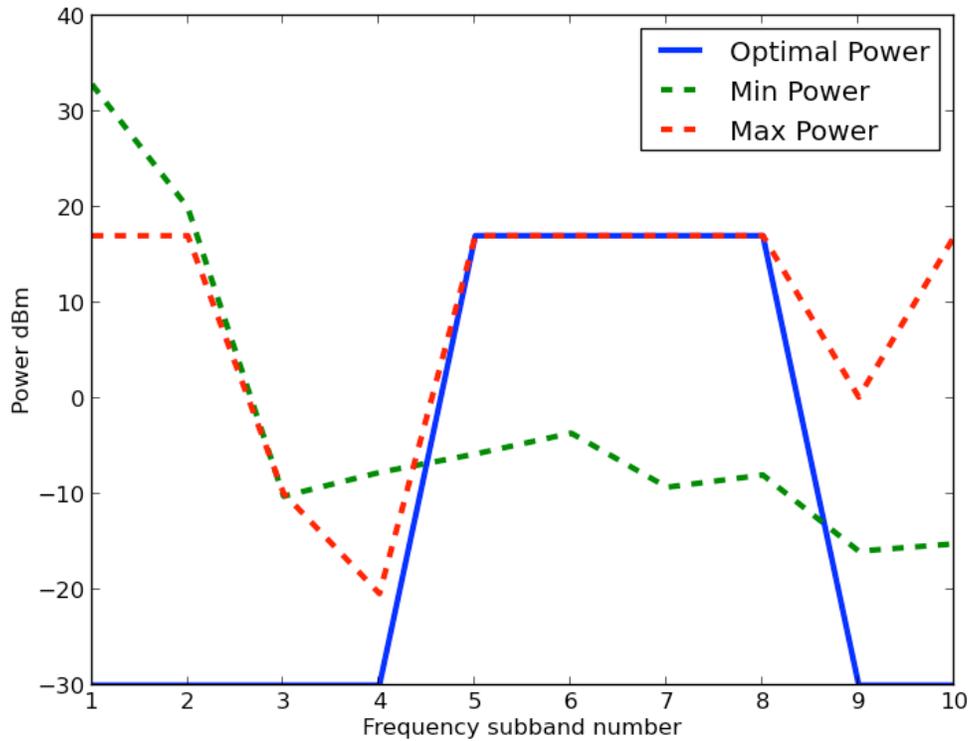


Figure 7-5: Power and Frequency selection by ROSA.

In this implementation of ROSA the maximum power  $P_{\max}$  [1] that can be transmitted at a frequency is calculated. This is the maximum transmit power that can be used such that minimum SINR threshold for all active primary and secondary users are maintained. The minimum power  $P_{\min}$  [1] required corresponds to the minimum power that has to be transmitted in order to ensure the SINR threshold at the intended receiver. In the above experiment the interference source was placed at the frequency corresponding to the first sub-band. Accordingly, we can see in Figure 7-5 the green dotted line which corresponds to  $P_{\min}$  is very high and the corresponding value of  $P_{\max}$  of the first sub-band is lower than  $P_{\min}$  thus it is not a spectrum hole and does not qualify for transmission at this instance. Also, the fall in  $P_{\max}$  (red dotted line) at the third, fourth, and ninth sub-bands are due to ongoing transmissions at Nodes E, F and primary user. This low value limits the possible transmit power allowed on those frequencies thereby ensuring that the other ongoing transmission are not interfered with. Finally the blue line shows the optimal power to be used at the selected frequency; in this case, the selected sub-bands for transmission are the fifth through eighth and the maximum power can be used since there is no other ongoing transmission in those sub-bands.

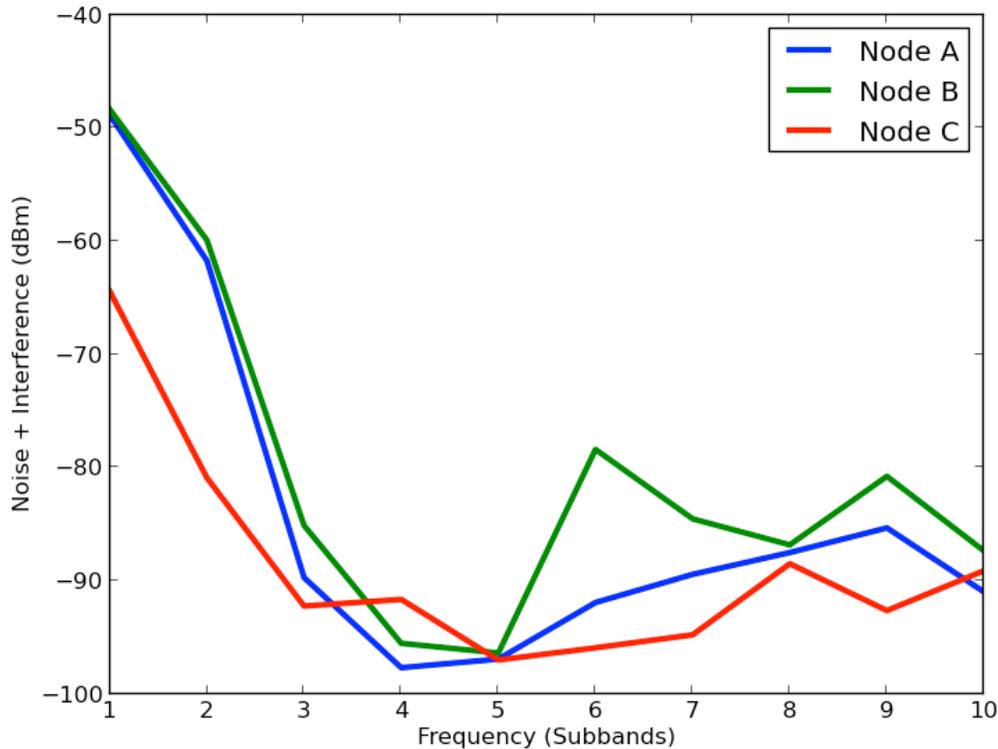


Figure 7-6: Noise + interference sensed at nodes B, C and D.

The implementation and testing of the PHY layer sensing piece is now described. A PHY layer for AXL is being developed on GNU Radio platforms and includes primitives for quickly sensing the environment and then communicating those results throughout the network using the collaborative virtual sensing scheme over the CCC. The sensing module is highly configurable, but can be used to simply estimate the power levels in configurable sub-bands such as those used by ROSA. Figure 7-6 showed some of the sensing results produced by the ROSA algorithms during testing.

It is important that the sensing module operate efficiently in real time, to avoid latency in sensing the environment, since any sensed data are already “stale” by definition. Having an efficient, integrated sensing scheme in order to collaboratively communicate with other network nodes will allow us to gather the most recent information available for optimization purposes.

Finally, the RcUBE and AXL frameworks also used a dedicated access control module, which has been referred to as an Access Control Layer (ACL) due to its central role in the cross-layer architecture. The ACL is able to load several distinct MAC layer protocols, and dynamically switch between them, just as the decision plane changes routing algorithms. MAC protocols are implemented using a specialized finite state machine that has simplified the porting of other protocols into AXL.

Although certain performance limitations practically exist with any Python implementation of a network architecture, this implementation successfully matches theoretical performance estimates in a stable fashion.

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The current implementation of ROSA's MAC protocol in AXL has reached expectations with fine-millisecond timing of MAC operations, hence the ROSA implementation matches the performance of GNU Radio benchmark programs run under optimal conditions. MAC protocols in general have been a point of some contention for many GNU Radio based demonstrations, and AXL's current capabilities represent a novel achievement in this field of research.

### 4.0 SUMMARY AND FUTURE WORK

Orthogonal frequency-division multiplexing (OFDM) is being used currently as the PHY layer implementation; a method of encoding digital data on multiple carrier frequencies. Future work will include extending to other modern code sequence types, and implementing a ROSA code sequence optimization type, in conjunction with current parameter optimization methods.

USRP daughterboards used early in testing did not readily permit a transmit gain control, so constant transmit power was assumed. Newer USRP daughterboards now available will allow for the implementation of a variable transmit power control and improve the ROSA implementation to include power allocation. This would be in addition to the spectrum allocation and routing optimizations already present.

After successful laboratory testing, experiments are expected to progress beyond the lab environment by transitioning the cross-layer software algorithms into actual commercially-available radio hardware. A trade study will determine whether the software remains in Python or if it is to be ported to a high-performance implementation in C or C++. With actual radios configured within a realistic or representative SDR ad hoc network environment, the expectation will be to perform network reshaping over time scales of milliseconds instead of current implementations that take a few seconds.

### 5.0 ACKNOWLEDGEMENTS

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