Adaptive Multi-Input-Output Medium Access Control (AMIO-MAC) Design using Physical Layer Cognition for Tactical SDR Networks

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Declaration

I, *M. Naeem Amjad Bharah* declare that this thesis titled “Adaptive Multi-Input-Output Medium Access Control (AMIO-MAC) Design using Physical Layer Cognition for Tactical SDR Networks” and the work presented in it are my own and has been generated by me as a result of my own original research.

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This thesis is dedicated to *my beloved parents*

Abstract

This article presents a novel cross-layer design strategy for tactical software-defined radio (SDR) networks. The approach takes into consideration the stringent criteria regarding latency, throughput, and dependability. An Adaptive Multi-Input-Output Medium Access Control (AMIO-MAC) protocol, an intelligent channel allocation method, and a hybrid physical layer that is multi-mode and multi-band powered by a cognitive engine are the components that make up the system that has been presented. SDR is able to function in a hybrid topology, thanks to the physical layer's innovative usage of a mixed combination of narrow-band and wide-band waveforms to satisfy differing range needs. This makes the physical layer one of a kind. The AMIO-MAC design guarantees a decrease in both the control phase and the data phase delay, while the MAC layer assures that the most of the time and frequency spectrum is utilized. Bandwidth and latency optimization are managed by the suggested trio consisting of the physical layer, the MAC layer, and cognition to achieve the quality of service that is required. The results of the simulation illustrate that the proposed design is superior to the conventional method of tactical radio MAC. The overall objective of the cross-layer design strategy that has been advocated for SDR networks is to achieve high throughput, improved quality of service, and flexible range capabilities. A hybrid physical layer that is capable of simultaneously supporting multiple bands has been proposed. A technique for the MAC layer that enables the software-defined radio to transmit data to numerous users who are operating on various bands within a single time slot by using the hybrid physical layer's capability to its greatest potential. In comparison to a conventional tactical radio network, this will result in decreased latency as well as a shorter scheduling period.

Keywords: *Software Defined Radio, Medium Access Control, Multi-mode, Multi-band, Control phase, data phase, Latency, Cognition*

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I would like to express my sincere gratitude and appreciation to my parents for their unwavering love, support, and encouragement throughout my academic journey. Their constant motivation and guidance have been instrumental in shaping my character and values. I am forever indebted to them for their sacrifices and dedication towards my education.

I would also like to acknowledge my loving wife for her patience, understanding, and support during this challenging and rewarding experience. Her unwavering love and encouragement have been a constant source of strength and inspiration for me. I am grateful for her constant support and for being my partner in every aspect of my life.

Finally, I would like to thank my supervisor "Dr. Umar Farooq" for his guidance, feedback, and support throughout my research. His knowledge and expertise have been invaluable in shaping my understanding of the subject matter and in helping me to achieve my academic goals.

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List of Abbreviations and Symbols

Abbreviations

MAC	Medium Access Control
SDR	Software Defined Radio
QoS	Quality of Service
TDMA	Time Division Multiple Access
FDMA	Frequency Division Multiple Access
CDMA	Code Division Multiple Access
TDM	Time Division Multiplexing
FDM	Frequency Division Multiplexing
OSI	Open System Interconnection
RSSI	Received Signal Strength Indicator
SNR	Signal-to-Noise Natio
OFDM	Orthogonal Frequency Division Multiplexing
FBMC	Filter Bank Multicarrier
DFE	Digital Front End
AFE	Analog Front End

DSP	Digital Signal Processing
MIMO	Multi-Input-Multi-Output
ARQ	Automatic Repeat Request
CPM	Continuous Phase Modulation
AMC	Adaptive Modulation and Coding
CE	Cognition Engine

CHAPTER 1

Introduction

Software defined radio (SDR) is a radio communication system where the traditional hardware-based signal processing tasks are performed by software running on a computer or a dedicated hardware platform. This allows for greater flexibility and adaptability in the communication system, as well as easier upgrades and modifications. The SDR paradigm has been gaining popularity in recent years due to the numerous advantages it offers over traditional radio communication systems.

One of the main advantages of SDR is the ability to reconfigure the radio communication system to support various wireless standards without the need for specialized hardware. This means that a single SDR device can be used for different applications, such as wireless LAN, cellular networks, and satellite communications, simply by reconfiguring the software. This not only reduces the cost of the hardware, but also reduces the complexity of the system, as the need for multiple dedicated radios is eliminated. Another advantage of SDR is the ability to perform signal processing tasks that were traditionally performed by hardware using software. This allows for greater flexibility in signal processing, as new algorithms can be implemented easily and quickly without the need for hardware modifications. Additionally, SDR can be used to implement cognitive radio systems, where the radio intelligently adapts its parameters to the changing communication environment. This can lead to more efficient use of the available spectrum and increased communication reliability.

SDR also allows for the development of more advanced radio communication systems, such as wireless sensor networks and Internet of Things (IoT) devices. These systems require low-power, low-cost radios that can operate in various frequency bands and support multiple wireless standards. SDR provides the necessary flexibility and adaptability to support these requirements. In addition, SDR can be used for various research and development purposes, such as simulation of wireless networks, testing of new communication protocols, and validation of new algorithms. SDR allows researchers to quickly and easily prototype new ideas and algorithms, reducing the time and cost required for traditional hardware-based prototyping.

There are some challenges associated with SDR, such as the need for high-performance computing platforms, the potential for security vulnerabilities due to the use of software, and the need for proper regulation of the use of the available spectrum. However, these challenges can be addressed through the development of efficient software algorithms, the use of secure software development practices, and the proper management of the spectrum. SDRs have the potential to revolutionize the way we think about radio communication, allowing for the development of more advanced wireless systems that can support various applications and requirements.

Tactical Radio environments are always needed to be most reliable, robust, secure, adaptable, and re-configurable due to the nature of the scenario which makes it a very demanding task to implement. A traditional network is usually providing stationary nodes and fixed infrastructure which is not a feasible approach for a tactical network because of its type. Software Defined Radios (SDRs) are providing secure, reliable, and efficient solution for all these communications requirements. Moreover, SDRs can support self-healing and self-forming ability to cater the dynamic environment. In such circumstances, physical communication range and variable bandwidth needs are also quite enigmatic.

Resources such as time and bandwidth are scarce, so SDRs have created a number of solutions to both the issue of managing sufficient QoS and varying physical ranges. Previously, authors have tried to address these issues using only the physical layer or only upper layers. Utilizing adaptive modulation and coding (ADC) techniques, improvements made in terms of data rate in TDMA and FDMA networks [2]. Utilizing any modulation strategy in the physical layer solely serves the aim of achieving the necessary QoS with the resources at hand. Higher OSI layers are used for this purpose to develop a suitable control technique that ensures that the requirements of users are met with a minimum amount of latency.

Narrow-band and wide-band waveforms are used in SDR implementations to address and optimize communication for provided ranges [3]. Narrow-band waveforms can offer wider field ranges since they have a shorter bandwidth for a particular transmitter power output.

However, due to absorptions associated with short wavelengths, wide-band waveforms cannot support long-distance communication even though they can deliver larger data rates [4]. A tactical network running on either narrow-band or wide-band waveforms under fluctuating channel conditions cannot meet a wide range of service quality and range criteria. Figure 1.1 depicts a mesh network with 16 nodes, in which each node appears to be connected to each other.

When all nodes are in close proximity to one other, operating in the same wide-band or narrow-band waveform and inside the acceptable range of a particular waveform, then these nodes are able to interact with each other. What if some nodes break that boundary and are now out of the working range of the wide-band, in a traditional radio network, all nodes are switched to narrow-band to be able to support communication to that moving node. This is a loss of QoS for all those nodes who were still able to communicate on wide-band with their desired destination node.

Figure 1.1 illustrates, with respect to node 5, two arcs that represent the ranges. The range for wide-band communication, which supports larger data rates, but is obviously limited to a short range, is shown by the innermost arc. As a result, only nodes 1, 7, and 12 can interact at high data rates with node 5. The farthest orbit demonstrates the range for narrow-band communication. As a result, node 5 can communicate with every other node at low data rates. Above scheme can work if high data rate is not really required by users, however, if higher data rates, or lower latency is needed, then this traditional radio networks are not serving the purpose and need improvements. Our scheme uses hybrid physical layer that can support variable bands, hence different data rates as needed by users simultaneously.

Now we have added another circle which denotes third band with medium data rate, this scheme enables another set of nodes to communicate with node 5 on medium throughput rather than low through-puts. This fixes the ad-hoc network's two key problems. To begin with, the network does not have to operate on a single waveform in order which completely solves the problem of moving node. As shown in the figure 1.2,

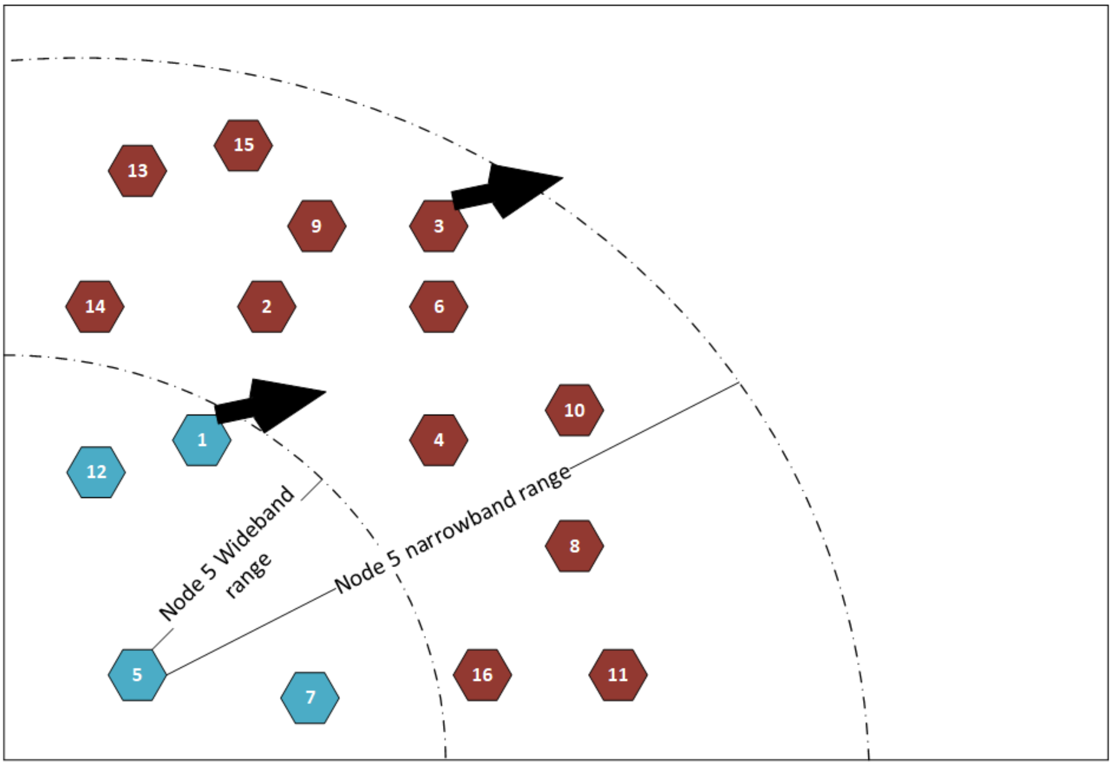


Figure 1.1: A 16 nodes SDR network with 2 bands to support range requirements

it may run multiple bands at the same time. This not merely provide the network a hybrid sense, but it also allows for a range of bit rates. Second, the mobile node that is leaving the first orbit does not have to give up; instead, it may transfer to a lower band and, therefore, lower data rates, without affecting date rates of the neighbour nodes.

The research paper presents a novel design for the AMIO-MAC protocol that uses an intelligent channel allocation scheme to optimize data efficiency in a multi-layer approach. The physical layer in this proposed design enables the use of multiple waveforms and multiple bands with only one RF front-end, allowing for the reception and processing of narrow-band signals with varying bandwidths and QoS resolution for different ranges by consulting the cognitive engine.

The cognitive engine provides a comprehensive understanding of resource on-demand (RoD) for the MAC layer to develop around. This allows for the SDR to have the flexibility to process anything that arrives at the physical layer, regardless of waveform, within the permitted bandwidth. The SDR can switch between narrow-band and wide-band waveforms based on specific conditions.

The proposed AMIO-MAC protocol design reduces the latency associated with

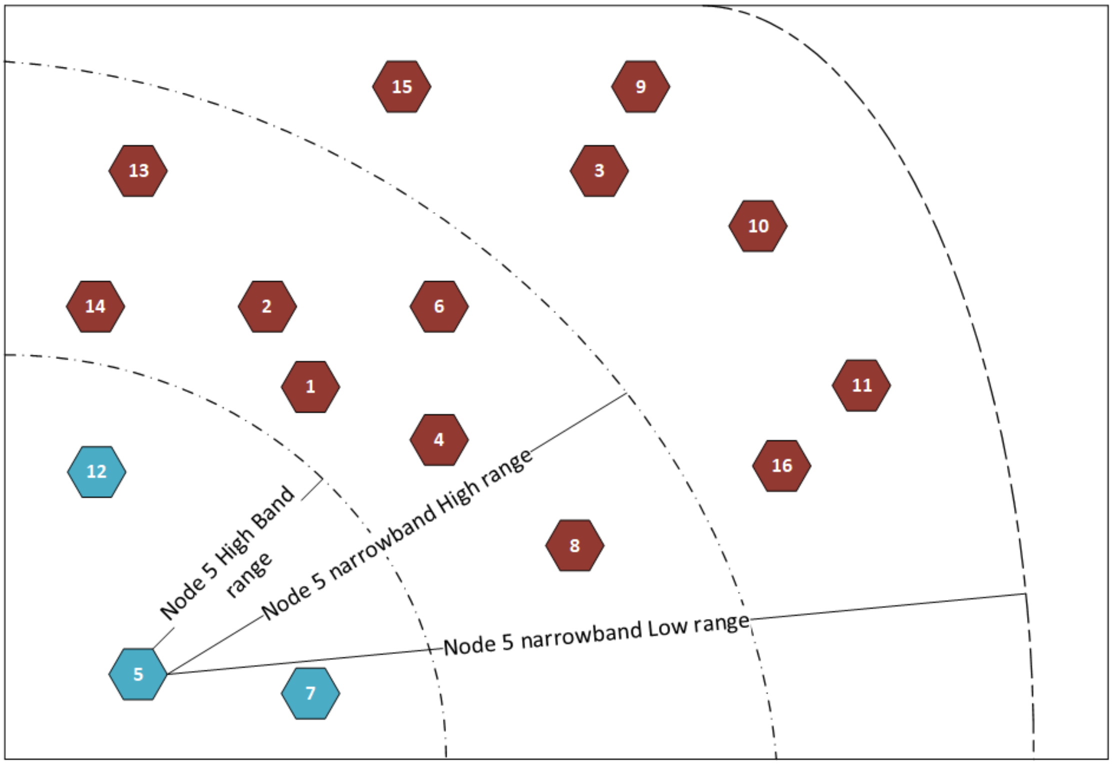


Figure 1.2: A 16 nodes SDR network with 3 bands to support range requirements

control allocation in larger networks by efficiently allocating slots. The protocol design addresses different range requirements by using the cognitive engine to select from available options based on RoD. This enhances the previously proposed scheme that supported multiple bands' receptions on a single radio.

The ability to receive and process multiband narrow-band and wide-band signals on a single radio using a common RF front-end is a notable contribution to the SDR field research. The design also allows for the ability to send multiband narrow-band and wide-band signals using a single RF front-end, further enhancing the capabilities of SDR networks. The multi-layer approach and intelligent channel allocation scheme, along with the cognitive engine, provide flexibility and adaptability to changing network demands. This research has the potential to contribute to the advancement of SDR technology, leading to more efficient and flexible wireless communication systems.

In this research, a multi-input-output multi-layer design is presented for SDR networks, that enhances our previously proposed scheme [1] that supported multiple bands receptions on a single radio. The suggested AMIO-MAC contributes significantly by reducing the latencies associated with the control allocation phase, particularly in larger networks. The following notable contributions to SDR field research are made by the design.

1. Ability to receive and process multiband narrow-band and wide-band signals on a single radio using a common RF frontend.
2. With a single RF front-end, the ability to send multi-band narrow-band and wide-band signals.
3. Different range requirements are addressed by employing the cognitive engine which helps selecting from the available options according to Resource on Demand.
4. Reducing control phase latency by applying above mentioned techniques to allocate slots in an efficient manner.

In addition to the four notable contributions mentioned in the text, the multi-layer AMIO-MAC protocol design can have several other advantages for SDR networks. One of the key advantages is its ability to enhance network security. The protocol allows for better encryption of data by implementing a dynamic key management scheme that changes the encryption keys in real-time, making it harder for attackers to decode the information. Moreover, the multi-layer design of the protocol enables the network to operate even in the presence of jamming signals by efficiently utilizing the available spectrum resources.

Another potential advantage of the protocol is its scalability. The design allows for easy integration of new nodes into the network, without requiring a complete overhaul of the existing infrastructure. This means that the protocol can support the growing demand for wireless communication in a cost-effective and efficient manner.

Furthermore, the cognitive engine employed in the protocol can also aid in spectrum sharing. By providing a comprehensive understanding of the available resources, the engine can help to allocate the spectrum efficiently among multiple users or applications, without causing interference or degradation in performance.

Overall, the multi-layer AMIO-MAC protocol design has several potential advantages and can significantly enhance the latency reduction, performance, security, scalability, spectrum sharing, and energy efficiency of SDR networks.

CHAPTER 2

Problem Formulation

In this chapter, we will be discussing the main problem that this research will be addressing. Also the challenges that researchers faced during the work, and the components of solution to the problem are also discussed here.

2.1 Problem Formulation

The hybrid framework design mentioned above presents a solution that is capable of addressing the diverse demands of SDR networks, including range requirements, data speeds, latency minimization, throughput enhancement, and consideration of channel conditions. The design is based on a multi-layer approach that combines the physical layer and MAC layer, with the use of a cognition engine for efficient channel allocation.

In SDR networks, the physical layer is responsible for the transmission and reception of signals, while the MAC layer is responsible for managing the data flow and ensuring efficient use of the available resources. The channel conditions, such as RSSI and SNR, are accessible at the physical layer and can be used to optimize the transmission parameters. However, the link layer, including the MAC layer, requires information about the data rate and network size to ensure optimal performance.

To address these challenges, the hybrid framework design employs simultaneous multi-carrier processing at the physical layer, which enables several transmissions without collisions. This feature can drastically reduce latency and enhance throughput. However, the MAC layer still requires the use of a cognition engine to choose the appropriate band and mode of operation based on input characteristics such as data rate and network size. A comprehensive multi-layer design is necessary to enable the coexistence of radios that can listen to multiple concurrent transmissions and communicate at various ranges/bands based on their specific service requirements.

The use of a cognition engine in the hybrid framework design enables efficient channel allocation by ensuring that the underlying physical layer parameters are aligned with the MAC layer requirements. The cognition engine takes into account the available resources and service requirements to optimize the allocation of bandwidth and ensure the efficient use of the available resources. This ensures that the network can handle the diverse demands of the various services and applications that run on it.

In conclusion, the hybrid framework design is a promising solution that can address the challenges of SDR networks, including range requirements, data speeds, latency minimization, throughput enhancement, and consideration of channel conditions. The design's multi-layer approach and the use of a cognition engine for channel allocation make it a promising solution for the future of SDR networks.

2.2 Proposed NB/WB Physical Layer Design

This research paper proposes a physical layer design that combines narrow-band and wide-band technologies to enable simultaneous transmission and reception of multiple signals, regardless of their bandwidths [5]. The aim is to achieve this goal with minimal changes to the wide-band analog front-end (AFE) by incorporating a digital front-end (DFE). By digitally mixing the signals, a composite signal is created and transmitted using the wide-band mode of the software-defined radio (SDR) waveform. On the receiver side, the composite signal is processed and filtered to extract each individual signal after passing through the wide-band AFE. This approach offers the advantage of processing multiple signals with different bandwidths using a single wide-band front end, while still meeting the required range specifications and quality of service standards.

The composite in Figure 2.1 illustrates multiple signals with varying bandwidths in the frequency domain. While the theoretical range of bandwidth options extends from 0 to $B_{RF} = f_b - f_a$, practical limitations exist. The narrow bandwidth signals are categorized into three types: low (B_L), medium (B_M), and high (B_H), while the wide bandwidth is denoted as B_{WB}. Within the analog wide-band RF bandwidth, there

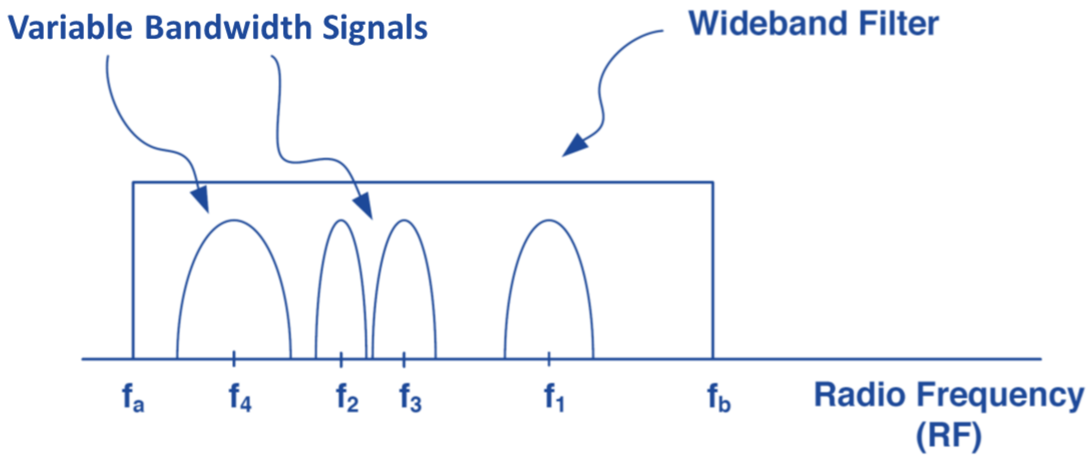


Figure 2.1: A digital quadrature composite signal comprising of different bandwidth signals [1]

are a fixed number of channels. These channels are divided into low data rate channels (n_L), medium data rate channels (n_M), high data rate channels (n_H), and wide-band channels (n_{WB}). It is generally observed that the number of low data rate channels is greater than the number of medium data rate channels, which in turn is greater than the number of high data rate channels, and finally the number of wide-band channels.

Figures 2.2 and 2.3 show the processing flow for the proposed hybrid system. Analog composite signal is received from the RF Front end and converted to digital form, then each user's data is passed to digital quadrature mixture blocks which are processing in parallel fashion. And then after right demodulation we get the actual user data. Similarly, on the transmission side, each user data is passed through modulator and up-sampler, and then handed over to digital quadrature mixture. After that mixed digital signal is converted to analog and transmitted as a composite signal.

The baseband modulation scheme that we will use are the same that were used previously i.e. continuous phase modulation (CPM) for narrow-band and filterbank multicarrier (FBMC) for wide-band. The details about these two modulation schemes are present in [1].

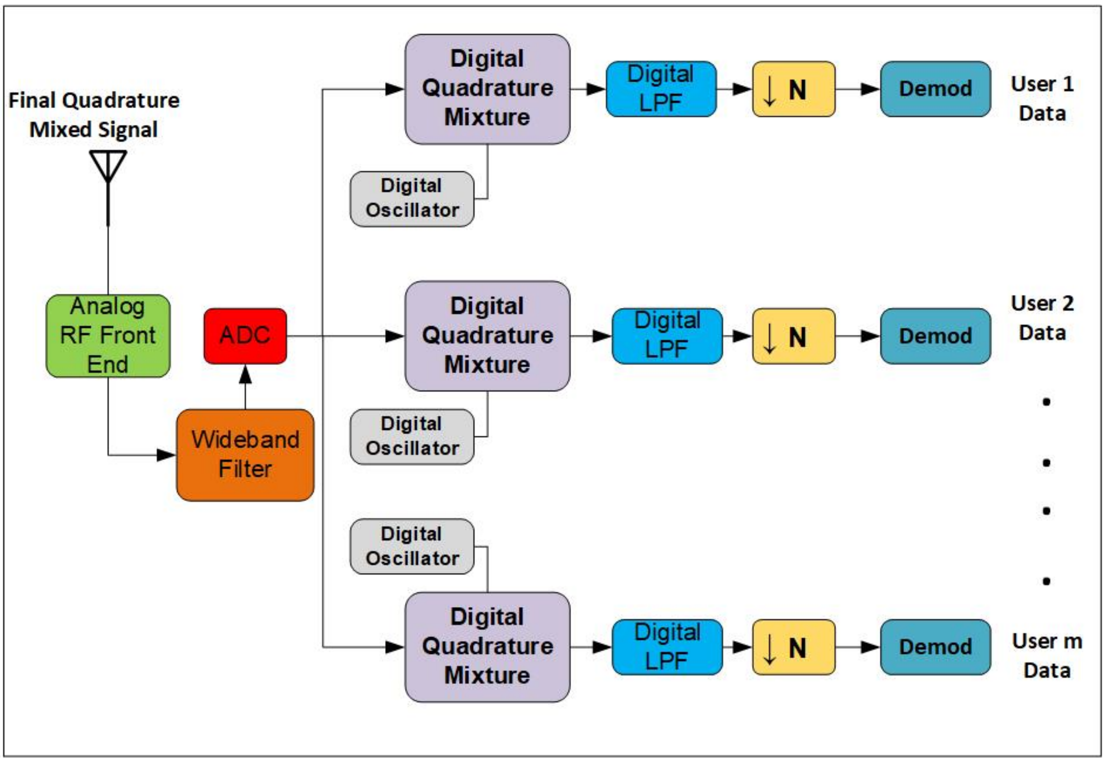


Figure 2.2: Block diagram of the proposed Receiver of hybrid scheme

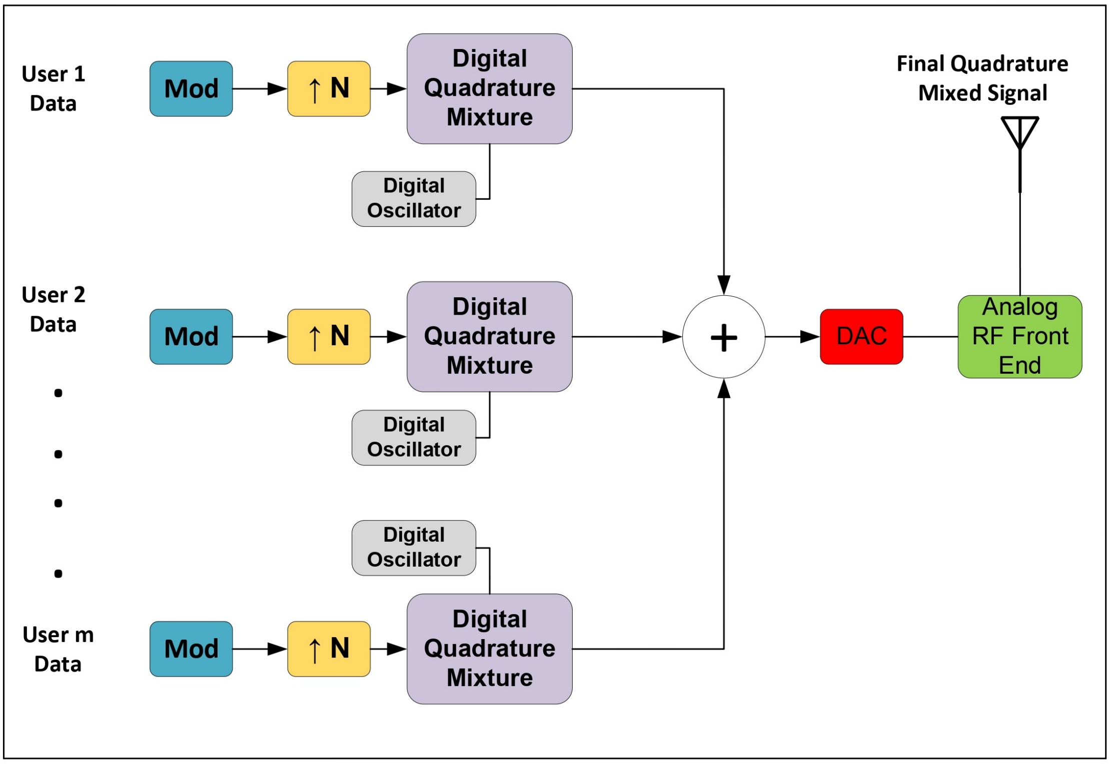


Figure 2.3: Block diagram of the proposed Transmitter of hybrid scheme

2.3 Proposed Cognition Engine

The intelligent cognitive engine, depicted in figure 2.4, serves as an advanced intermediary between the physical layer and MAC. Its primary function is to optimize the utilization of the proposed PHY by analyzing the channel state using metrics such as RSSI and SNR. Taking into account the distance between SDR nodes and the required data service, the cognitive engine determines whether to approve or reject service requests. It selects the most suitable waveform and adjusts the necessary parameters to achieve the desired quality of service (QoS) in the data phase.

During the control phase, the cognitive engine provides crucial information about simultaneous requests from other nodes, enabling the MAC to allocate time slots for higher priority nodes. The MAC, which will be discussed in the subsequent section, is responsible for selecting the appropriate slots for the data phase. The cognitive engine then communicates this information to the PHY, instructing it to transmit data during the designated turn in the data phase. In essence, the cognitive engine acts as an optimizer for physical and MAC layer parameters, leveraging information from both layers to determine the optimal band or channel mode for establishing a reliable link.

The cognitive engine is a crucial component of cognitive radio networks, as it enables the efficient utilization of available spectrum resources by intelligently interpreting the channel state based on various parameters such as RSSI and SNR. The cognitive engine acts as an intermediary between the physical layer and the MAC layer, optimizing the utilization of the proposed PHY by selecting the most suitable waveform and selecting the necessary parameters for the desired QoS in the data phase.

One of the key advantages of cognitive radio networks is the ability to dynamically adapt to changing channel conditions, enabling efficient and reliable communication even in highly dynamic environments. This is achieved through the cognitive engine's ability to interpret the channel state and select the most appropriate transmission parameters for the given conditions. By doing so, the cognitive engine can ensure that the network is operating at its maximum potential, while minimizing interference and improving the overall performance of the system.

The proposed MAC layer, described in the following section, builds on the cognitive engine's ability to prioritize resources by selecting slots for the data phase and

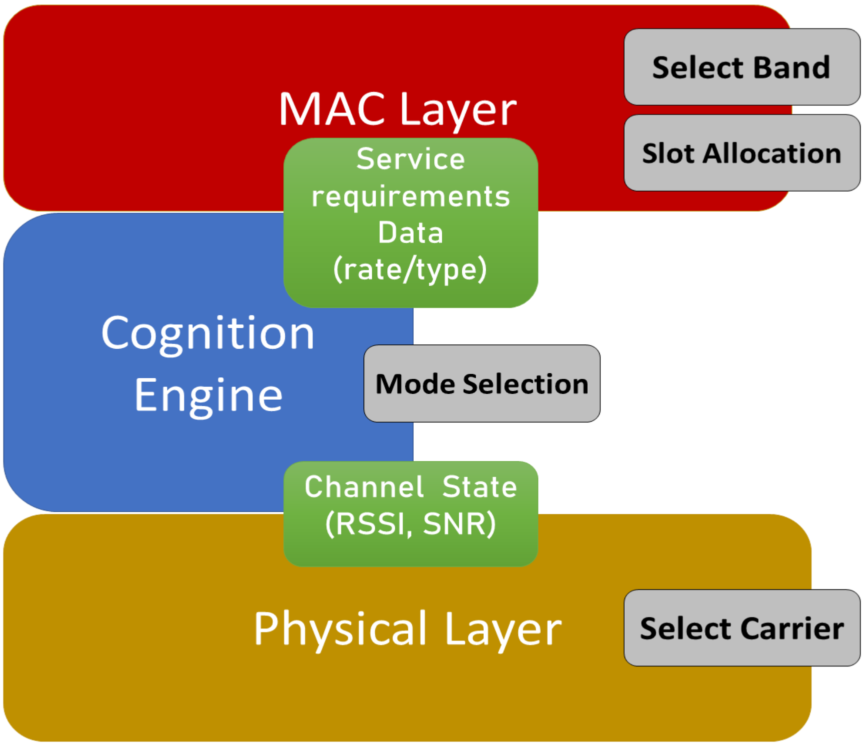


Figure 2.4: Design of Layers with cognition engine [1]

updating the cognitive engine accordingly. By doing so, the MAC layer can ensure that the network is operating at its maximum potential, while minimizing interference and improving the overall performance of the system.

Overall, the cognitive engine plays a critical role in cognitive radio networks by enabling efficient and dynamic spectrum utilization through the intelligent interpretation of channel state information. By optimizing the physical and MAC layer parameters, the cognitive engine can ensure that the network is operating at its maximum potential, while minimizing interference and improving the overall performance of the system. As such, it represents a crucial component of any cognitive radio network and is essential for the successful implementation of these advanced communication systems.

Chapter 3

Literature Review

Over the past few decades, there has been significant research in the field of wireless communication systems. In recent years, the proliferation of wireless devices and the increasing demand for higher data rates have motivated researchers to explore new ways of enhancing wireless networks.

Multicarrier reception is a technique that involves using multiple subcarriers to transmit data in parallel, allowing for higher data rates and better spectral efficiency. There has been a significant amount of research on this topic, including the use of orthogonal frequency division multiplexing (OFDM) and filter bank multicarrier (FBMC) techniques. One notable study by A. Goldsmith and S. Jafar [6] explored the benefits of using multicarrier modulation for wireless communication systems and presented some theoretical limits on the achievable data rates. Cognitive radio networks (CRNs) are wireless networks that can adapt their transmission parameters and operating frequencies based on the available spectrum and the communication requirements. There has been significant research on CRNs, including the use of machine learning and optimization techniques to enable more efficient spectrum utilization. A recent study by S. Haykin [7] presented an overview of CRN technology and discussed some of the key challenges in designing efficient and effective CRNs.

Cross-layer MAC protocols are designed to enable communication between the physical layer and the MAC layer in wireless networks. By integrating information from multiple layers, cross-layer MAC protocols can enable more efficient communication and better resource utilization. A study by R. Jain et al. [8] presented a comprehensive cross-layer MAC framework for cognitive radios, which makes it possible for radios to coexist that are able to listen to multiple transmissions at once and communicate over various distances and bands depending on the needs of the service.

The reconfiguration of the analog components for adjustment of RF receivers in SDRs, is a laborious procedure since it is practically complex as explained in [9]. In order to achieve flexibility, the digital-front-end is reconfigured, that is using multiplierless desgin to minimize the system delays. Authors have updated some programming settings of multiple components of the system to achieve this [10, 11]. [12] provided a comprehensive guide on the design of adaptable and multi-mode radio frequency (RF) front-end circuits. Authors have showed that Resource on Demand can be managed by sharing DSP blocks using Digital Front end. Authors have presented a design featuring adaptive digital-front-end for receiving multiple modes of a wireless node. This was made possible by multiplexing different blocks of DSP and a highly adaptable DFE [13]. To accommodate diverse requirements according to network load and channel usage in the down link of code division multiple access (CDMA), another approach is proposed in [14]. For the resource distribution over several nodes, sequential optimization model is presented. A fuzzy rule design for channel adaptation for wide-band waveform is provided in [15] for software defined radios. By using the best waveform parameters, a successful link adaptation strategy should be able to reduce the overhead of packet retransmissions while still providing the maximum data throughput needed by an end user or application. Even when the channel conditions are good enough to permit increased throughput, computational complexity exists and thus the power consumption must be reduced by regulating the throughput at the necessary level.

Authors in [16] have proposed a unique link, transmit power adaptation algorithm to increase the efficiency of the network performance. To comply with the required QoS, an innovative design was presented for multi-input multi-output (MIMO) network link adaptation efficiency. Kim et al. [16] enhances the performance of wireless communication systems while considering energy efficiency. The proposed link adaptation technique aims to dynamically adjust the transmission parameters, such as modulation scheme and transmit power, based on the channel conditions and energy constraints. The research involves the design and implementation of the energy-aware link adaptation algorithm. This algorithm considers both the quality of the wireless channel and the energy consumption of the system. It dynamically selects the optimal transmission parameters that achieve a balance between data rate and energy efficiency. Overall, the research contributes to the field of wireless communication by introducing an energy-aware link adaptation technique specifically tailored for MIMO-OFDM systems. The technique optimizes the trade-off between communication performance and energy consumption, making it a valuable approach for energy-constrained wireless communication environments

Authors in [17] discuss the design and implementation of a link adaptation algorithm for re-transmission-based cognitive radio systems. The proposed algorithm aims to improve the throughput and reliability of the system by using automatic repeat request (ARQ) and adapting the transmission parameters based on the channel conditions. The paper provides a detailed analysis of the algorithm's performance under different conditions and shows that it can significantly improve the system's performance compared to conventional fixed-rate transmission schemes.

Hui Chen et al. [18] presents a cross-layer scheduling algorithm for wireless multimedia transmission that considers quality of service (QoS) requirements and utilizes adaptive modulation and coding techniques. The proposed algorithm aims to maximize the system's spectral efficiency while ensuring the required QoS for different types of multimedia traffic. The paper provides a detailed analysis of the algorithm's performance under various conditions and shows that it outperforms existing scheduling algorithms in terms of throughput, delay, and packet loss rate. A. El Shafie et al. [19], presents a stability analysis of an ordered cognitive multiple-access protocol that enables secondary users to access the licensed spectrum. The paper proposes a mathematical model for the protocol and analyzes its stability conditions in terms of the traffic load and the parameters of the protocol. The paper provides a detailed analysis of the stability conditions and shows that the proposed protocol can achieve stable and efficient operation under certain conditions. The paper also includes numerical results that validate the theoretical analysis and demonstrate the effectiveness of the proposed protocol.

In the presence of orthogonal licensed main bands, each of which is allotted to a PU, authors of [20], have developed a band allocation mechanism for buffered cognitive radio users. Based on their needs for queue stability, the bands are assigned to the cognitive radio users. The benefit of the suggested strategy compared to various well-known strategies is also discussed. A system for amateur drone surveillance using software-defined radio (SDR) and wireless acoustic networking is given in [21]. The paper proposes a wireless acoustic communication method for the drone's audio sensing and transmission, which can provide better range and reliability than traditional RF communication methods. The paper also discusses the implementation of the proposed system using SDR technology and presents experimental results that demonstrate the effectiveness of the proposed method. In [22], The receiver described in 1 by the authors can analyze signals from several narrow-band users. But the only disadvanage of this research is that it solely relies on continuous phase modulation (CPM).

H. Yang et al. [23] proposes a novel cross-layer restoration scheme for IP over Optical Transport Networks (OTNs) using Software Defined Networking (SDN). The proposed scheme utilizes SDN to enable cross-layer interaction between the IP layer and the optical layer, which can improve the restoration performance in case of network failures. The paper presents the detailed design of the proposed scheme, including the SDN-based network architecture and the cross-layer restoration algorithm. H. Yang also proposed scheme that aims to optimize the resource allocation and performance of OaaS networks by jointly considering the application layer, network layer, and physical layer [24]. The paper presents the detailed design of the proposed CSO scheme, including the optimization model and algorithm for resource allocation.

I. Nosheen et al. [25] proposes a cross-layer design for a multihop, self-healing, and self-forming SDR tactical network. The proposed design integrates the physical layer, MAC layer, and network layer to improve the network's performance and reliability. The paper presents a novel scheme for route discovery and maintenance, which allows the network to form and heal itself in a self-organized manner. The paper also proposes a priority-based MAC protocol that enhances the network's reliability and energy efficiency. [26] proposes a self-forming protocol for tactical networks consisting of software-defined radios (SDRs) in hybrid TDMA/FDMA scheme. The protocol is designed to divide the network into multiple sub-nets, each with its own leader node, and dynamically form and dissolve these sub-nets based on the network's requirements. The protocol is evaluated through simulations and is shown to improve network performance in terms of throughput, latency, and reliability compared to other protocols. In [27], author proposes a mathematical model for cross-layer protocol optimization in tactical networks consisting of software-defined radios (SDRs). The model considers different layers of the protocol stack, including the physical, medium access control, and network layers, to optimize the performance of the SDRs in terms of throughput, delay, and energy efficiency. These cross-layer algorithms typically have the drawback of not taking into account multiple bandwidth support or the physical layer characteristics.

In Zalonis [28] covers the different modulation and coding schemes used in Adaptive Modulation and Coding (AMC), approaches to AMC, and their advantages and disadvantages. Author also discusses the impact of channel estimation errors on AMC performance and highlights the need for robust AMC algorithms that can adapt to dynamic channel conditions. Additionally, it presents the latest research and development trends in AMC, including joint source-channel coding, machine learning-based AMC, and multiuser AMC. Overall, the paper provides a comprehensive overview of AMC techniques and their advancements in wireless communication systems.

Zeeshan et al. [29] proposed a new cognitive communication scheme that combines Non-Orthogonal Multiple Access (NOMA) with hybrid narrowband/wideband Software-Defined Radio (SDR) waveform. This scheme aims to improve the spectral and energy efficiency of the cognitive radio system by dynamically allocating resources based on the instantaneous channel conditions. The proposed approach uses a hybrid waveform to achieve high spectral efficiency and low energy consumption. The system leverages the cognitive engine's ability to intelligently interpret the channel state based on various parameters such as RSSI and SNR, select the most appropriate transmission parameters, and allocate resources to multiple users based on their priority.

One potential disadvantage of [29] is the complexity of the system, which may require significant computational resources to operate efficiently. The cognitive engine's architecture and the hybrid narrowband/wideband SDR architecture may be complex, and their implementation may require specialized hardware and software, which could increase the system's cost and reduce its scalability. Another potential disadvantage is the system's susceptibility to interference, especially in highly congested environments. The NOMA technique used in the proposed system may reduce interference, but it may not eliminate it entirely, especially if there are many users sharing the same frequency and time resources.

The paper [30] focuses on the performance evaluation of a Software Defined Radio (SDR) Ultra-Wideband (UWB) receiver utilizing turbo decoding. The study employs a cross-layer approach, considering the interaction between the physical layer and the higher layers of the communication system. The paper investigates the performance of the SDR UWB receiver by analyzing various key parameters, such as bit error rate (BER), signal-to-noise ratio (SNR), and packet error rate (PER). The turbo decoding technique is employed to enhance the receiver's performance in terms of error correction capability.

The authors in [30] conduct extensive simulations and experiments to evaluate the cross-layer performance of the SDR UWB receiver. They analyze the impact of different modulation schemes, coding rates, and SNR levels on the system's performance. The study also considers the effects of interference and multi-path fading on the receiver's performance. The results and findings of the research provide insights into the performance characteristics of the SDR UWB receiver with turbo decoding. The analysis helps in understanding the trade-offs between different modulation schemes, coding rates, and SNR levels, which can aid in optimizing the design and operation of UWB receivers in SDR systems.

Iker et al. [31] presents a novel design approach for C-MAC protocols tailored specifically for wireless environments. These protocols aim to efficiently manage the contention among multiple nodes trying to access the shared communication medium. To validate the effectiveness of the proposed C-MAC solutions, the paper conducts a comprehensive experimental evaluation.

George et al. [32] focuses on the design, development, and deployment of airborne cognitive networking systems. The paper addresses the challenges of communication in airborne environments and proposes cognitive networking as a solution. The main focus of the paper is on the design and development of cognitive networking algorithms and protocols specifically tailored for airborne communication. It highlights the need for adaptive and intelligent networking approaches that can dynamically adjust to changing environmental conditions, such as high mobility and unpredictable network dynamics. The paper provides a detailed overview of the design principles and architecture of the proposed airborne cognitive networking system. It discusses various aspects including spectrum awareness, learning algorithms, decision-making mechanisms, and cooperation strategies among airborne nodes.

Authors in [33] gave a novel concept of fine-grain partial MAC virtualization, which is a unique approach to support cross-layer design in wireless ad hoc networks. The proposed approach offers greater flexibility and control over MAC layer parameters. By allowing fine-grained virtualization, it enables the adaptation of MAC protocols and optimizations based on specific network conditions and application requirements. This flexibility can lead to improved network performance and resource utilization. The research emphasizes the importance of cross-layer design and optimization in wireless ad hoc networks. By facilitating cross-layer interactions and optimizations, the proposed approach enables the exploitation of synergies between different protocol layers, potentially resulting in enhanced network efficiency and performance

Despite all these advantages the research [33] has practical implementation challenges. The introduction of fine-grain partial MAC virtualization adds complexity to the network architecture and introduces potential overhead. The research does not explicitly address the impact of this added complexity and overhead on overall system performance and resource utilization. Further investigation is needed to quantify these effects and optimize the approach accordingly.

Shome et al. [34] proposes a novel cross-layer architecture for software-defined radio (SDR) networks based on the principles of software-defined networking (SDN). The proposed architecture, called CrossFlow, aims to address the challenges of managing and optimizing the complex interactions between different layers in SDR systems. The key components of the this architecture include the SDR controller, which acts as the central authority responsible for resource allocation and optimization, and the CrossFlow agents deployed in each SDR node to facilitate communication between the layers. The architecture enables dynamic configuration and adaptation of the SDR system based on network conditions and application requirements.

The authors also discuss the experimental evaluation of CrossFlow using a testbed, demonstrating its effectiveness in enhancing the performance and adaptability of SDR networks. The results highlight the advantages of the proposed architecture, including better throughput, reduced interference, and improved QoS provisioning. The proposed architecture offers a practical solution for addressing the complexities and challenges associated with SDR communication, opening new avenues for future research and development in this field.

The paper [35] addresses the challenge of efficient spectrum utilization and resource allocation in cognitive radio networks by leveraging the flexibility and programmability of SDR. The authors discuss the concept of cross-layer design and its potential benefits in cognitive radio networks. They highlight the advantages of incorporating SDR technology, which enables dynamic reconfiguration and optimization of resources across multiple layers. The literature review also covers related work on cross-layer resource allocation approaches for cognitive radio networks, showcasing different methodologies and algorithms proposed by researchers in the field. The proposed approach aims to optimize resource allocation by considering the interactions between different layers in the network. It introduces a cross-layer design that allows for dynamic reconfiguration and optimization of resources across multiple layers. By exploiting the capabilities of SDR, the approach enables intelligent resource allocation based on real-time network conditions and user requirements.

A resource allocation algorithm is given that considers various factors such as channel conditions, interference levels, and quality of service (QoS) requirements. The algorithm takes into account information from the physical layer, data link layer, and network layer to make informed resource allocation decisions. It aims to maximize spectrum utilization, minimize interference, and ensure QoS provisioning for cognitive radio users. The results demonstrate that the cross-layer resource allocation algorithm outperforms traditional approaches by achieving higher throughput, reduced interference, and improved QoS. The approach offers significant benefits in terms of efficient spectrum utilization and adaptability to dynamic network conditions.

With this literature review, we can see there are some limitations that we will try to cater in this research. Some authors have restricted their design to the configuration of the parameters of only one waveform (wide-band or narrow-band). Control phase latency did not improve with these algorithms as compared to Conventional Tactical Radio network in which all radios transmit sequentially. Multiple output technique with multi-layer design is not seen in any design which support multi-band transmissions and receptions. In order to solve these issues, this study proposes a multi-input, multi-output and multi-layer architecture that is effective and adaptable and can process a variety of signals demanding different QoS for tactical networks' long and short-range communications.

Chapter 4

Proposed AMIO-MAC Algorithm

A novel MAC layer algorithm is explained in this section that makes use of the cognitive engine and hybrid physical layer shown in previous sections. The cognitive engine and physical layer are responsible for managing the link parameters and service requirements respectively. MAC layer's function is to select an appropriate frequency band and allocate feasible slots for the demanded service quality.

For reference purposes, a traditional SDR MAC design is shown here, which makes use of single-input narrow-band with fixed bands for control and data slots. This comparison is discussed here to signify how much this new scheme will be beneficial for the users. The Classical Tactical Radio MAC (CTR-MAC) uses single-input physical layer and fixed frequencies for data/control slots in TDM/FDM fashioned tactical radio networks. After this discussion, the novel adaptive multi-input-output MAC (AMIO-MAC) design is introduced. This scheme is an improved version of our previous work AMI-MAC [1] which presented variable bandwidth support with multiple control frequencies for data phase by taking advantage of hybrid physical layer.

A classic tactical radio network can operate on one waveform either narrow-band or wide-band which support only fixed-bandwidth bands. Only one frequency band is reserved for the control slot, other available frequency bands are used in the data slots. Control phase is dedicated for negotiating bands and slots to be used in data phase. While data phase is dedicated for time slots allocated for data transfer purpose.

Figure 4.1 presents a conventional CTR-MAC design that supports M frequency bands and N time slots. In this design, the control phase utilizes a specific frequency f_c dedicated to the transmission of control information. The data transfer phase, on the other hand, employs frequencies f_1 to f_M for data transmission.

In the control phase, the network relies on a master-slave configuration, multiple radio interfaces, and sub-nets to enhance its performance. The control information is exchanged using the designated control frequency f_c, allowing nodes to coordinate and establish communication links. However, as the network size increases, the number of nodes also grows, resulting in a higher number of required time slots in the control phase. Consequently, this leads to increased control phase latency.

It is important to note that this conventional radio network design has limitations in terms of scalability. As the number of nodes increases, the control phase latency grows due to the increased time slots required for control information exchange. This can result in longer delays in establishing communication links and allocating resources, potentially impacting the overall network performance.

To mitigate the control phase latency in such conventional designs, alternative approaches and protocols can be explored. For example, the adoption of advanced medium access control (MAC) protocols, adaptive resource allocation algorithms, or the integration of cognitive radio techniques can help reduce latency and improve the efficiency of control phase operations. These advancements aim to address the scalability challenges of conventional radio networks, enabling them to support larger network sizes while minimizing control phase latency.

Unlike CTR-MAC, the AMI-MAC [1] benefited from the hybrid physical layer to receive multiple signals, to receive variable-sized bands, and to receive narrow-band and wide-band waveforms simultaneously. The ability to freely receive multiple signals removes the radio constraint of tuning the radio to single frequency. This feature can be used in several ways to significantly improve tactical radio network performance.

This concept is further enhanced after some experimentation to AMIO-MAC which supports multiple input and multiple output. Nodes can transmit to multiple users simultaneously without worrying about tuning the radio to more than one frequency. This requires a whole new algorithm to be followed in Request/Allocation phase as well as in data phase slots assignment.

Notations:

- β: Class of band from $\{WB, H, M, L\}$

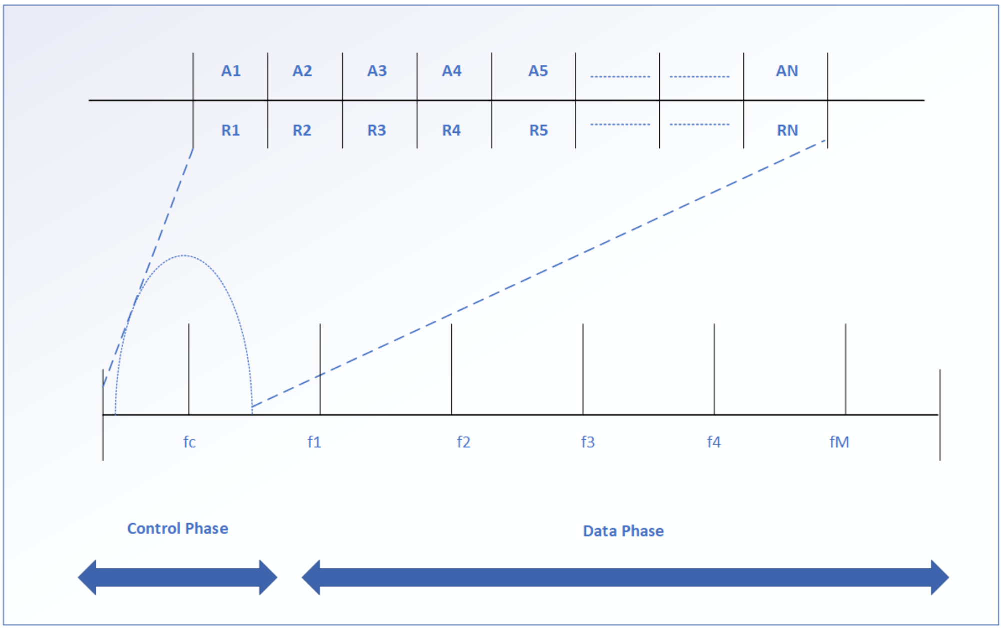


Figure 4.1: A sketch of CTR MAC layer working

- n_β: Number of bands in β class, $n_{ch} \in \{n_L, n_M, n_H, n_W\}$
- $K = \sqrt{N}$: Control frequency channels
- $F_c = \{f_{c1}, f_{c2}, ..., f_{cK}\}$: Control frequencies Set
- N: Number of Nodes in Network
- $N_{T,\beta}$: Data slots required for allocation in given channel type
- $\Delta = max(N_{T,\beta}) \times K$: Maximum data frame size
- T_{Dy}: y^{th} data slot, where $y = 1, 2, ..., \Delta$
- $\mathbf{C} = [\mathbf{C_1}|\mathbf{C_1^T}]$: $K \times 2K$ order time-frequency matrix

Figure 4.2 depicts the control phase of AMIO-MAC with frequency f_c vs Time slot T_c table. AMI-MAC and AMIO-MAC keep the control and data phase separate for that reason. Number of time slots in control phase are depending only on the number of nodes in the network. But unlike CTR-MAC, this protocol requires $2 \times K$ number of time slots as shown in this figure. First K slots are giving transmit opportunity to all the nodes, and the failed attempts will be catered in second K time slots of the matrix. An example of this table is given in the working example part in table 5.1 where 16 nodes are present in the network, and table is using 8 time slots.

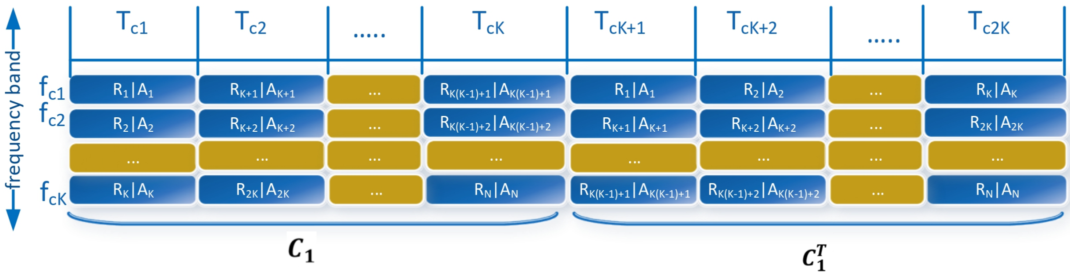


Figure 4.2: Proposed time-frequency matrix for AMIO-MAC [1]

Multiple simultaneous bands can be received and transmitted in control phase as well as in data phases. So, a radio can send data to multiple nodes in the same time slot but different bands. This design significantly reduces the control phase latency by packing transmissions in the same slot. This physical layer can also support simultaneous control and data phase with their frequency combinations, but that implementation gives a lot of issues in the practical scenario. However it can be possible in future works if we are able to eliminate those issues.

In the Request Algorithm 1, every node in the network gets a turn to send requests to their desired destinations. These requests are transmitted in control frames. After sending the requests, each node checks if it can communicate with the desired source node over the desired channel. If the criteria for communication are met, the destination nodes send replies (allocations) back to the source nodes. These allocation messages contain information about the communication slots and channel specifications. The control frame is organized into time slots assigned to nodes in a specific order.

In the control frame handling process, the algorithm iterates through each received request. If the request is destined for the current node, it searches for a certain number of empty data slots in the data phase table specific to the requested band. If the required number of empty slots is found, they are marked as reserved for the communication of the involved nodes, and an ACK (acknowledgment) is sent back to the requester node. This informs other nodes in the network that these slots are now occupied.

However, if the Quality of Service (QoS) requirements cannot be fulfilled, a NACK (negative acknowledgment) is sent to the node that made the request. This indicates that the requested communication cannot be supported. Additionally, the

Algorithm 1: Sending Requests Control Phase

```
Initialization: Choose $\beta$, $n_\beta$, $N_{T,\beta}$ and $N$
if TX data available then
    Transmit all Request Messages ;
else
    Process the Received Request Message for current node ;
    Fill time-frequency matrix $\mathbf{C}$ ;
    if request intended for me then
        // Find available slots in requested band class $\beta$ ;
        $y = 1$ ;
        while $y \leq \Delta - N_{T,\beta}$ do
            for $(k = 1 : n_{ch})$ do
                if ($T_{Dy}$ to $T_{D(y+N_{T,\beta}-1)}$ are available) then
                    Select $k^{th}$ channel ;
                    Break;
                else
                    $y = y + N_{T,\beta}$ ;
                end
            end
        end
        if $k \neq 0$ then
            Reserve $T_{Dy}$ to $T_{D(y+N_{T,\beta}-1)}$ for $B_{\beta,k}$ in data phase table ;
            Set PHY mode according to service quality and range ;
            if QoS can be served then
                Send Allocation Message with ACK ;
            else
                Send Allocation Message with NACK ;
            end
        end
    end
end
```

Algorithm 2: Receive Allocation Messages

```
for Every Allocation Message do
    if (ACK Found) then
        Process Allocation ;
        Update Data Table ;
    else
        // NACK Found ;
        if (current node is destination) then
            if (Lower QoS Available) then
                Make a message with lower QoS ;
            else
                Request network layer for enabling multi-hop link ;
            end
        end
    end
end
```

algorithm suggests that if the user has prior knowledge about the network and knows that all nodes will require low data rate channels due to range requirements, they can set the parameter n_β for the corresponding band class $\beta = L$ accordingly. By doing so, fewer data slots will be needed. Otherwise, if all nodes request low band channels and the available data slots Δ are insufficient, not all nodes will be able to communicate on band $\beta = L$.

Similarly, in the Allocation Algorithm 2, the received allocation messages are processed one by one. If an ACK is present in the allocation packet, the algorithm updates the data phase table accordingly and proceeds with the next allocation. However, if a NACK is present, the current node needs to take steps to enable lower QoS communication with the other node. With this algorithm running in the entire network, each node maintains an updated data phase table, which keeps track of occupied slots by other nodes, ensuring they do not attempt to overwrite them.

Overall, these algorithms handle the control phase in an SDR network, where nodes send requests, receive allocations, and update their data phase tables to establish communication channels and ensure efficient resource allocation.

The proposed AMIO-MAC (Adaptive Medium Access Control) protocol incorporates a control phase and a data phase to efficiently allocate resources in a tactical radio network. During the control phase, request messages for slot allocations are sent, and allocation messages are returned in the same slot to the corresponding sender. This enables every node in the network to request and schedule their transmissions/receptions for the subsequent data phase.

Figure 4.2 illustrates the structure of the control phase, as described in [1]. It consists of K control frequencies and 2K control time slots. In a network with N radios, K can be equal to N, representing the number of control frequencies. However, to ensure that transmitting nodes can receive requests made for them, an additional matrix is required by transposing the original KxK time-frequency matrix, denoted as C1. Thus, the complete control phase involves matrices C = [C1 | C1T], which includes 2K time slots.

To minimize latency in the control phase of the tactical radio network, a limited number of time slots are utilized. For example, in a 49-node network, only 14 time slots may be required. The nodes are prioritized based on their IDs, with lower IDs assigned higher priority. During the data phase, nodes select their preferred time slots and bands according to their priority.

The priority of nodes is determined by their IDs, ensuring that lower IDs have higher priority. The available RF bandwidth is divided into bands of variable sizes, spanning from low to high frequencies. Each band can have multiple time slots allocated to it, denoted as T_D, to fulfill the required service demands. The number of data slots reserved for each mode is represented by $N_{T,L}$, $N_{T,M}$, $N_{T,H}$, and $N_{T,WB}$, corresponding to low, medium, high, and wide-band modes, respectively.

The maximum size of the data phase is determined by the mode with the largest number of reserved data slots, multiplied by K. However, in practice, the actual number of time slots utilized may be lower than the maximum size. The MAC protocol may dynamically adjust the data phase to reduce latency and improve overall system performance.

By efficiently managing the control and data phases, the AMIO-MAC protocol optimizes the allocation of time slots and frequency bands. Prioritizing nodes based on their IDs and utilizing variable-sized bands enable effective resource allocation, reducing latency and improving network performance in tactical radio networks.

Overall, the proposed AMIO-MAC protocol enhances the efficiency of resource allocation by incorporating a control phase and a data phase. The control phase allows for requesting and scheduling transmissions/receptions, while the data phase allocates time slots and frequency bands based on node priority and available bandwidth. By minimizing latency and optimizing resource utilization, the AMIO-MAC protocol improves the overall performance of tactical radio networks.

The proposed AMIO-MAC (Adaptive Medium Access Control) design aims to provide a unique solution for allocating time slots and frequency bands in the data phase of wireless communication systems. This allocation is crucial for reducing latency and improving the overall performance of tactical radio networks.

In the proposed design, during the request phase of each control slot, the radio receiver captures all request messages from radios seeking bandwidth allocation. These radios request specific bands, and the reservation process begins. The cognitive engine confirms the reservation, and the goal is to minimize the number of time slots used. To achieve this, the bands are allocated first, followed by the allocation of time slots.

Radios that are addressed during the request phase reserve allocation slots for the data phase with the assistance of the cognitive engine. The reservation details are then announced through an allocation message during the same time slot. Radios that receive these allocation messages update their time-frequency matrix to reflect the allocated resources for the data phase.

The proposed AMIO-MAC design is presented in algorithms 1 and 2, providing a step-by-step description of the reservation and allocation process. These algorithms serve as a guideline for implementing the design in practical scenarios. To illustrate the effectiveness of the design, a comprehensive example is presented, demonstrating how the proposed AMIO-MAC protocol operates in practice.

One key advantage of the proposed design is the allocation of resources based on priority, which is determined by the IDs of the nodes. This ensures that the highest priority nodes are allocated the required resources, leading to an improvement in the quality of service. By efficiently utilizing variable-sized bands and multiple time slots for each band, the proposed design maximizes the utilization of available bandwidth, contributing to enhanced network performance.

Through the example presented in the research work, it is demonstrated that the proposed AMIO-MAC protocol outperforms traditional MAC protocols in terms of latency and network throughput. The allocation of resources in a strategic and adaptive manner allows for better resource management and optimization, resulting in improved overall system performance.

In summary, the research work introduces the AMIO-MAC design, which addresses the allocation of time slots and frequency bands in the data phase of wireless communication systems. By prioritizing nodes based on their IDs and efficiently utilizing available bandwidth, the proposed design offers improved quality of service, reduced latency, and enhanced network throughput. The algorithms and comprehensive example provide insights into the practical implementation and effectiveness of the AMIO-MAC protocol.

CHAPTER 5

AMIO-MAC Example and Results

In this chapter, we will analyze and assess the improvements in efficiency of the network with this new approach. First lets look at an example of tactical radio network using AMIO-MAC and see how beneficial is the new algorithm. Then we will look at the simulation results of control and data phase for different parameters.

5.1 Working Example

Within this particular section, we present a practical demonstration of our proposed approach using a mesh network consisting of 16 SDR nodes (referred to as $N = 16$). Following the suggested algorithm, the nodes are prioritized and arranged in a time-frequency matrix during the control phase. For this particular case, we set $K = \sqrt{N} = \sqrt{16} = 4$. Although the example mesh network consists of nodes that are not directly connected to each other, we use dotted lines to indicate a certain level of connectivity between specific nodes for clarity purposes. To construct the control frame, we utilize a time-frequency matrix, denoted as C, with dimensions of $K \times 2K = 4 \times 8$. This matrix is employed to facilitate the request/allocation phase of the 16 radios operating on 4 concurrent bands, with carrier frequencies ranging from f_{c1} to f_{c4}. The time slots T_{c1} to T_{c8} are allocated for this phase. Table 5.1 presents the time-frequency matrix, highlighting the distribution of nodes during the request/allocation phase (R|A).

The prioritization of nodes follows a downward sequence, where each subsequent

Table 5.1: Matrix representing Time Vs Frequency for control phase with $N = 16$

	T_{c1}	T_{c2}	T_{c3}	T_{c4}	T_{c5}	T_{c6}	T_{c7}	T_{c8}
f_{c1}	1	5	9	13	1	2	3	4
f_{c2}	2	6	10	14	5	6	7	8
f_{c3}	3	7	11	15	9	10	11	12
f_{c4}	4	8	12	16	13	14	15	16

node is assigned a lower priority compared to the previous one. For instance, node 1 holds the highest priority, followed by node 2, and so on. During the control phase, the nodes select their respective time slots and frequency bands based on their priority and the cognitive engine's algorithm. For the purpose of this example, we assume that the spectrum is divided, leading to the allocation of resources within four different band classes: low ($n_L = 8$), medium ($n_M = 4$), high ($n_H = 2$), and wide-band ($n_{WB} = 1$). Consequently, each node is situated within one of these four ranges to establish communication. Figure 5.1 illustrates this relationship with respect to node 5, showcasing the utilization of orbits B_L, B_M, B_H, and B_{WB}.

In table 5.1, first K columns are representing T_{c1} to T_{c4} time slots, where nodes in a single column (time slot) will not be able receive control requests from each other. Because all the nodes in a single column are going to be in transmission mode, in order to fix this limitation, there are other K columns where all the nodes matrix is transposed so that those nodes can send control requests which was not possible in first K columns. Hence, there will be $2 \times K$ columns in our proposed design for the given number of nodes.

Referring to diagram 5.1, node 5 demonstrates the ability to maintain simultaneous connections with nodes 4 and 12. Node 5 utilizes the wide-band class to communicate with node 12 and the medium band class to communicate with node 4. For the purpose of this example, we assume uninterrupted service and the capability for all nodes to communicate, at the very least, in narrow-band mode. Consequently, we can breakdown the data frequency bands as $B_{L,1}$ to $B_{L,8}$ for the narrow-band class, $B_{M,1}$ to $B_{M,4}$ for the medium band class, $B_{H,1}$ and $B_{H,2}$ for the high band class, and $B_{WB,1}$ for the wide-band class. Furthermore, there are four time slots designated for $N_{T,L}$, three for $N_{T,M}$, two for $N_{T,H}$, and one for $N_{T,WB}$. The data phase encompasses time slots ranging from T_{D1} to T_{D16}, considering that the maximum potential data slots are $\Delta = 16$. It is worth noting that typically, the number of time slots consumed during

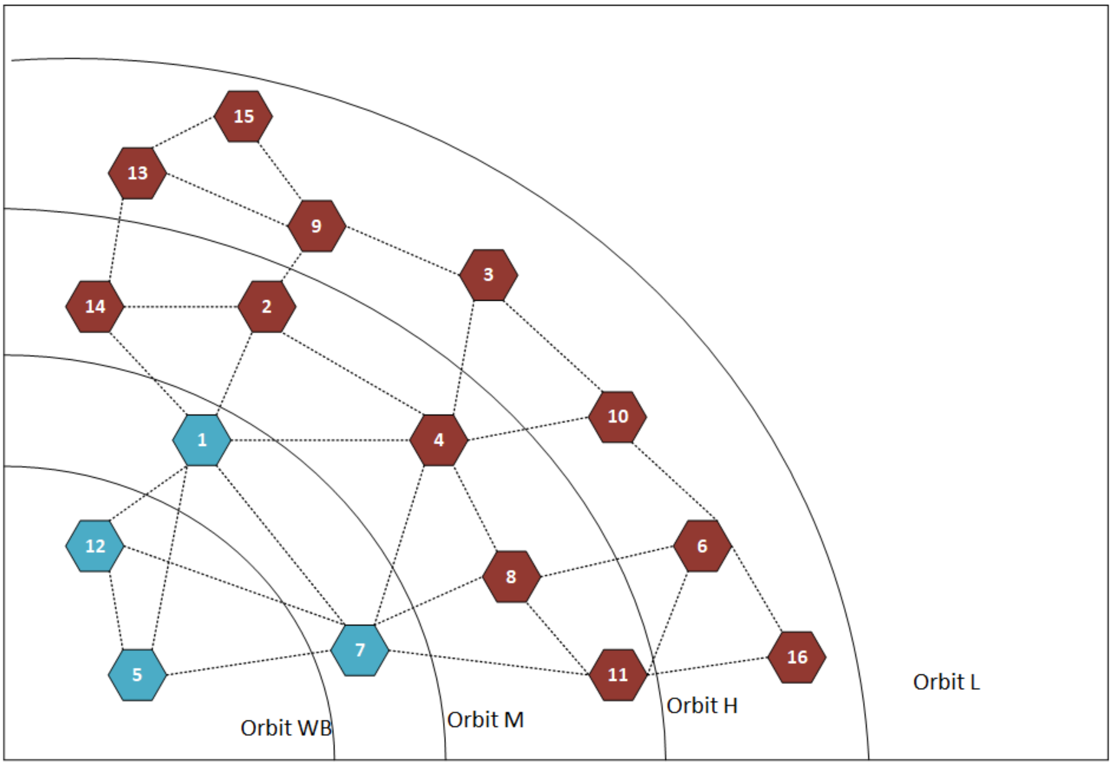


Figure 5.1: A Mesh SDR Network with multi-band orbits of node 5

the data phase is less than Δ.

During the control time slot T_{c1}, nodes 1 to 4 engage in simultaneous transmission of request messages to their respective desired nodes. They then await allocation messages from those nodes, as depicted in Figure 5.2 and Table 5.2. The physical layer characteristics allow each node to transmit requests to multiple nodes, providing an advantage in the process. Nodes 1 till node 4 are unable to receive each other's transmissions due to their aligned request phases. However, they may receive acknowledgements directed towards them throughout the allocation process. Node 1's request will be received by all other nodes, including the initially intended recipient, node 13. Considering that node 1 has higher priority than other nodes requesting in T_{c1}, the remaining nodes will avoid occupying the slots designated for node 1→13, assuming that the service will be either acknowledged or denied. The cognitive engine will assess the channel conditions as node 1 has requested a low data rate service from node 13. As a result, node 13 and node 1 can establish communication at low data rates.

Once the request from node 1 is accepted by the cognitive engine of node 13 and communicated to the MAC, the initial four time slots within $B_{L,1}$, the first available

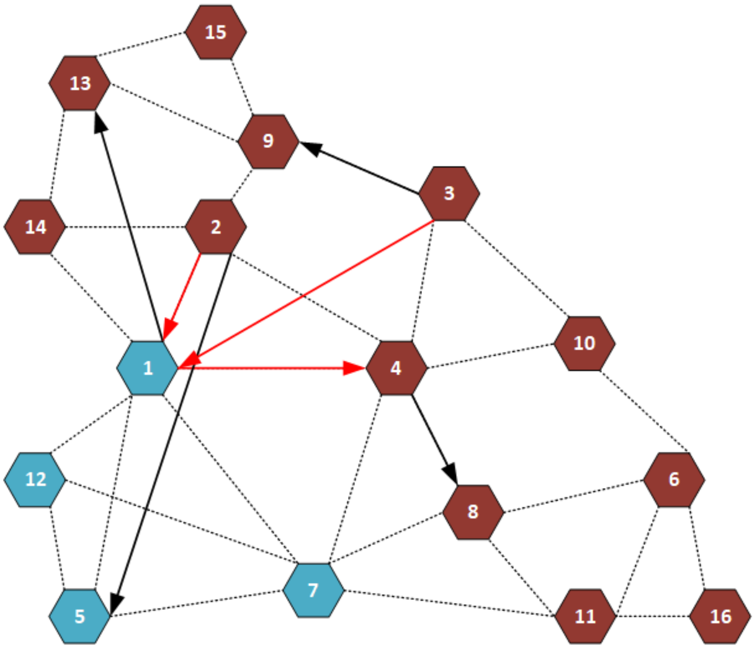


Figure 5.2: A Mesh SDR Network with arrows showing Request and Allocations phase in T_{c1}

Table 5.2: Request Allocation phase of T_{c1}

Tx Node (Request)	Rx Node (Allocation) Band
1	13 Low, 4 Low
2	5 Medium, 1 Low
3	1 Low, 9 High
4	8 Wide-band

band, will be allocated. Specifically, 1→13 will be assigned to T_{D1} through T_{D4} in $B_{L,1}$. As a result of this acknowledgment from node 13 to node 1, the allocation table is updated. Nodes 2, 3, and 4 receive a similar acknowledgement from node 13, resulting in changes to their respective allocation entries in the table. However, since node 4 is already in transmit mode during the R|A phase, it will not send any allocation back to node 1 despite the request for low data rate communication. On the other hand, node 4 will request node 8 for wide-band communication, and node 8 will allocate T_{D1} for the 4→8 communication link. Additionally, node 3 requests high band communication with node 9, and the allocation of T_{D1} to T_{D2} in $B_{H,1}$ fulfills this request. Thus, the completion of T_{c1} entails both successful and unsuccessful allocations.

Figure 5.3 and table 5.3 depict the Request Allocation schedule for T_{c2}. Node

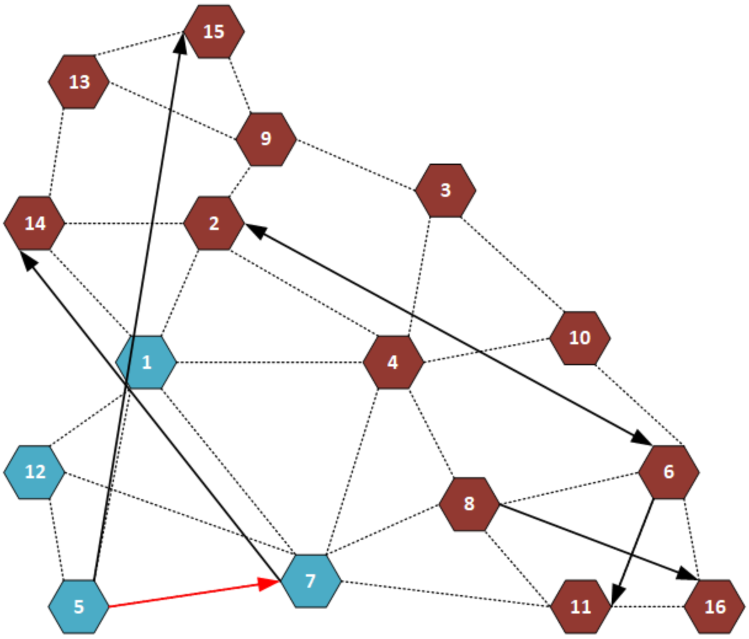


Figure 5.3: A Mesh SDR Network with arrows showing Request and Allocations phase in T_{c2}

5,6,7 and 8 are sending requests to their desired destinations and in response those nodes will may or may not send allocations to these nodes. Node 5 is requesting simultaneously to two nodes 15 and 7, among them 7 is involved in current R|A phase so it will not send acknowledgement to node 5. Node 15 on the other hand, will send allocation to node 5 for low band $B_{L,2}$ in T_{D1} to T_{D4}. Node 6 requests node 11 for medium band connection, node 11 according to the algorithm will allocate $B_{M,2}$ in T_{D1} to T_{D3}. Wide-band data rate is requested from node 2 by node 6, which in return sends allocation on $B_{WB,1}$ in T_{D2} as T_{D1} is already occupied in this band. Similarly, node 7 requests low data rate link from node 14, cognitive engine of node 14 checks the channel underlying conditions, accepts the request and asks MAC layer to allocate slots. MAC layer allocates $B_{L,3}$ in T_{D1} to T_{D4} as $B_{L,1}$ and $B_{L,2}$ are already used by higher priority nodes. In the same fashion, 8→16 will get $B_{L,4}$ in T_{D1} to T_{D4}. The proposed cross-layer design makes it possible to achieve this performance increase in the data phase.

The T_{c3} time slot schedule is shown in figure 5.4 and table 5.4. Node 9 requested high band connection from node 3, which accepts and sends allocation for T_{D3} to T_{D4} on $B_{H,1}$ as first 2 data slots are already booked. Node 10 wants low band link with node 4, and gets T_{D1} to T_{D4} on $B_{L,5}$. Node 11 requests from node 6 for medium band slots,

Table 5.3: Request Allocation phase of T_{c2}

Tx Node (Request)	Rx Node (Allocation) Band
5	15 Low, 7 Wide-band
6	11 Medium, 2 Wide-band
7	14 Low
8	16 Low

and gets allocation in T_{D1} to T_{D4} on $B_{M,3}$ for 11→6. Node 12 requests 7 for wide-band, node 7 sends back an allocation for T_{D3} on $B_{WB,1}$. Node 12 sends 14 for medium band, and gets allocation for $B_{M,3}$ on T_{D4} to T_{D6}.

The provided Figure 5.4 and Table 5.4 illustrate the time slot schedule (T_{c3}) for a specific network scenario. In this scenario, Node 9 initiates a request to establish a high band connection with Node 3. Node 3 accepts the request and proceeds to allocate time slots T_{D3} to T_{D4} on the high band channel $B_{H,1}$ for their communication. However, due to prior reservations, the first two data slots are already occupied, so the allocated slots for Node 9 and Node 3's communication start from T_{D3}.

Meanwhile, Node 10 expresses its desire for a low band link with Node 4. It receives an allocation for time slots T_{D1} to T_{D4} on the low band channel $B_{L,5}$, thereby establishing a communication channel between Node 10 and Node 4.

Furthermore, Node 11 requests medium band slots from Node 6. In response, Node 6 acknowledges the request and assigns time slots T_{D1} to T_{D4} on the medium band channel $B_{M,3}$ for their communication. These allocated time slots facilitate seamless communication between Node 11 and Node 6, ensuring the successful transmission of data.

The time slot allocations in this network scenario highlight the efficient utilization of different frequency bands to accommodate the communication needs of different nodes. By dynamically allocating time slots based on bandwidth availability and node requests, the system optimizes resource allocation and enhances overall network performance.

Node 12 seeks a wide-band connection from node 7. Node 7 responds by sending an allocation for time slot T_{D3} on the wide-band channel $B_{WB,1}$, facilitating communication between node 12 and node 7. Additionally, node 12 sends a request to node 14 for a medium band link. It receives an allocation for the medium band channel $B_{M,3}$,

Table 5.4: Request Allocation phase of T_{c3}

Tx Node (Request)	Rx Node (Allocation) Band
9	3 High
10	4 Low
11	6 Medium
12	7 Wide-band

spanning time slots T_{D4} to T_{D6}

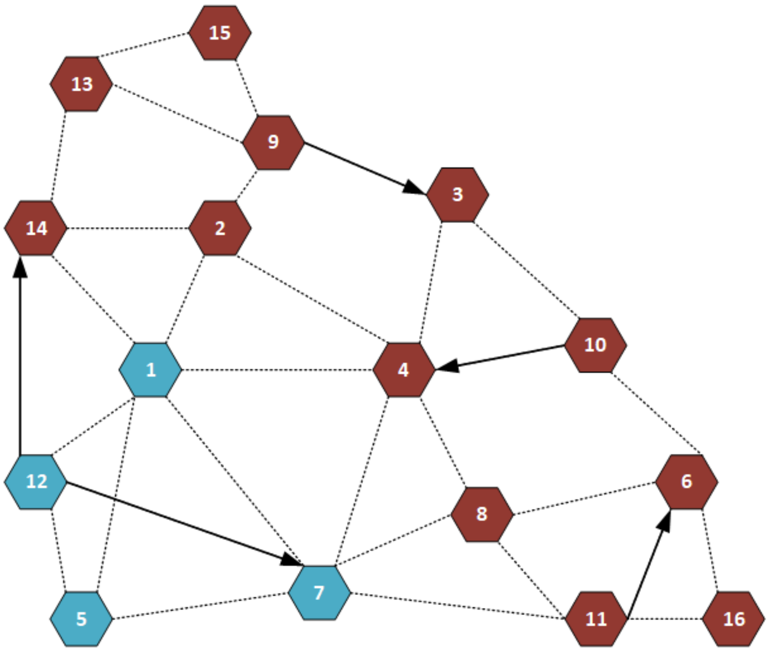


Figure 5.4: A Mesh SDR Network with arrows showing Request and Allocations phase in T_{c3}

Figure 5.5 and table 5.5 are showing the schedule of T_{c4} time slot. In this scenario, several nodes participate in the communication process. Node 13 initiates a request for a medium band connection from node 12. The request is accepted, and as a result, node 12 allocates specific time slots, namely T_{D4} to T_{D6}, on the medium band channel $B_{M,1}$. This allocation enables communication between node 13 and node 12 over the specified time slots and channel. Node 13 also requests a low band link from node 1. Node 1 responds positively to the request and allocates time slots T_{D5} to T_{D8} on the low band channel $B_{L,1}$. These allocated time slots and channel allow node 13 to establish communication with node 1.

Moving on, node 14 requests medium band slots from node 10. Node 10 accepts the request and allocates time slots T_{D4} to T_{D6} on the medium band channel $B_{M,2}$. This allocation enables node 14 to communicate with node 10 over the specified time slots and channel. In addition to the medium band request, node 14 also requests a high band link from node 2. Node 2 acknowledges the request and allocates time slots T_{D5} to T_{D6} on the high band channel $B_{H,1}$. This allocation facilitates communication between node 14 and node 2 over the designated time slots and channel.

Node 15 requests two types of connections. It requests a low band link from node 8 and a high band link from node 13. Node 8 responds by allocating time slots T_{D5} to T_{D8} on the low band channel $B_{L,2}$ for communication between node 15 and node 8. However, there is a conflict when attempting to establish communication with node 13 since it is already in transmission mode. Consequently, the communication between node 15 and node 13 is rescheduled for the next control slots. Similarly, node 16 requests low band links from nodes 8 and 1. Node 8 allocates time slots T_{D5} to T_{D8} on the low band channel $B_{L,3}$ for communication between node 16 and node 8. Furthermore, node 16 also receives an allocation from node 1, assigning time slots T_{D5} to T_{D8} on the low band channel $B_{L,4}$. These allocations allow node 16 to establish communication with node 8 and node 1 over the respective time slots and channels.

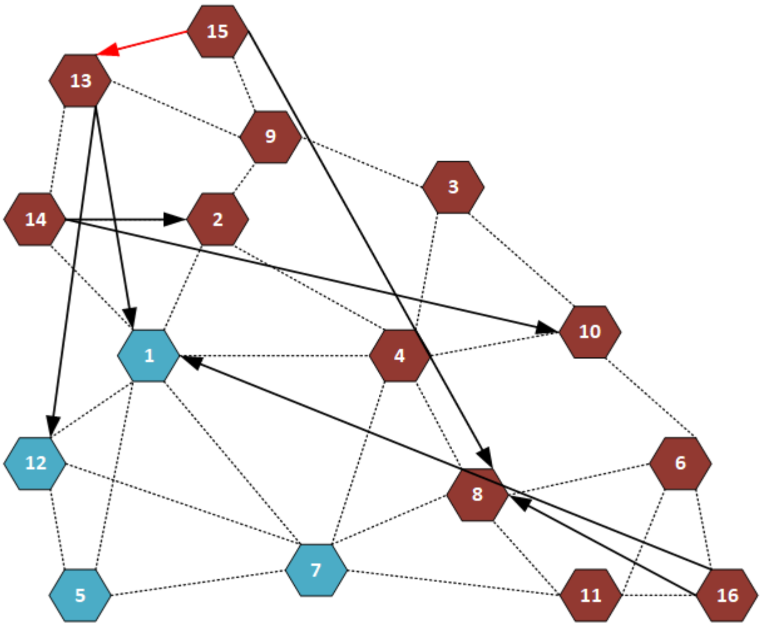


Figure 5.5: A Mesh SDR Network with arrows showing Request and Allocations phase in T_{c4}

Table 5.5: Request Allocation phase of T_{c4}

TX Node (Request)	RX Node (Allocation) Band
13	12 Medium, 1 Low
14	10 Medium, 2 High
15	8 Low, 13 High
16	8 Low, 1 Low

The R|A phase has been experienced by each of the 16 nodes at least once by the time T_{c4} ends. It is clear that the requests 1→4, 2→1, 3→1, 5→7, and 15→13 could not have been fulfilled because they were in the current T_c's simultaneous R|A phase. The problem is fixed in the remaining portion of the control stage, where the method calls for concatenating the transposed form of this 4 by 4 matrix. Figure 5.6 illustrates the composite control time slots T_{c5} to T_{c8} where the remaining nodes which faced conflict of transmission in previous slots, can again try their R|A phase.

Here node priority plays a critical role, because when nodes in T_{c1} send out the requests in the network, other nodes update their data phase tables accordingly. For example, if node 2 sends request to node 13 for high band, then other nodes will mark reserved in first available high band with the earliest possible data slots, and allocation packet from node 13 will also confirm those nodes about the data slots numbers. Low priority nodes get data slots in their desired band when all high priority nodes have finished their allocations.

The control slots T_{c5} to T_{c8} contain the failed R|A attempts (from first K slots) as well as new link attempts (see figure 5.6). These failed attempts are represented with red arrow in the figures 5.2, 5.3, 5.4 and 5.5. In time slot T_{c5}, link 1→4 (failed attempt of T_{c1}) gets T_{D5} to T_{D8} on $B_{L,5}$. In the same way, 5→7 (failed attempt of T_{c2}) will get T_{D4} on $B_{WB,1}$. Table 5.7 gives all the details about these request and allocation attempts for T_{c4} to T_{c8}.

In time slot T_{c6}, 2→1 (failed attempt of T_{c1}) link gets T_{D9} to T_{D12} on $B_{L,1}$. Similarly, 14→13 (failed attempt of T_{c4}) acquires T_{D7} to T_{D8} on $B_{H,1}$. In the same way, time slot T_{c7} gives chance to node 3 to create a link 3→1 (failed attempt of T_{c1}) to allocate T_{D9} to T_{D12} on $B_{L,2}$. But in T_{c8}, all requests/allocations were completed, hence, there was no request/allocation in T_{c8}. As a result, there are 26 connections scheduled in this control phase, and 12 out of Δ=16 were used for all this communication.

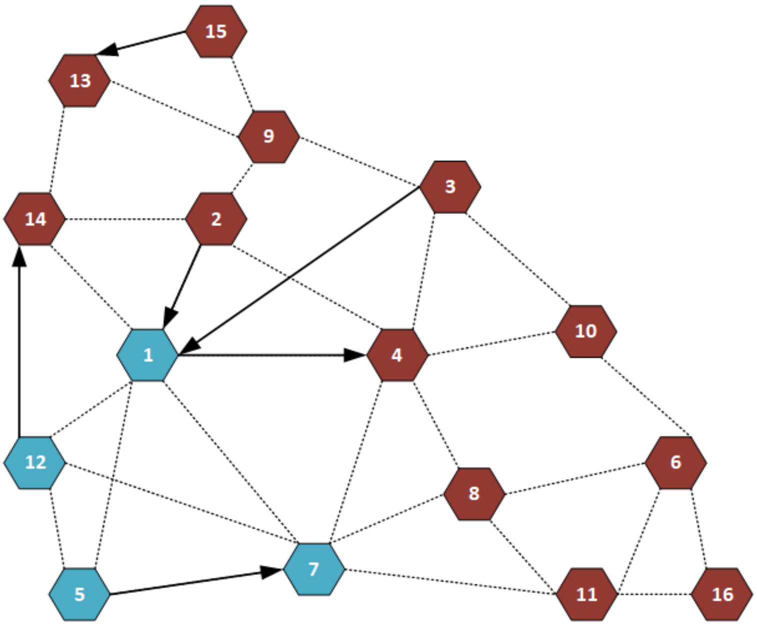


Figure 5.6: A Mesh SDR Network with arrows showing Request and Allocations phase in T_{c5} to T_{c8}

Table 5.6: Request Allocation table for $N = 16$, T_{c1} To T_{c3}

	$T_{c1} R\|A$	$T_{c2} R\|A$	$T_{c3} R\|A$
f_{c1}	$R^{13}_{1,L}\|A^{1,T_{D1:D4}}_{13,B_{L1}}, R^{4}_{1,L}\|A^{\times}_{\times}$	$R^{15}_{5,L}\|A^{5,T_{D1:D4}}_{15,B_{L2}}, R^{7}_{5,W}\|A^{\times}_{\times}$	$R^{3}_{9,H}\|A^{9,T_{D3:D4}}_{3,B_{H1}}$
f_{c2}	$R^{5}_{2,M}\|A^{2,T_{D1:D3}}_{5,B_{M1}}, R^{1}_{2,L}\|A^{\times}_{\times}$	$R^{11}_{6,M}\|A^{6,T_{D1:D3}}_{11,B_{M2}}, R^{2}_{6,W}\|A^{6,T_{D2}}_{2,B_{W1}}$	$R^{4}_{10,L}\|A^{10,T_{D1:D4}}_{4,B_{L5}}$
f_{c3}	$R^{1}_{3,L}\|A^{\times}_{\times}, R^{9}_{3,H}\|A^{3,T_{D1:D2}}_{9,B_{H1}}$	$R^{14}_{7,L}\|A^{7,T_{D1:D4}}_{14,B_{L3}}$	$R^{6}_{11,M}\|A^{11,T_{D1:D3}}_{6,B_{M3}}$
f_{c4}	$R^{8}_{4,W}\|A^{4,T_{D1}}_{8,B_{W1}}$	$R^{16}_{8,L}\|A^{8,T_{D1:D4}}_{16,B_{L4}}$	$R^{7}_{12,W}\|A^{12,T_{D3}}_{7,B_{W1}}, R^{14}_{12,M}\|A^{12,T_{D4:D6}}_{14,B_{M3}}$

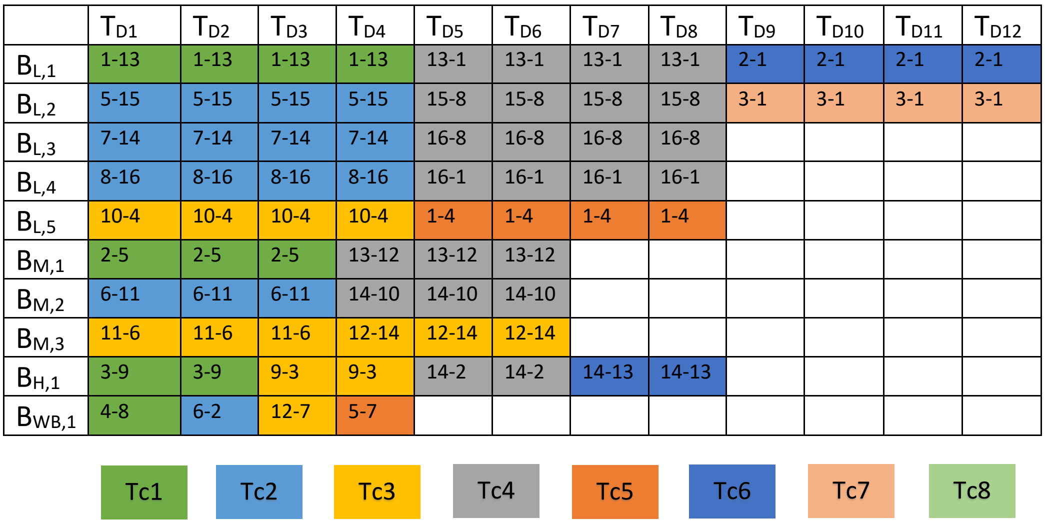
$$R^{q}_{p,\beta}|A^{p,T_{Dm_1}:T_{Dm_2}}_{q,B_{\beta j}} \tag{5.1.1}$$

Spectrum allocation for data phase is also shown for all band classes. Notation is explained in 5.1.1 which shows the symbols that is being used in tables 5.6 and 5.7 for request and allocation of spectrum. An allocation of the j^{th} channel of the band class β from node q to node p in the time slots T_{Dm_1} through T_{Dm_2}, after a request for the band class β from node p to node q. If the allocation message contains $\times$, the cognitive engine has rejected the service in the desired band class.

The tables 5.6 and 5.7 and the figure 5.7 displays the whole R|A control phase

Table 5.7: Request Allocation table for $N = 16$, T_{c4} To T_{c8}

	$T_{c4}R\mid A$	$T_{c5}R\mid A$	$T_{c6}R\mid A$	$T_{c7}R\mid A$	$T_{c8}R\mid A$
f_{c1}	$R^{12}_{13,M}\mid A^{13,T_{D4:D6}}_{12,B_{M1}}, R^{1}_{13,L}\mid A^{13,T_{D5:D8}}_{1,B_{L1}}$	$R^{4}_{1,L}\mid A^{1,T_{D5:D8}}_{4,B_{L5}}$	$R^{1}_{2,L}\mid A^{2,T_{D9:D12}}_{1,B_{L1}}$	$R^{1}_{3,L}\mid A^{3,T_{D9:D12}}_{1,B_{L2}}$	$R^{\times}_{4}\mid A^{\times}_{\times}$
f_{c2}	$R^{10}_{14,M}\mid A^{14,T_{D4:D6}}_{10,B_{M2}}, R^{2}_{14,H}\mid A^{14,T_{D5:D6}}_{2,B_{H1}}$	$R^{7}_{5,W}\mid A^{5,T_{D4}}_{7,B_{W1}}$	$R^{\times}_{6}\mid A^{\times}_{\times}$	$R^{\times}_{7}\mid A^{\times}_{\times}$	$R^{\times}_{8}\mid A^{\times}_{\times}$
f_{c3}	$R^{8}_{15,L}\mid A^{15,T_{D5:D8}}_{8,B_{L2}}, R^{13}_{15,H}\mid A^{\times}_{\times}$	$R^{\times}_{9}\mid A^{\times}_{\times}$	$R^{\times}_{10}\mid A^{\times}_{\times}$	$R^{\times}_{11}\mid A^{\times}_{\times}$	$R^{14}_{12,M}\mid A^{12,T_{D4:D6}}_{14,B_{M3}}$
f_{c4}	$R^{8}_{16,L}\mid A^{16,T_{D5:D8}}_{8,B_{L3}}, R^{1}_{16,L}\mid A^{16,T_{D5:D8}}_{1,B_{L4}}$	$R^{\times}_{13}\mid A^{\times}_{\times}$	$R^{13}_{14,H}\mid A^{14,T_{D7:D8}}_{13,B_{H1}}$	$R^{\times}_{15}\mid A^{\times}_{\times}$	$R^{\times}_{16}\mid A^{\times}_{\times}$



	T_{D1}	T_{D2}	T_{D3}	T_{D4}	T_{D5}	T_{D6}	T_{D7}	T_{D8}	T_{D9}	T_{D10}	T_{D11}	T_{D12}
$B_{L,1}$	1-13	1-13	1-13	1-13	13-1	13-1	13-1	13-1	2-1	2-1	2-1	2-1
$B_{L,2}$	5-15	5-15	5-15	5-15	15-8	15-8	15-8	15-8	3-1	3-1	3-1	3-1
$B_{L,3}$	7-14	7-14	7-14	7-14	16-8	16-8	16-8	16-8				
$B_{L,4}$	8-16	8-16	8-16	8-16	16-1	16-1	16-1	16-1				
$B_{L,5}$	10-4	10-4	10-4	10-4	1-4	1-4	1-4	1-4				
$B_{M,1}$	2-5	2-5	2-5	13-12	13-12	13-12						
$B_{M,2}$	6-11	6-11	6-11	14-10	14-10	14-10						
$B_{M,3}$	11-6	11-6	11-6	12-14	12-14	12-14						
$B_{H,1}$	3-9	3-9	9-3	9-3	14-2	14-2	14-13	14-13				
$B_{WB,1}$	4-8	6-2	12-7	5-7								

Figure 5.7: Data phase for $N = 16$ nodes using AMIO-MAC algorithm

and data phase updated matrix. The color codes are used for ease of understanding the different time slots in control phases. Figure 5.7 is showing the scheduling that was negotiated in control phase by all the network. The color codes are representing the set of data slots that were decided in a certain time slot. As we can see, most of the links were successfully created in first K time slots. And this proposed algorithm gives ability to support more links to the network while requiring limited number of data and control slots.

5.2 Simulation Results and Discussion

In this section, we present the results of simulations to prove that proposed AMIO-MAC scheme is better than AMI-MAC [1] and CTR-MAC in every aspect. As our design is backed by hybrid design [5] and its cognition engine simulation results are shown in figure 5.8. As this work is a combination of PHY and MAC design, so PHY level improvements are also shown and discussed here. The table 5.8 taken from [1] is depicting all the simulation parameters that are in use.

Table 5.8: Parameters Used in Simulations

Parameter	**Values**
Low bandwidth B_L	25 kHz
High bandwidth B_H	200 kHz
Medium bandwidth B_M	100 kHz
Wide-band bandwidth B_{WB}	1 MHz
Medium band data rate (D_M)	211.4 kbps
High band data rate (D_H)	420.5 kbps
Low band data rate (D_L)	50.1 kbps
Wide-band data rate (D_{WB})	1.1 Mbps
Control slot time (T_c)	6.6 ms
Data slot time (T_d)	11.8 ms
Control data size (P_c)	41 Bytes

For this research, we will be checking the improvements in control phase latency and data phase latency performance of the protocols when number of nodes or number of transmission links are increased in the network. The article explains the process of waveform/parameter adaptation in the physical layer based on the underlying channel conditions. This layer is responsible for controlling all the link parameters. Figure 5.8 presents the SNR VS throughput analysis of four different types of band classes to depict how this process works. The curves on the graph represent the potential throughput of all modes within a band class vs the SNR values.

The data is taken from the bandwidth values of low, high, medium, and wide-band channels in table 5.8. The Stanford University Interim (SUI) fading channel model is used to simulate these modes and provide the findings. If a node requires a throughput of 950 kbps and has an SNR of 10 dB, Cognition Engine chooses mode 1 of the high bandwidth channel as the best viable alternative, as shown in figure 5.8. Conversely, if the SNR is 20 dB, the suggested CE finds mode 3 of the wide-band channel, which satisfies the desired throughput requirement.

When sequential transmissions occur in TDM/FDM networks, it may cause a delay in the control phase that can interfere with real-time connections like voice conver-

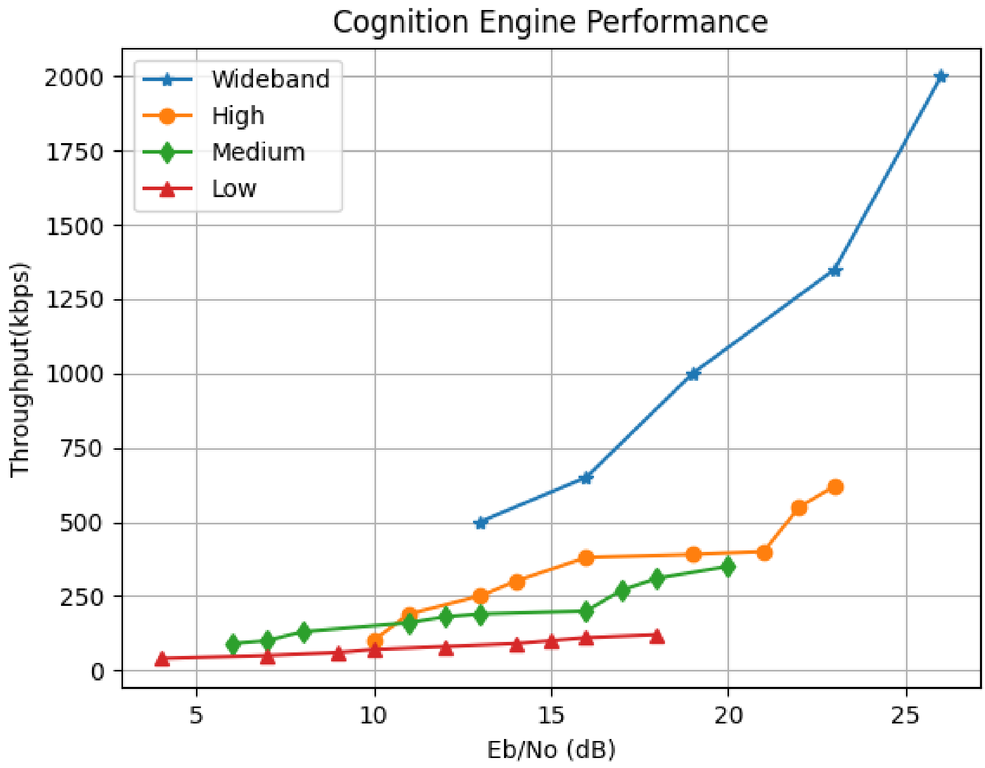


Figure 5.8: Working of the proposed cognition engine

sations. Figure 5.9 depicts the relationship between the number of nodes and latency. For CTR-MAC, a linear increase in the control phase latency is observed. However, the proposed AMIO-MAC supports networks of a much larger size because it significantly reduces control phase delay through simultaneous broadcasts.

The network topology defines the total number of data slots that are required by a radio network. As shown in figure 5.9, the number of nodes increase trend cause the linear increase in control phase latency in the case of CTR-MAC, because it cannot support multiple transmissions and receptions as proposed in current research. And this increase in latency is not acceptable in time critical communications which are the core of a tactical radio network. Whereas, AMI-MAC and AMIO-MAC are performing exactly same because the control phase time slots relation with the number of nodes is the same in both algorithms. The total number of control slots which are required in AMI-MAC and AMIO-MAC are $2 \times \sqrt{N}$. CTR-MAC requires $2N$ data slots in the worst-case scenario where every radio is communicating with a central node (star topology). However, AMIO-MAC only requires N data slots in such scenarios. The size

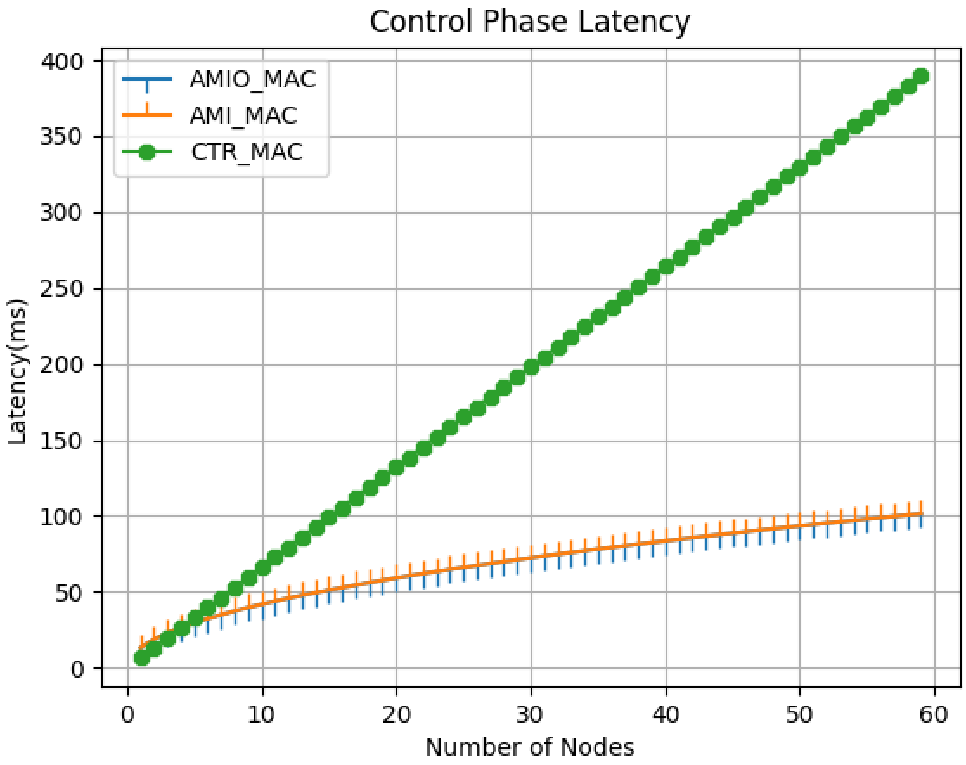


Figure 5.9: Control phase latency for CTR-MAC, AMI-MAC and AMIO-MAC

of the data phase is usually adjustable depending on the network requirements.

Figure 5.10 shows the trend of data phase latency vs number of data links present in the network. As can be seen, the number of transmission nodes increase cause the CTR to perform very badly in a linear manner which proves that CTR-MAC cannot be used when number of data links increase in the network. Whereas, AMI-MAC performs quite well in the comparison of CTR-MAC as it is supporting multiple receptions simultaneously, so number of data slots are not that high, hence, data phase latency is quite minimized. On the other hand, AMIO-MAC is giving multiple transmissions simultaneously on top of AMI-MAC algorithm, so number of data slots requirement is further decreased as shown in the figure 5.10. Therefore, data phase latency is much better in AMIO-MAC case, because less number of data slots can cover more transmissions as compared to AMI-MAC.

The proposed AMIO-MAC scheme and CTR-MAC are compared based on their control phase time delay. The control phase is a critical aspect of Medium Access Control (MAC) protocols in wireless networks that determines how the network devices access

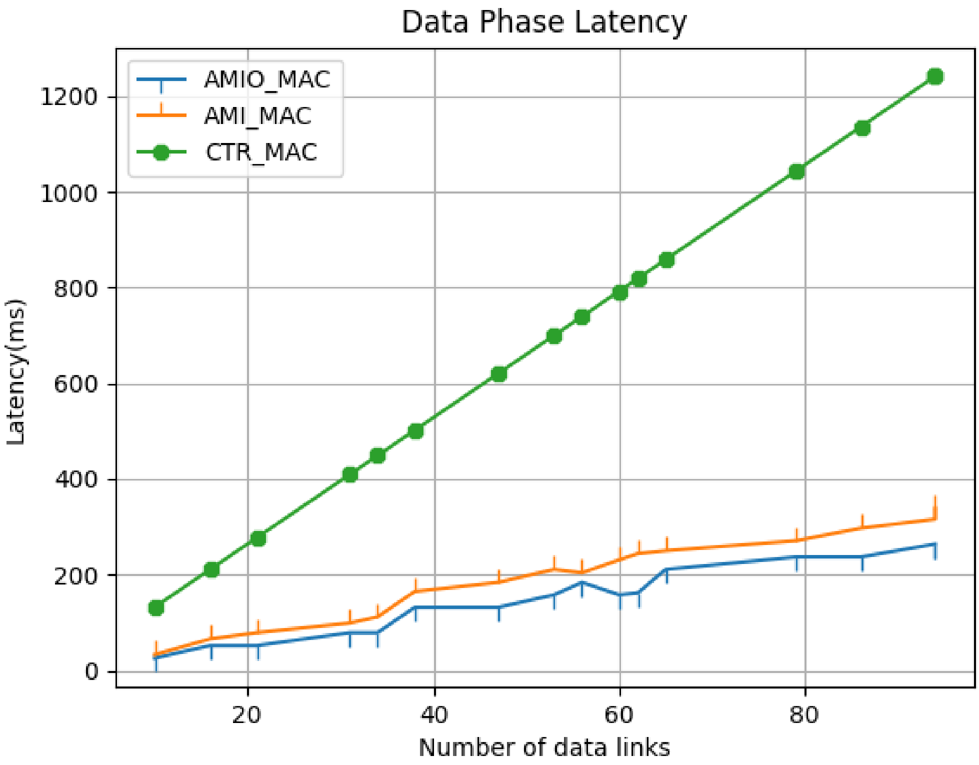


Figure 5.10: Data phase latency for CTR-MAC, AMI-MAC and AMIO-MAC

the shared wireless medium. The time delay for the control phase in AMIO-MAC is estimated to be O($\sqrt{N}$), where N is the total number of radios in the network. In contrast, CTR-MAC's delay is $O(N)$, which means that as the number of radios in the network grows, CTR-MAC's delay will increase linearly, while AMIO-MAC's delay will increase more slowly.

Although AMIO-MAC has better performance than CTR-MAC in terms of time delay, it requires a more complex design for both the receiver and transmitter to handle many simultaneous signals. This complexity arises because AMIO-MAC relies on multi-user detection techniques to separate signals from different transmitters in the same frequency band. Overall, the choice between AMIO-MAC and CTR-MAC depends on the specific requirements of the wireless network. If low delay is critical and the network devices can support the complex design of AMIO-MAC, then it may be the better choice. However, if simplicity is preferred over performance, then CTR-MAC could be a more suitable option.

Chapter 6

Conclusion

This research introduces a novel approach to enhance tactical software-defined radio (SDR) networks by integrating a cross-layer design. The primary objectives include improving throughput, enhancing quality of service (QoS), and enabling flexible range capabilities. The proposed design incorporates a multi-band multi-mode physical layer and an adaptive multi-input-output MAC (AMIO-MAC) design powered by an intelligent cognitive engine.

To address different range requirements while maintaining QoS, we proposed a hybrid narrow-band/wide-band waveform for the physical layer. This waveform allows the system to accommodate various bandwidths and operate in a hybrid topology using the same wide-band RF front end configuration. By leveraging this flexibility, the physical layer can receive and transmit multiple signals with different bandwidths, adapting to the dynamic needs of the network.

Our proposed design focuses on reducing latency in both the control and data phases by effectively utilizing time and frequency resources. The cognition engine plays a vital role in optimizing resource allocation, adapting to changing network conditions such as node mobility and interference. The AMIO-MAC protocol dynamically adjusts transmission parameters in real-time, resulting in better spectral efficiency, improved resource utilization, higher throughput, and enhanced QoS.

Experimental results demonstrate the effectiveness of our proposed design, showcasing its superiority over traditional tactical radio MAC protocols in terms of latency and network throughput. The adaptive nature of the AMIO-MAC protocol allows the network to respond to changing conditions promptly, optimizing performance in challenging tactical environments.

In conclusion, our cross-layer design presents a unique approach to designing SDR networks that can accommodate varying QoS requirements and operate efficiently in dynamic and demanding tactical scenarios. The experimental results validate the feasibility and effectiveness of our proposed design, laying the foundation for further research and development in addressing the challenges posed by emerging communication technologies like 5G and beyond. Future investigations can explore enhancements and extensions to our design to unlock its full potential in next-generation wireless networks.

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