Wireless Ethernet

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This dissertation explores the design of a flexible, distributed Medium Access Control (MAC) protocol without central control, aiming to increase spectrum efficiency compared to shared bandwidth fixed spectrum allocation while allowing for simultaneous full-duplex communication.

The proposed MAC provides a means to establish a dedicated full-duplex point-to-point link between two nodes using cyclostationary signatures for signalling. The proposed MAC may also benefit from advances in developing full-duplex transceivers to reduce the required transceiver count.

A prototype implementation using MATLAB as well as stub implementations in Simulink and Iris are discussed.

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Chapter 1

Introduction

This introduction contains a brief Overview providing a road-map for this dissertation and outlines the Motivation and research question for investigating Wireless Ethernet. This is rehashed by outlining the problem underlying the motivation and presenting a brief overview of the proposed solution in Problem, meet Solution.

1.1 Overview

This dissertation consists of the following parts:

State of the Art Review of the state of the art relating to areas influencing the design of a wireless MAC protocol and the techniques considered for the Design below.

Design Proposes a MAC protocol which is designed to address the research question posed in the Motivation.

Implementation Reviews implementation aspects of the MATLAB reference implementation and the Simulink and Iris implementation stubs.

Evaluation Describes evaluation scenarios for the proposed MAC.

Conclusion Considers the contribution made towards answering the research question, future work which can follow and closing thoughts.

1.2 Motivation

The transition from bus-based to switched Ethernet, with dedicated media and bandwidth, was an enabling factor behind modern high-speed wired networking [Christensen et al., 1994].

Meanwhile wireless networks such as IEEE 802.11 [Hiertz et al., 2010] need to use a multiple access scheme such as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) [Choi et al., 2006] to manage the shared medium, the air, which has similar drawbacks to bus-based Local Area Network (LAN)s.

Time Division Multiple Access (TDMA) similarly offers non-optimal performance if not all time-slots are occupied.

Contrasting the current state of wireless communications and the evolution of wired networks provides the motivation to investigate whether dedicated bandwidth wireless links can be established in a flexible manner.

Recent developments in software defined radio and increased interest in Dynamic Spectrum Access (DSA) also provide both the enabling technologies such as full-duplex radios and cyclostationary signatures for the development of such an approach and the momentum for driving the required regulatory changes to make spectrum management more flexible [Sutton et al., 2008].

Thus, this dissertation aims to answer the following research question:

> *Is it feasible to develop for wireless networks an equivalent of switched LAN as it relates to wired networks?*

1.3 Problem, meet Solution

As described in the Motivation, most widely deployed wireless networks currently face issues which can be traced back to the fact they operate using a shared medium which requires a multiple access scheme to manage. As a result their spectrum resources are not used efficiently.

The proposed MAC aims to address this issue by providing a means to allocate dedicated bandwidth to a link between two nodes in a flexible manner, taking advantage of a technique called “cyclostationary signatures”. A further improvement in spectrum efficiency may be achieved by using full-duplex transceivers as opposed to two separate channels for sending and receiving data.

This solution has been implemented as a prototype in MATLAB and stubs in two other implementation approaches as well as providing a foundation for potential evaluation.

Chapter 2

State of the Art

This chapter serves as an overview of the main body of research this dissertation draws upon.
It considers:

Communication Paradigms such as key characteristics of a communications channel, the development of Orthogonal Frequency Devision Multiplexing (OFDM) as a multiplexing scheme (and a basis for future advances) and the evolution of modern wired LANs

Wireless MAC Protocols particularly for cognitive radio, including a broad classification and the key challenges addressed

Recent Developments such as Full-Duplex Wireless, the advent of Cognitive Radio and the development of Cyclostationary Signatures.

As noted in the Motivation, the development of wired LANs provides the key motivation and more recent developments in wireless networks are the key enablers to answering the research question posed and will be investigated to provide a common ground when discussing the Design.

Figure 2.1 provides a schematic overview of how the topics covered are connected and relate to the remainder of the dissertation.

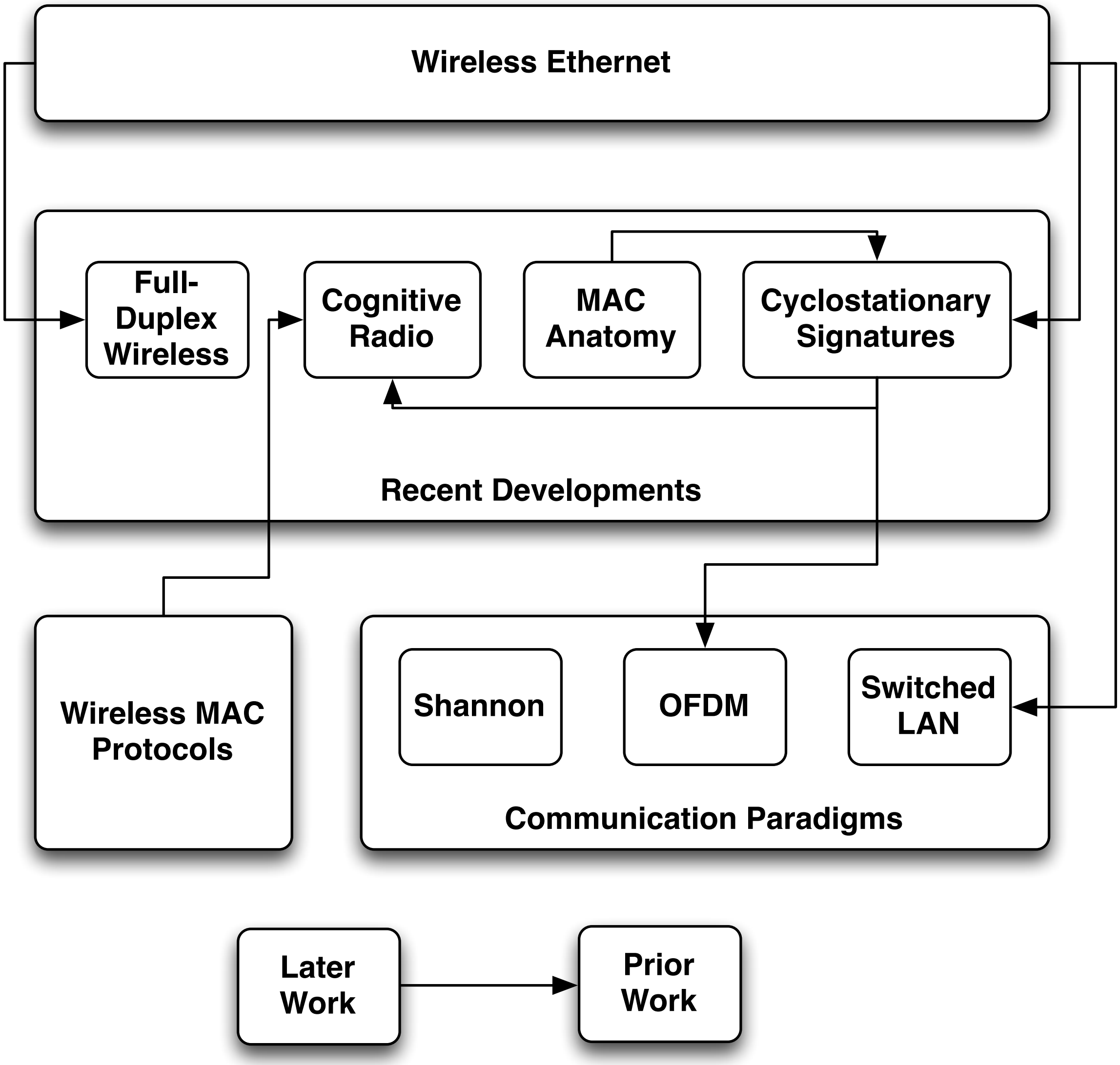


Figure 2.1: Relationships between state of the art topics and Wireless Ethernet

2.1 Communication Paradigms

This section briefly outlines Shannon's contributions to the Foundations of communication systems, OFDM's role as the primary multiplexing scheme for current MACs and the background to current Switched LAN topologies.

2.1.1 Foundations

Claude Shannon [Shannon, 1998] considered the fundamental aspects of communication in the presence of noise and described a general model of communication systems involving the following six components: a Source, Transmitter, Channel, Noise Source, Receiver and Destination; as well as defining key metrics such as the channel capacity based on the number of distinguishable signals.
Shannon also presented a proof of the Sampling Theorem:

Theorem 1. *If a function $f(t)$ contains no frequencies higher than W cps [Hz], it is completely determined by giving its ordinates at a series of points spaced $\frac{1}{2}W$ seconds apart*

In other words if a function contains no frequencies higher than n Hz it can be reconstructed by sampling at $2n$ Hz.
Shannon also presented a geometrical system for modelling communication systems, and an estimate (and proof) of the channel capacity C in the presence of noise, as a function of its bandwidth W [Hz], the transmitter power P and the average noise power N:

$$C = W \log_2 \frac{P + N}{N} \tag{2.1}$$

2.1.2 OFDM

Ballard [Ballard, 1966] outlined the key concepts behind a multiplexing scheme dubbed ORTHOMUX which is now better known as OFDM, as an alternative to the existing frequency or time-division multiplex approaches.
Critically a certain bandwidth is subdivided into a number of narrower orthogonal subcarriers with equidistant central frequencies.
Two subcarriers repeating over the period T are orthogonal if their average product is

0. So for $P_n(t)$ and $P_m(t)$ the following must hold if they are orthogonal:

$$\frac{1}{T}\int_0^T P_n(t)P_m(t)dt = \begin{cases} 0 & n \neq m \\ 1 & n = m \end{cases} \tag{2.2}$$

Modulation consists of multiplying the subcarriers by amplitudes a_n which are the information in each channel. At the receiver, the amplitudes for each subcarrier are extracted by correlating the received signal and the subcarrier waveform.

The key properties of the orthogonal waveforms and their suitability for the transmission of digital data were considered, as well as bandwidth requirements for transmission. An interesting feature is the ability to sample different subchannels at sampling rates related by powers of two, allowing for transmission at different data rates.

Weinstein and Ebert [Weinstein and Ebert, 1971] tweaked this approach by replacing the a number of analogue components with a specialized digital component computing a fast Fourier transform (FFT), having recognized that frequency-division multiplexing can be considered a discrete transformation of the input data.

This development was key to enabling the widespread adoption of OFDM as a multiplexing scheme, as evidenced by its use in many now widespread standards such as IEEE 802.11 and 802.16. [Sutton, 2008]

2.1.3 Switched LAN

The mid-90s saw a move towards full-duplex, switched LANs [Christensen et al., 1994]. The desire for improved fault tolerance had led an initial transition from passive broadcast media, such as the Ether [Metcalfe and Boggs, 1976], to dedicated media, sharing bandwidth in a star topology with a repeater or concentrator. However in these topologies all stations attached to the star would still see all frames transmitted.

More intelligent concentrators allowed for frames to be switched to the relevant port for the destination address indicated. Now a station connected directly to a concentrator will only see frames destined for itself. This has the benefit of eliminating the need to contend with other stations for medium access, radically simplifying the MAC protocol for using this dedicated medium and also allowing reception at any time since there are no collisions to listen for.

Each station thus has a full-duplex dedicated medium with dedicated bandwidth at its disposal. This situation is a significant improvement over bus-based Ethernet which suffers from essentially the same efficiency as slotted Aloha when many small packets are being transmitted constantly [Metcalfe and Boggs, 1976]. Figure 2.2 illustrates a bus-based LAN using Ethernet with two segments or collision domains. The two stations on Ether Segment #1 cannot transmit simultaneously as their transmissions will collide, while the station on Ether Segment #2 can transmit essentially at will.

Christensen et al. also note the positive impact these topology changes can have on client-server architectures and outline the performance characteristics of shared and dedicated bandwidth LANs.

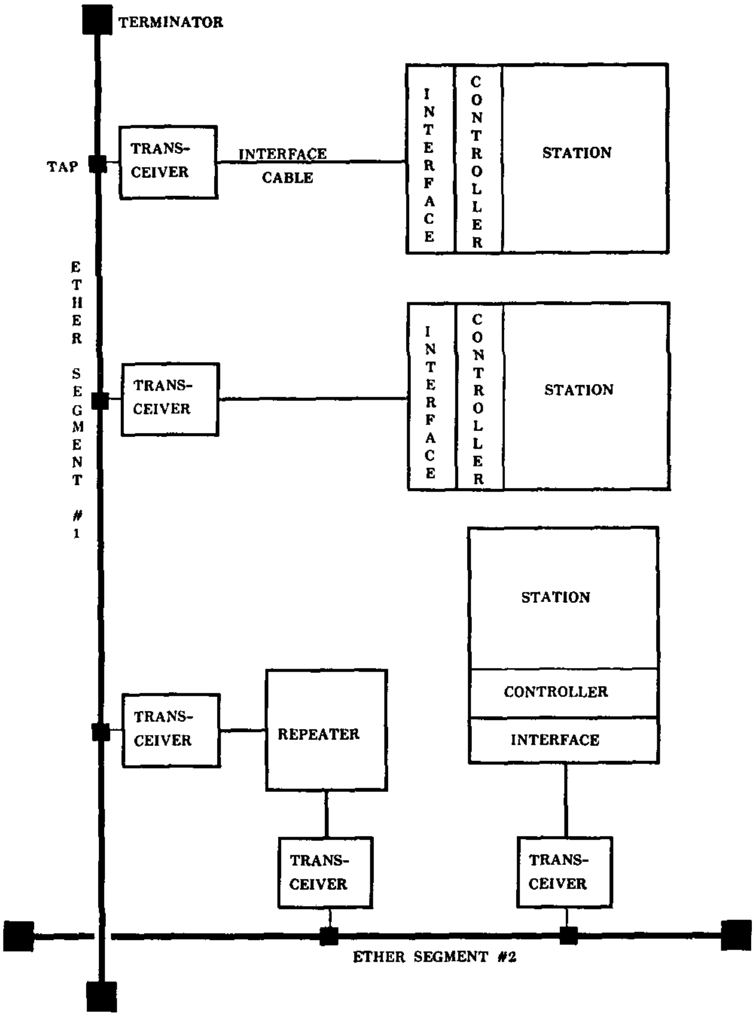


Figure 2.2: A two-segment Ethernet (reproduced from [Metcalfe and Boggs, 1976])

2.2 Wireless MAC Protocols

MAC is described by Tanenbaum [Tanenbaum and Wetherall, 2010] as a sublayer of the data link layer intended to decide the next user of a shared random access channel.

De Domenico et al. surveyed MAC approaches for cognitive radio [De Domenico et al., 2012], identifying two main categories: Dynamic Spectrum Allocation (DSA) and Direct Access Based (DAB).
The latter aims to optimize between a pair of sender and receiver nodes, while the former generally aims to optimize globally using an optimization algorithm.

DAB protocols can generally classified as either contention based or coordination based, where the former relies on a sender/receiver handshake and channel negotiation and the latter relies on nodes sharing their sensing outcome with neighbours.

DSA protocols are differentiated primarily by the type of underlying algorithm such as stochastic, genetic, game or graph theoretic or even swarm intelligence.

Beyond this general categorization, the need for a method to exchange control information is also identified. Three options are presented for this: either a common control channel amongst all nodes, a phase-based "split-phase" approach with a control phase followed by a data phase or finally a frequency hopping sequence aimed at reducing the dependency on a single control channel.

The following areas are discussed in-depth with reference to the solutions proposed by the MAC protocols being surveyed:

Spectrum Sensing Cognitive radios must be aware of spectrum opportunities and spectrum usage, both of which are provided by spectrum sensing. Sensing is necessary when two nodes set up a link for communication. In-band sensing during transmission is performed to avoid collisions with primary users while out-of-band sensing is used to seek resources opportunisticly. Typically nodes with only one transceiver must make a trade-off between sensing and efficiency since the channel cannot be sensed while transmitting and resources are required to share sensing results. The latter depends on whether sensing is performed centrally or distributed.

Dynamic Spectrum Allocation Having sensed the spectrum, channels must be allocated to users wishing to use these. Since DAB protocols only aim to optimize between sender and receiver, spectrum allocation considers only local requirements.

DSA protocols on the other hand will attempt to maximise a utility function such as price to the network as a whole vs. benefit or reward to an individual node.

Dynamic Spectrum Sharing Three methods for coexistance with other users are outlined: overlay, underlay and interweave spectrum access. The latter being the most widely used as generally there is a lack of knowledge regarding primary users. In this case the channels being used are sensed and a handover to another channel initiated when a primary user is detected. Coexistance with other cognitive users must also be considered, however. Underlay transmissions meanwhile use licensed bands while limiting their transmitted power to keep interference below a certain threshold. Finally overlay transmission supposes a-priori knowledge of primary user messages which can be filtered by cognitive users.

Dynamic Spectrum Mobility As channel availability varies spatially and temporally, cognitive radios coexisting with primary and secondary users must perform handovers to continue transmission seamlessly when leaving a channel in favour of a licensed user.

2.3 Recent Developments

This section reviews the development of feasible Full-Duplex Wireless, the roots of Cognitive Radio, the introduction of Cyclostationary Signatures and concludes by considering MAC Anatomy.

Full-Duplex Wireless would enable a simplification of the proposed MAC by removing the need for managing two separate channels, as well as lowering hardware costs for a physical implementation. Meanwhile MAC Anatomy provides a road-map for the development of a MAC, based on the use of Cyclostationary Signatures which are just one of many developments rooted in the broader area of Cognitive Radio.

2.3.1 Full-Duplex Wireless

Gummalla and Limb [Gummalla and Limb, 2000] proposed a full-duplex feedback channel to be used in conjunction with a modified Time Division Duplex (TDD) transceiver architecture due to the lack of a full-duplex radio at the time.

This allows for a narrow-band in-band feedback channel which can be used by receiving nodes to provide feedback to the sender, but also enables a node in range of another receiving node to receive data if the senders are out of range of each other. The radio design proposed and considerations for spectral placement of the feedback channels are designed to minimize interference in the transceiver. The proposed MAC protocol, named Wireless Collision Detection (WCD) eliminates both the hidden and exposed node problem and yields promising throughput results in simulations.

Multi-channel full-duplex wireless communications were considered by Choi et al. [Choi et al., 2006], using either 2 or 3 transceivers. The key concept introduced in the MAC protocol presented is the home channel chosen by a node. Nodes tune their receiver to this channel permanently until opting to switch to another, as well as ensuring that no nodes within two hops use the same home channel. Transmitting nodes tune their transmitter to the home channel of the receiver and transmit using the IEEE 802.11 Distributed Coordination Function.
The benefits of chosing these disjunct channels are given as reduced contention and improved collision avoidance and handling, as well as transmitting while receiving. However, overhead is required for communicating the home channel to neighbouring nodes: either via a dedicated control channel and third transceiver or through broadcasts on multiple channels. Protocol details are outlined, and simulation results presented giving improved throughput and delay compared to IEEE 802.11.

Choi et al. [Choi et al., 2010] and subsequently Jain et al. [Jain et al., 2011] presented a novel technique for achieving full-duplex wireless communications using a single channel.

The initial publication [Choi et al., 2010] details a technique called "Antenna Cancellation", which in combination with noise cancellation and digital interference cancellation provides about 60 dB of interference reduction on a 5 MHz channel. Antenna cancellation uses two transmit antennas and one receive antenna, with the transmit antennas placed at d and $d + \frac{\lambda}{2}$ from the receive antenna, creating destructive interference leading to a null at the receive antenna, leaving a weaker signal to be cancelled. The technique suffers from reduced reduction over a wider channel, however, making it unsuitable for IEEE 802.11 which has 20MHz or wider channels.

Despite these weaknesses of the initial approach, the potential benefits of addressing the following issues using full-duplex wireless are significant:

Reduced hidden terminal problem A typical scenario where the hidden terminal problem might occur is with two nodes attempting to communicate with an access point but the nodes are out of receive range of each other. In this case both nodes may send data at the same time causing a collision. The window in which these collisions might occur can be significantly reduced if the access point begins sending once it has received data from a node. A collision can now only occur in the time after a node commences transmission but prior to the access point responding.

Reduced congestion and improved fairness In a similar scenario with an access point and multiple nodes routing data through the access point typically the access point also contends for medium access. In particular this means while in the uplink each client has effectively $\frac{1}{n}$ of the channel capacity at its disposal, in the downlink from the access point, the load for all clients must be contained within the acess point's share of the channel, yielding a downlink capacity of $\frac{1}{n}\frac{1}{n} = \frac{1}{n^2}$ for each client. In a full-duplex scenario the access point can transmit while receiving data from a client, thus equalizing the capacity for up- and downlink.

Multi-hop wormhole routing In a multi-hop scenario typical store-and-forward routing can cause significant overheads which may be addressed using wormhole routing where the packet is transmitted to the next hop as it is still being received.

A year later [Jain et al., 2011] refinements to the original technique were introduced to address the lack of attractiveness of a three-antenna full-duplex solution compared to Multiple Input Multiple Output (MIMO), the constrained bandwidth and manual tuning required in the initial design. The refined design requires only two antennas and takes advantage of a technique called "balun cancellation" using a balanced/unbalanced (balun) circuit which inverts the transmitted signal, allowing better cancellation over wider bandwiths. An algorithm is also presented to automatically tune the phase and amplitude used for cancellation. A full-duplex MAC was implemented and evaluated, including a comparison to MIMO.

Most recently [Bharadia et al., 2013] further advances in full-duplex transceiver design have increased the amount of interference cancellation possible, using a single antenna, to 110 dB and been demonstrated as suitable for bandwidths as high as 80 MHz and modulation orders up to 256-Quadrature Amplitude Modulation (QAM), making it suitable for use with Long Term Evolution (LTE) and IEEE 802.11ac Wireless LAN (WLAN) [Kneckt et al., 2011].

2.3.2 Cognitive Radio

The term Cognitive Radio was introduced in Mitola's seminal paper [Mitola and Maguire, 1999]. This outlines the concept of a Radio Knowledge Representation Language, reasoning about the radio environment, radio etiquette as well as the cognition cycle.
The cognition cycle outlined in Figure 2.3 considers how a cognitive radio interacts with the outside world by observing external stimuli, processing these to inform internal learning and decision-making processes and finally proceeds to act, after which this cycle repeats.

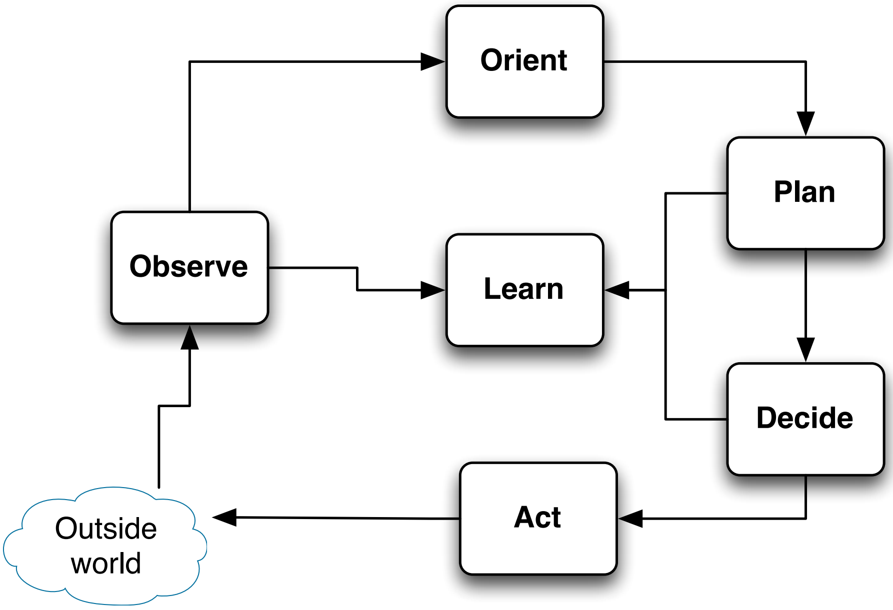


Figure 2.3: Cognition Cycle Overview (reproduced from [Mitola and Maguire, 1999])

More recently Mahmoud et al. [Mahmoud et al., 2009] discussed the use of OFDM for Cognitive Radio, the key method for adapting to the radio environment being to selectively disable subcarriers used by primary users or other secondary users.
Cognitive radio and related technologies have enabled progess in dynamic spectrum access beyond traditional regulatory methods [Tan et al., 2007; Sutton et al., 2008] in order to allow greater efficiency and improved access to spectrum.

2.3.3 Cyclostationary Signatures

In his Ph.D. thesis [Sutton, 2008], Paul Sutton describes a technique called "cyclostationary signature" based on embedded cyclostationary features which allows receivers to identify a signal as well as determine the carrier frequency.

This removes the need for a dedicated control channel in a system where new nodes can learn the parameters of existing nodes in this manner.
The signatures described are embedded by a process called "subcarrier mapping" which duplicates OFDM subcarriers to generate statistical independence between these mapped subcarriers resulting in a spectral correlation. This process is outlined in greater detail in subsection 3.2.1. In a related paper [Sutton et al., 2008] further details of cyclostationary signatures are discussed, including performance considerations when implementing these. In particular the detection of a cyclostationary signature in a IEEE 802.16 WiMax channel requires on the order of 60 OFDM symbols.

More recently [Cao et al., 2012] the use of cyclostationary signatures in order to embed additional information beyond functioning as a marker for rendezvous was investigated and found to allow about 70 bits of data to be added with an overhead of 10% of the available OFDM subcarriers.

Current work [Tallon et al., 2013] also considers a similar approach which allows physical layer characteristics to be embedded using a cyclostationary signature to configure basic physical layer parameters such as bandwidth, number of subcarriers and modulation order.

2.3.4 MAC Anatomy

Colman O'Sullivan's Ph.D. thesis [O'Sullivan, 2012] outlines the composition of a cognitive MAC protocol, or rather its "anatomy" by considering the entire process of developing a Cognitive Radio MAC and presents both a general decomposition of what makes a MAC protocol as well as a reconstruction by means of a specific implementation. The thesis uses the Iris architecture for testing cognitive radio designs [Sutton et al., 2010] which has proven itself in a number of experimental situations [Doyle et al., 2010] in order to develop CycloMAC which makes use of the anatomy defined and also employs cyclostationary signatures to remove the reliance on design-time decisions regarding operating frequency and similar parameters other MACs exhibit.

The anatomy constitutes a distinct step forward from previous work outlined above and referred to in its motivation, which does not reflect on the entire process of designing a cognitive radio MAC and instead tends to focus on a certain aspect of MAC functionality while making sweeping assumptions for example by assuming the availablity of a static control channel.

A high-level view of a MAC anatomy is given by a schema which describes the following key points:

- interaction with higher layers
- four key roles for basic medium access: “define”, “deliver”, “control & coordinate”, “edge case” (each role is further divided into resource allocation and subsequent exploitation)
- awareness available to the MAC either externally or within the system
- a set of physical layer (PHY) dependencies which describe contracts, knobs (settings) and meters (readings) that the transceiver must provide for the MAC to fulfil its functionality

An example schema is shown in Figure 2.4. This should aid in providing an intuition of what the four medium access roles outlined above refer to and how relationships with its abutting layers are expressed.

As the schema describes a MAC using cyclostationary signatures for bootstrap and rendezvous, the resource allocation role is largely occupied by a block representing this functionality. Note that it interfaces with external awareness in the form of a geolocation database for looking up spectrum information and with the knobs and meters the PHY should provide as cyclostationary analysis requires access to the radio.

Apart from these and some further contracts the PHY must fulfil, resource exploitation is split amongst scheduling and synchronization which *define* how the channel can be used, Automatic Repeat Request (ARQ) which *delivers* reliable channel use and of course the in-band control channel is used to *control and coordinate* exploitation.

The higher layer send and receive functions are tied to the delivery mechanism for exploitation since these are only interested in reliable data transmission and reception.

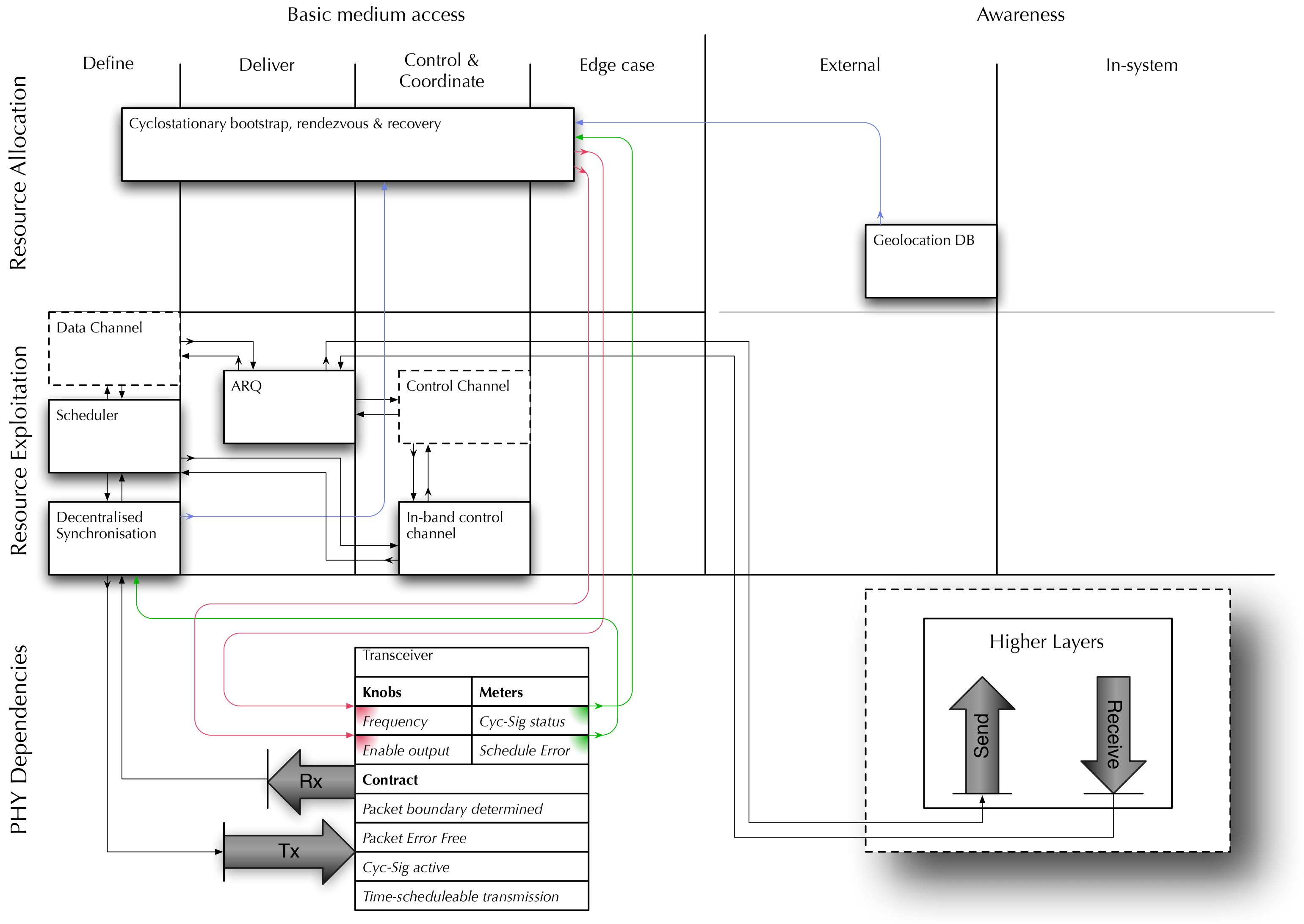


Figure 2.4: A completed anatomy schema (reproduced from [O'Sullivan, 2012])

2.4 Summary

This chapter has presented an overview of key pieces of literature relating to the development of a MAC protocol for ad-hoc full-duplex wireless communications. Ranging from fundamental metrics affecting data communications, existing MAC protocols and current areas of research including cognitive radio and breakthroughs in full-duplex wireless communications.

Cognitive radio and dynamic spectrum access have provided the catalyst for a wide array of recent developments in wireless communications, moving away from traditional centralized networks with static spectrum allocations.

These take advantage of PHY layer advances such as Full-Duplex Wireless and the development of large numbers of innovative Wireless MAC Protocols combined with more flexible signalling techniques like Cyclostationary Signatures.
Initial applications of Cognitive Radio are founded on OFDM which developed from infeasible to implement to de-facto standard for wireless modulation.

However, one of the key evolutions in wired networks to dedicated bandwidth with Switched LANs has yet to be mirrored in wireless systems, not least due to the inherent nature of the different media. The table below provides a high-level review of the key developments in chronological order.

Timeframe	Developments
1949	Shannon's foundations of communication systems
1970s	Development of OFDM
1990s	Transition to Switched LAN
1999	Introduction of the term Cognitive Radio
2008	Cyclostationary Signatures
2010	Demonstration of feasible Full-Duplex Wireless
2012	MAC Anatomy
2013	Extended information using Cyclostationary Signatures

Chapter 3

Design

This chapter proposes a MAC protocol using cyclostationary signatures intended to allow flexible, full-duplex, dedicated wireless communication between multiple nodes.

It details the Requirements to be fulfilled by MAC, the Components needed to address the requirements, the Operation of the MAC and finally presents some sample scenarios to illustrate the proposed design.

3.1 Requirements

The following requirements are synthesized from the original dissertation topic proposed by Stefan Weber:

> The focus of this project is the development of a protocol that allows two mobile devices to dynamically allocate channels for full-duplex communication. The allocation would be temporally limited and would have to be accomplished without a central entity being present.

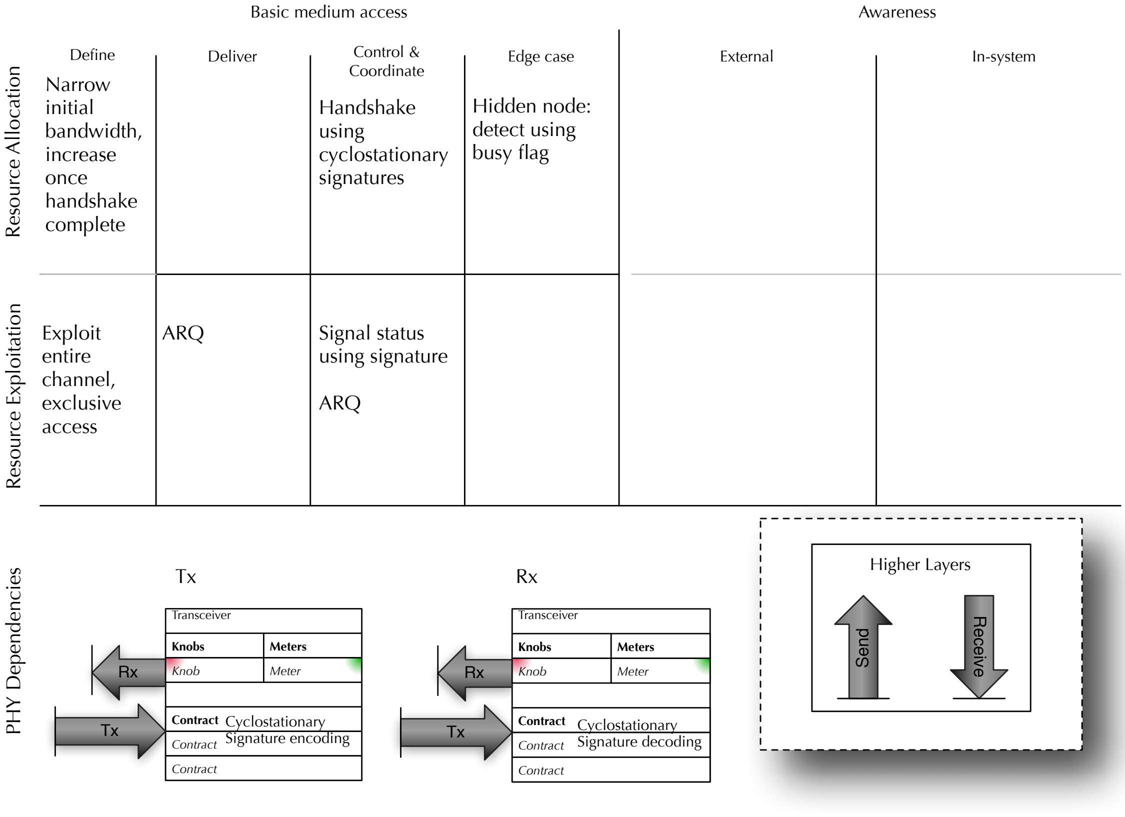
Thus, the protocol should:

- provide a dedicated point-to-point link between two nodes
- enable full-duplex communication
- not require a central entity for coordination
- be flexible in terms of operation frequency

For the purpose of this design only co-existence with nodes operating the same system is considered (*disregarding other primary users or systems*).

This link is intended to be analogous to a connection between two Ethernet interfaces in switched Ethernet [Christensen et al., 1994] which ensures each link has an isolated, independent collision domain and thus no need for multiple access schemes due to exclusive media access while requiring little setup overhead as well as allowing flexibility with switches featuring multiple interconnected interfaces.

Figure 3.1 provides a sketch of an anatomy schema [O'Sullivan, 2012] for the protocol reflecting the requirements stated above.



	Basic medium access				Awareness	
	Define	Deliver	Control & Coordinate	Edge case	External	In-system
Resource Allocation	Narrow initial bandwidth, increase once handshake complete		Handshake using cyclostationary signatures	Hidden node: detect using busy flag		
Resource Exploitation	Exploit entire channel, exclusive access	ARQ	Signal status using signature ARQ			

Figure 3.1: Anatomy schema sketch outlining the proposed MAC
See detail below.

Notably, the "control & coordinate" duties are managed using cyclostationary signatures, both for link establishment and control. The hidden node issue is also addressed by this signalling approach.

In terms of defining the resource to be allocated the MAC seeks to find a pre-defined narrow bandwidth opportunity which may be increased once a link has been established and both associated nodes can cooperate to find spectrum opportunities available to both. Meanwhile, due to the dedicated nature of the link, resource exploitation can proceed with the assumption of exclusive access to the channel provided.

When interacting with the PHY the sketch presumes two half-duplex transceivers for Transmit (TX) and Receive (RX) respectively although a full-duplex transceiver would also be suitable in this role.

These considerations are outlined in greater detail below.

3.2 Components

Two major components are necessary to fulfil the requirements outlined above, a signalling mechanism and a minimum hardware configuration.

3.2.1 Signalling

The proposed protocol requires a means to exchange information in order to rendezvous, handshake, establish and maintain a link with the characteristics stated above.
Cyclostationary signatures provide a tool to enable rendezvous between two nodes on unknown frequencies without the need for out-of-band signalling such as a common control channel or split-phase signalling once a channel has been established [Sutton et al., 2008]. Additionally information for use during link establishment [Tallon et al., 2013] and other parts of the life cycle of a link can be embedded in such a signature.[Cao et al., 2012]

In this case embedding a cyclostationary signature serves two purposes: frequency rendezvous as well as providing an in-band control channel for operation.

Figure 3.2 illustrates how the two types of features are embedded. A single feature is embedded to appear at the Direct Current (DC) subcarrier, or center frequency of the channel, while a number of features are embedded at a different cyclic frequency and may be interpreted as a bit sequence depending on whether a certain feature is present or not.

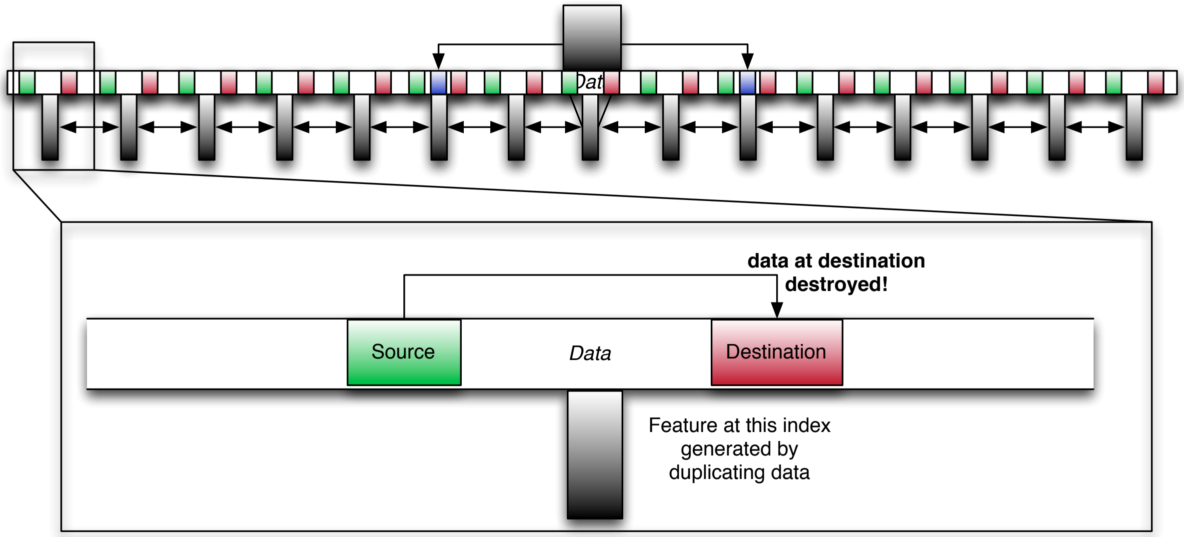
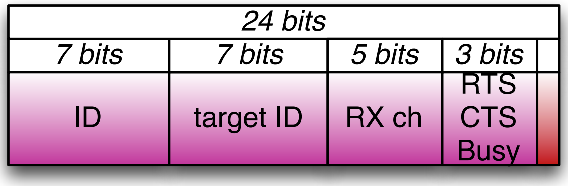


Figure 3.2: Features embedded (top) using subcarrier mapping (bottom)

A feature is embedded by a process called "subcarrier mapping" which copies a set of QAM modulated symbols to a certain offset, destroying the symbols at the destination. The distance between these duplicate sets of subcarriers determines the cyclic frequency at which a feature can be detected. This process is performed on data to be transmitted after it has been modulated as QAM symbols but before these are converted to the actual OFDM symbols which are transmitted by the radio.

A receiver looking for a signature at a certain cyclic frequency crucially does not have to demodulate the signal, but rather only compute a correlation function averaged over time.
Once a signature has been detected it can be mapped to a bit sequence based on which features are present or not.
The bit sequence can subsequently be mapped to the signalling frame structure shown in Figure 3.3 which provides the necessary information for the operation of the MAC protocol without requiring an in-depth knowledge of the physical layer characteristics. The fields contained in this signalling frame are discussed in detail below.

Evidently if a large number of features are embedded a significant overhead is incurred (red areas in Figure 3.2) as the duplicate symbols reduce the number of symbols which could be transmitted normally without the embedded feature. Thus when preparing data to be sent, depending on the number of bits n_{features} being embedded and the size of the sets of subcarriers being mapped $n_{\text{sigCarriers}}$, the amount of data symbols accepted l_{data} when embedding the features must be varied. If all possible features



24 bits				
7 bits	7 bits	5 bits	3 bits	
ID	target ID	RX ch	RTS CTS Busy	

Figure 3.3: Signalling Frame contents

are embedded, the least amount of data can be accepted. On the other hand if no features are embedded, the maximum amount of data l_{max} can be accepted as normal.

$$l_{\text{data}} = l_{\text{max}} - n_{\text{features}} \cdot n_{\text{sigCarriers}}$$

However, there is one benefit to the duplicate symbols which can be reaped assuming the signature is decoded successfully, that is to use these as a basic form of redundancy to ensure data was received correctly. The mapped subcarriers can be compared and whether they match or not may be signalled to higher layers or used to trigger a retransmission to avoid passing erroneous data up to higher layers.

3.2.2 Hardware

Each node requires $2n$ transceivers (or n full-duplex radios where feasible). Each transceiver pair is analogous to an Ethernet interface where a simple device may have one interface only, but an interconnection device such as a switch would have several more.
In each pair one transceiver is initially tuned to an idle channel for receiving data and the other is tuned to a second idle channel for transmission. Figure 3.4 attempts to illustrate the analogy between wired Ethernet and a similar topology supported by nodes operating the proposed protocol.

3.2.3 Signal Characteristics

The signal transmitted must allow for the embedding of cyclostationary features, thus it must use OFDM, further it shall use 64-QAM modulation and have a bandwidth of 1 MHz with 256 subcarriers and 55 guard carriers. This conservative choice was made to ensure a link can be established quickly. Once both nodes can communicate they can discover spectrum opportunities available to both nodes much more easily and thus increase bandwidth as necessary.

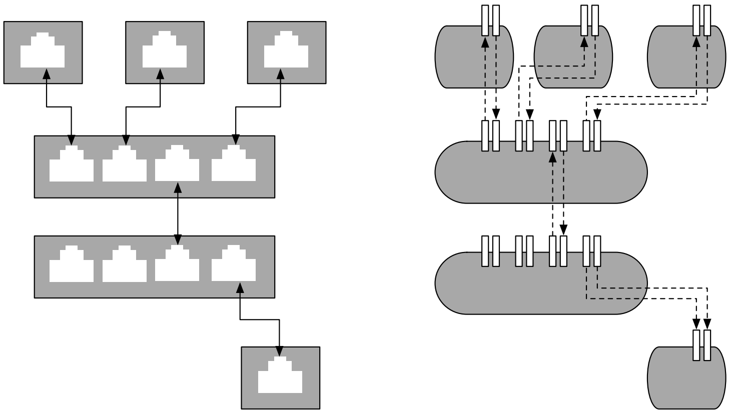


Figure 3.4: Comparison between wired and wireless switching

3.3 Operation

This section details the operation of the proposed MAC. An overview of the states and transitions described is provided in Figure 3.5. The signalling frame layout it shown in Figure 3.3.

3.3.1 Bootstrap

When initializing a node must choose home channels for both its TX and RX transceivers. These channels are used by the node when it is *Idle*. Once these have been chosen, the TX transceiver must transmit a signalling frame containing the node's 7 bit ID and 5 bit RX channel offset relative to the center frequency of the TX channel in 1 MHz steps. If the node uses a full-duplex transceiver the offset may be 0.

Both this step as well as the Handshake described below are two steps which align well with the principle of Cognitive Radio as they require sensing abilities to find spectrum opportunities and nodes to connect to.

3.3.2 Handshake

When a node has data ready to transmit it must establish a link with the intended destination.

First the *Busy* bit is set in the signalling frame to indicate the node is not available for connections from other nodes.

Next the RX transceiver scans for a signalling frame with the destination node ID.

There are multiple scenarios which can now be encountered:

Idle destination If the destination node is *Idle* the sender tunes its TX transceiver to the

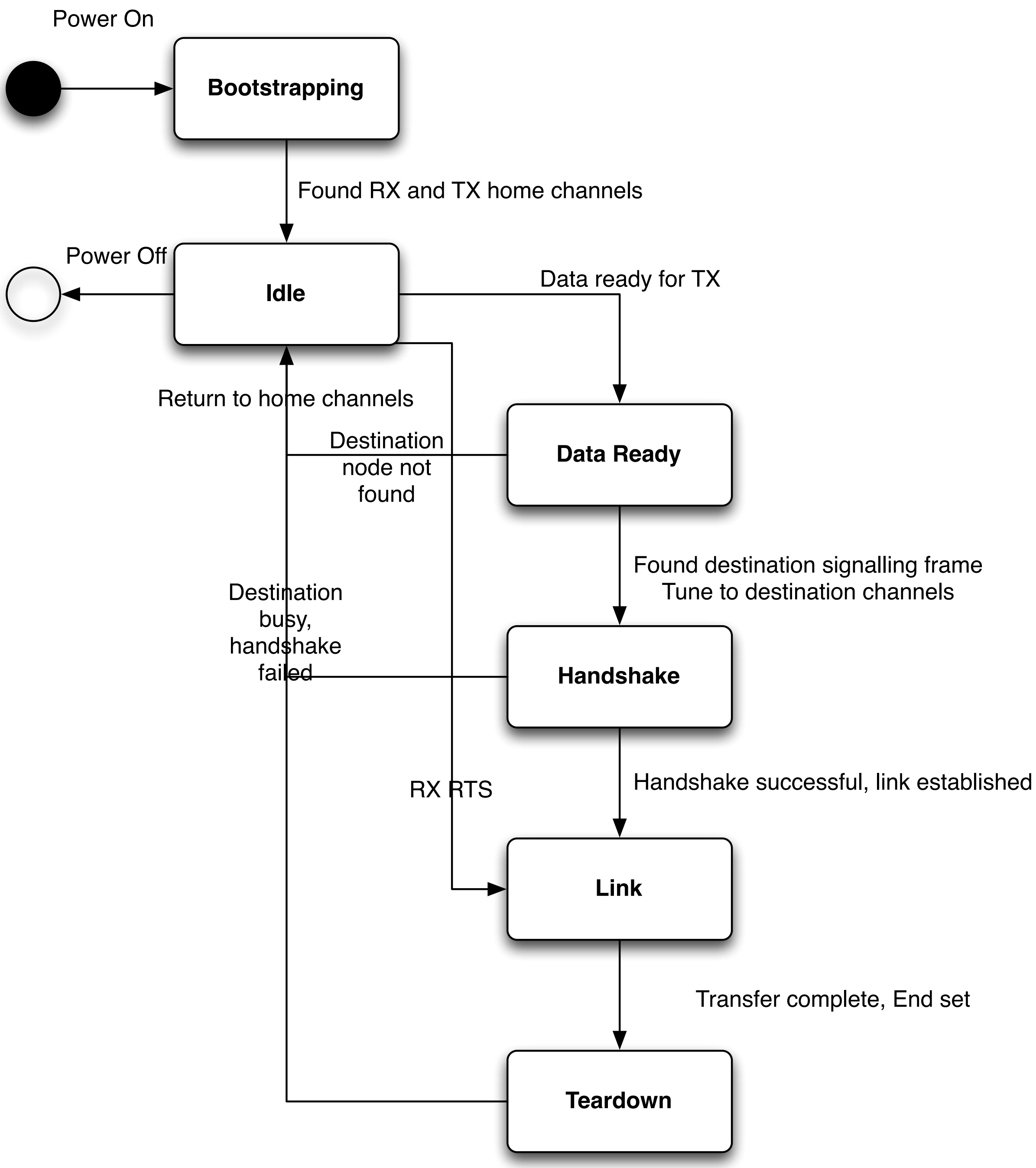


Figure 3.5: Overview of MAC States and Transitions

destination's RX channel, sets the destination node ID as the target node ID and Ready to Send (RTS) in its own signalling frame. Note that the RX transceiver is already tuned to the destination's TX channel as a result of scanning for the destination's signalling frame. Once the destination has received the signalling frame on its RX channel and is ready to receive it sets the Clear to Send (CTS) flag and target ID to the sender ID in its own signalling frame. Now the sender can set the *Busy* flag and begin transmission. The receiver also sets the *Busy* flag and may transmit now.

Busy destination If the destination node is not idle, i.e. it has the *Busy* or *CTS* flags set the sender must abort its transmission attempt and return to its home channels. This behaviour is intended to address the case of a hidden node already transmitting to the destination.

No destination If no node with the desired ID is found the transmission attempt is aborted.

3.3.3 Data Transfer

Once a link has been established both nodes may send data as it becomes available.
This basic link using the Signal Characteristics defined above could now also be enhanced by cooperation of both nodes to discover common spectrum opportunities or adjusting other parameters. Any changes which would preclude another node establishing a link with either node must be visible in the signalling frame using the active *Busy* flag.

3.3.4 Teardown

Once a node wishes to cease transmission it sets the *End* flag in its signalling frame. It may now no longer transmit.
The other node in the link should cease transmitting as soon as possible and set its own *End* flag.
Both nodes should now return to their home channels.

3.3.5 Idle

An idle node advertises its node ID and RX channel while tuned to home channels.

3.4 Sample Scenarios

Figure 3.6 attempts to visualise some sample scenarios the MAC is designed to handle.

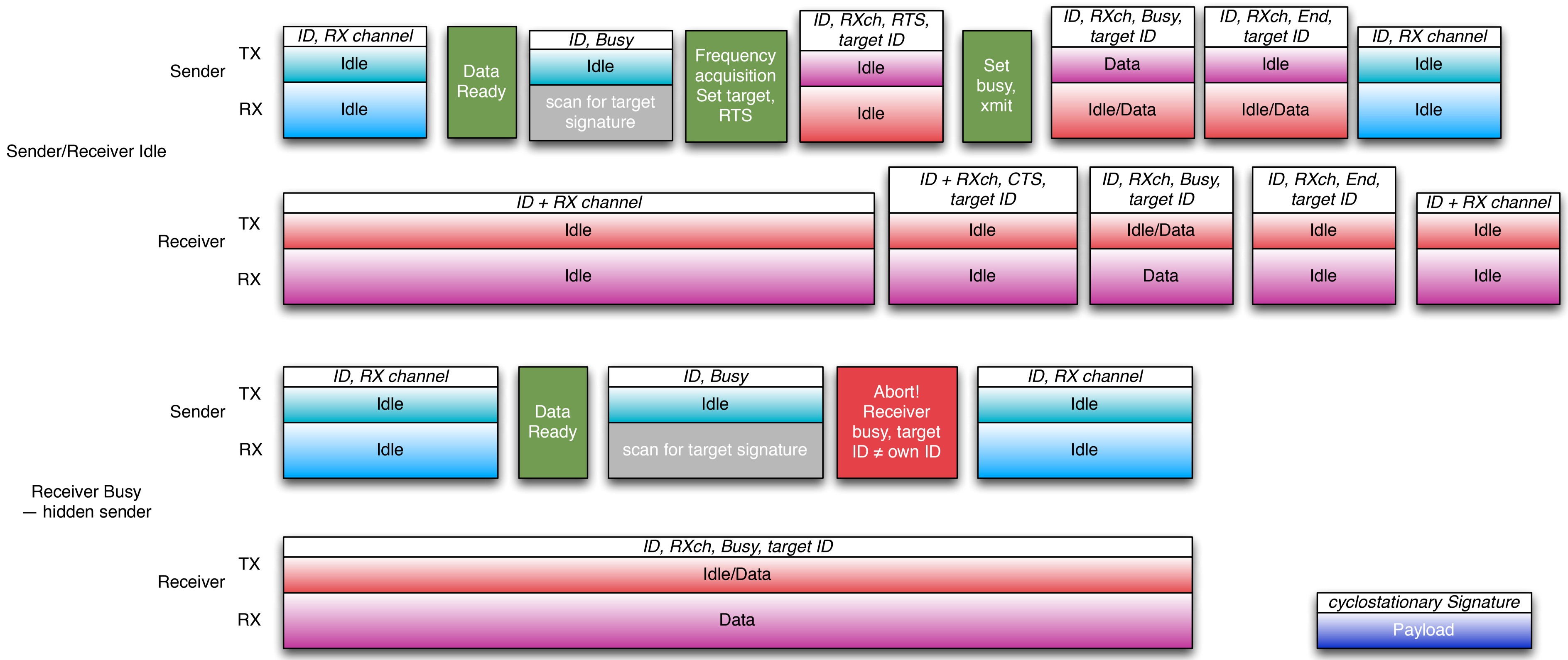


Figure 3.6: Visualisation of example MAC scenarios

The first scenario (Sender/Receiver Idle) involves the ideal case of both the sender and receiver being idle and thus the link being esablished, maintained and ended without incident.
The second scenario (Receiver Busy) considers a case where the receiver is currently *Busy*, for example due to a hidden sending node.
The visualisation also aims to clarify the spectrum used by the MAC depending on its role in a link and current state, in particular when a link is established the sender of the RTS tunes to the receiver's channels!

3.5 Summary

This chapter outlined the design of the proposed MAC which can be considered in De Domenico et al.'s classification as a DAB MAC since it focuses on a point-to-point link between two nodes, as well as having an in-band (common) control channel.

The proposal consists of a description of the signalling mechanism using cyclostationary signatures as well as the state machine governing the MAC's operation.

Chapter 4

Implementation

This chapter discusses the implementations of the design outlined above, including the Encoding used to map a bit sequence to a cyclostationary signature and the operational details of the proposed MAC.
Appendix A provides an overview of the MATLAB reference implementation on a file by file basis as well as a listing of the constants used throughout all implementations.

4.1 Encoding

The encoding was initially prototyped in MATLAB [The MathWorks Inc., 2013a] based on a simulation of cyclostationary signatures with the aim of enabling a later migration into Simulink [The MathWorks Inc., 2013b] and Iris [Sutton et al., 2010] to allow testing using Ettus Research USRP software defined radios [Ettus Research, 2012]. All three implementations are similar in that they modify the QAM symbols used to generate OFDM symbols when transmitting and intercept the raw received signal for analysis.

As outlined in Signalling a bit sequence which can be interpreted as signalling information should be embedded in transmitted data using a corresponding set of cyclostationary features. Sutton et al. [Sutton et al., 2008] outline the method for detecting cyclostationary signatures using a time-smoothed cyclic cross periodogram as an estimator for the cyclic cross spectrum.
The time-smoothed cyclic cross periodogram is defined over L windows as

$$\hat{S}_x^\alpha[k] = \frac{1}{L}\sum_{l=0}^{L-1} X_l[k]X_l^*[k-\alpha]W[k]$$

where $X_l[k]$ is the Fourier transform of $x[n]$ and $W[k]$ is a smoothing window, with ach window having the length of one OFDM symbol. Using this a simple detector for a single cyclic frequency can be implemented by

$$y_\alpha = \max_m \sum_{k=0}^{K-1} \hat{S}_x^\alpha[k] W[m-k]$$

The result of this process should be an array of points with the same length as the size of the FFT used, as shown in Figure 4.1. In this case the FFT had a length of 272 corresponding to an OFDM symbol with 256 subcarriers and a cyclic prefix length of 16. For each subcarrier this approximates the spectral correlation across all symbols in the window used by the detector and is thus naturally high for the guard carriers and embedded features while being lower where no features were embedded.

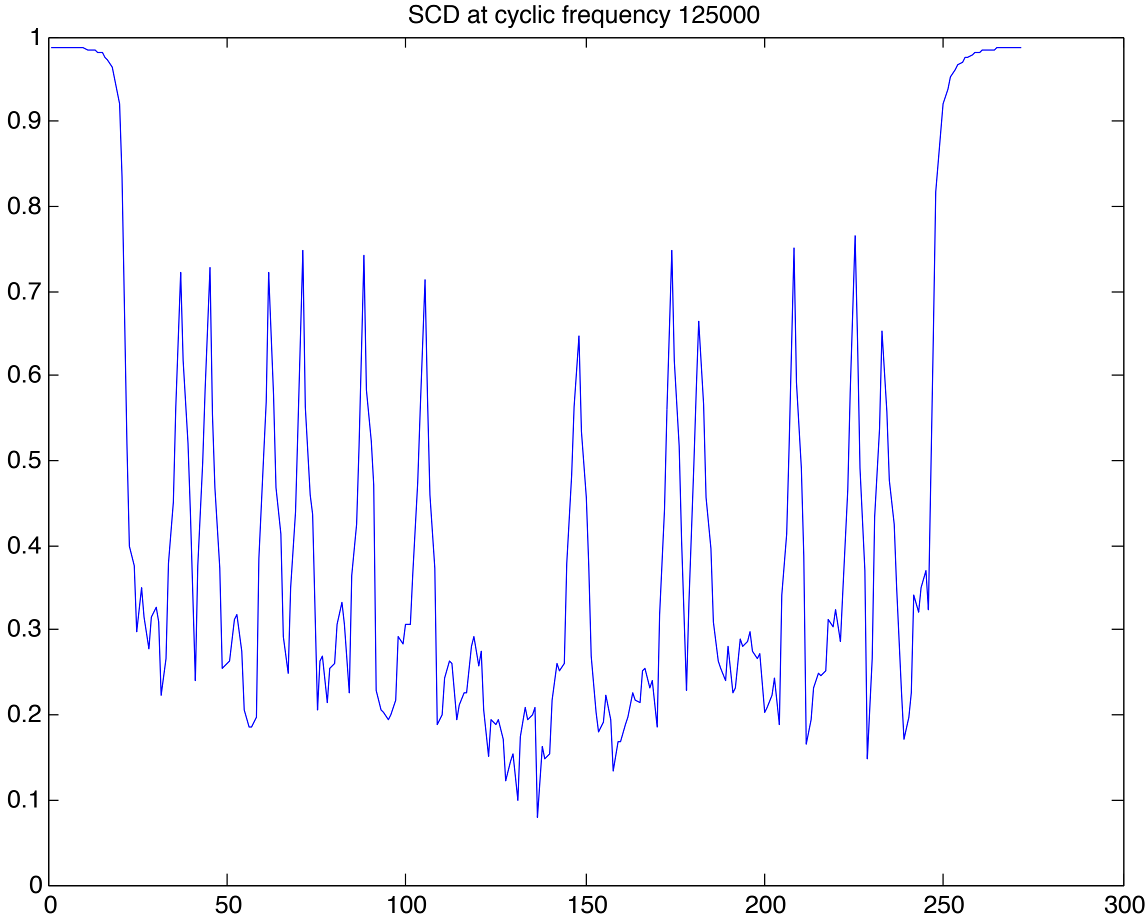


Figure 4.1: Detected Cyclostationary Signatures

These points can now be mapped to a bit sequence and subsequently a signalling frame. The indices of feature peaks are identified based on a threshold and smoothed by ensuring they are correctly spaced. The peaks are then compared with reference indices of the possible feature locations to determine whether a feature is present or not and accordingly if the corresponding bit is 0 or 1.

In this case the bit sequence encoded using the signature is `11011010 10000100 11001011`. This mapping was implemented in `decodeFeatureBits.m` which is outlined below, starting with Listing 4.1 which defines the function interface and critically the detection threshold for a feature peak.

```
function bits = decodeFeatureBits( cycloRow, fftSize, numFeatures, alpha )
%decodeFeatureBits Decodes the bits specified by the features in cycloRow

% First: Threshold cycloRow and note indices of peak values
lastSignatureIndex = 30; % In case first bit is 0
thresholdIndexes = [ ];
threshold = .4;
```

Listing 4.1: `decodeFeatureBits`: initialisation

The loop in Listing 4.2 checks each point in the array returned by the detector whether it is above the threshold and sufficiently far apart from the previous signature based on the cyclostationary frequency which is directly related to alpha. Each qualifying peak has its index added to thresholdIndexes.

```
% Go through detected row
for index=1:fftSize
    % If we are above the detection threshold
    if cycloRow(index) > threshold
        % And far enough from the last peak
        if ((index-lastSignatureIndex)/alpha) > 0.8
            % Note the index and add to the array
            lastSignatureIndex = index;
            thresholdIndexes = [thresholdIndexes,index];
        end
    end
end
%thresholdIndexes
```

Listing 4.2: `decodeFeatureBits`: thresholding of detected signatures

In Listing 4.3 a set of reference indices is generated against which the detected peaks can be matched. These depend on the number of guard carriers, the length of the cyclic prefix and the maximum number of features that may be embedded.

Finally in Listing 4.4 the peak indices found can be compared against the reference indices and used to set the relevant bits to `1`.

```
% Signatures should be between the guard bands at the low and high end
% Also depends on alpha and the maximum possible number of features
lowestIndex = 37;
highestIndex = 240;
% Generate reference indices where features should be located
referenceIndexes = zeros(1,numFeatures);
for feature=1:numFeatures
    referenceIndexes(feature)
    = lowestIndex+(feature-1)*((highestIndex-lowestIndex)/numFeatures);
end
```

Listing 4.3: `decodeFeatureBits`: generation of reference indices

```
% Identify bit sequence based on peak indices and reference indices
bits = zeros(1,numFeatures);
peak = 1;
% Go through reference indices and compare with peak indexes
if numel(thresholdIndexes) ~= 0
    for ref=1:numel(referenceIndexes)
        % Set a 1 if the reference and peak index are close enough
        if abs(thresholdIndexes(peak)-referenceIndexes(ref)) < 5
            bits(ref) = 1;
            peak = peak + 1;
        end
        % Break out of the loop if we have run out of peaks to check
        if peak > numel(thresholdIndexes)
            break
        end
    end
end
%whos;
end
```

Listing 4.4: `decodeFeatureBits`: comparison of reference and thresholded indices

4.1.1 Redundancy

The detected feature bits are key to treating the duplicated symbols used to generate them as redundancy. Once the bits have been determined, the corresponding symbols can be checked to ensure they match and the result provided as feedback to higher layers. Similarly when data is ready to be sent, the amount of data actually transmitted will vary based on the number of features and needs to be communicated to higher layers.

Once data has been received with an embedded signature, the mapped subcarriers can be collapsed as implemented in `ReceiveCyclostationarySignature.m` and outlined in Listing 4.5.

```
% Remove mapped symbols
mapPointArray = zeros(1, numFeatures);
featureSpacing = floor(200/(numFeatures+1));
for k=1:numFeatures
    mapPointArray(k) = k*featureSpacing;
end

for bit=numel(bits):-1:1
    if (bits(bit) == 1)
        up = floor(alpha/2);
        dst = mapPointArray(bit) + up;
        demodSymbols =
        [demodSymbols(1:dst-1)
         demodSymbols(dst+numSigCarriers:numel(demodSymbols))];
    end
end
```

Listing 4.5: Collapse mapped subcarriers to remove redundancy

4.2 MAC

The MAC has only been implemented in a skeletal form in MATLAB with implementation stubs in Simulink and Iris which did not yield the desired progress during implementation.

The MATLAB implementation takes advantage of the MATLAB Parallel Computing Toolbox to create a Single Program Multiple Data (SPMD) job with 3 workers.

These workers specialize on one of the following roles: MAC, Receiver or Sender, similar to an operating system network device driver [Corbet et al., 2005]. These components are intended to be analogous to threads in alternative implementations. Their roles are as follows:

MAC Manages the MAC state machine based on inputs either from signalling frames received or data from higher layers pending transmission.

Receiver Processes data received by decoding the signalling frame and removing mapped symbols and notifies MAC of received signalling frames.

Sender Processes data queued to be sent by embedding the signalling frame with a suitable amount of data for transmission.

The relationships between these components and their higher layers are illustrated in Figure 4.2.
The MAC component interacts with the Sender and Receiver as well as the next layer up in the stack to pass up data received and prepare data to be sent. The Sender and Receiver components meanwhile deal with the physical layer.

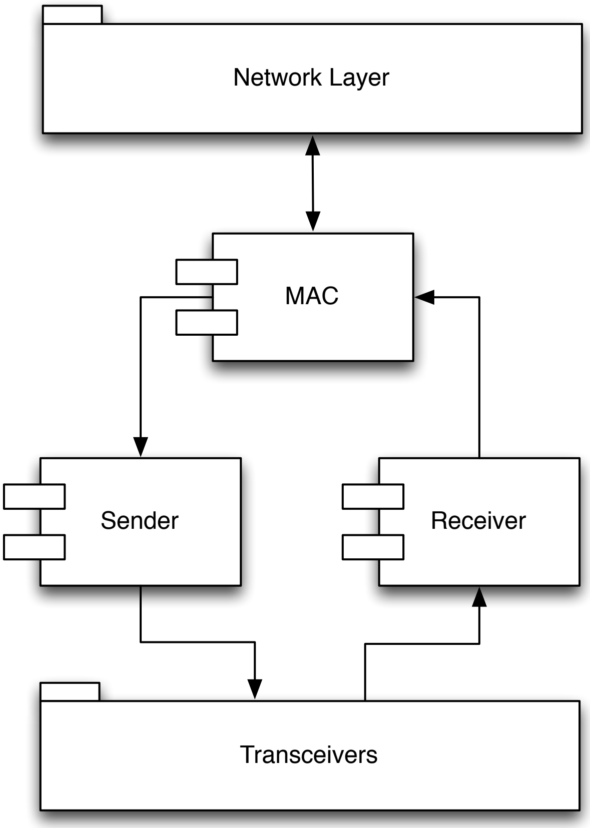


Figure 4.2: MAC Components in the context of adjacent layers in the network stack

When running the MAC on multiple nodes for testing purposes these can be configured to perform a certain role at launch using a profile. These profiles are as follows:

Sender The node commences by sending an RTS and subsequently transmits a fixed amount of data and then terminates the connection.

Receiver The node awaits an incoming RTS, responds with a CTS and exchanges data until the sender terminates the connection.

Busy Receiver Upon receiving an incoming RTS, the node responds with *Busy*.

The physical layer was substituted with a User Datagram Protocol (UDP) socket for the purpose of this implementation to avoid modelling physical layer issues, some of which are discussed in subsection 4.2.1. As a result of this the rendezvous and bootstrapping procedures such as determining home channels and finding other nodes are not reflected in the implementation.

4.2.1 Alternative Implementation Challenges

This section discusses the challenges encountered in efforts to duplicate the functionality of the MATLAB implementation in Simulink and Iris.

Simulink

Simulink [The MathWorks Inc., 2013b] is a model-based simulation environment which supports model creation using existing MATLAB functions and a library of "blocks" for performing various functions. Despite supporting MATLAB function blocks, these cannot be used in Simulink without accomodating certain constraints of the code generation system used to compile these blocks for higher simulation performance. These relate primarily to providing the C compiler sufficient information to perform static memory allocation for data structures used by the function and blocks it communicates with, but also restrict the set of MATLAB functions which can be called and must thus be replaced by alternatives.

This process is highly time consuming as the relevant errors are only flagged iteratively after an attempted compilation process and not in line when revising the MATLAB function block.

Finally, however, despite developing a working Simulink model using a loop-back approach, attempts to develop this into discrete components for multiple nodes failed as the interface with the USRP software radios returned data from the noise floor even when no transmission took place.

The Simulink implementation is contained in two models: `CycloNodesTx.slx` and `CycloNodesRx.slx`. The top-level models for these are shown in Figure 4.3 and Figure 4.4 respectively. It should be noted that these are representations of the actual model created in Simulink and not just schematic overviews.

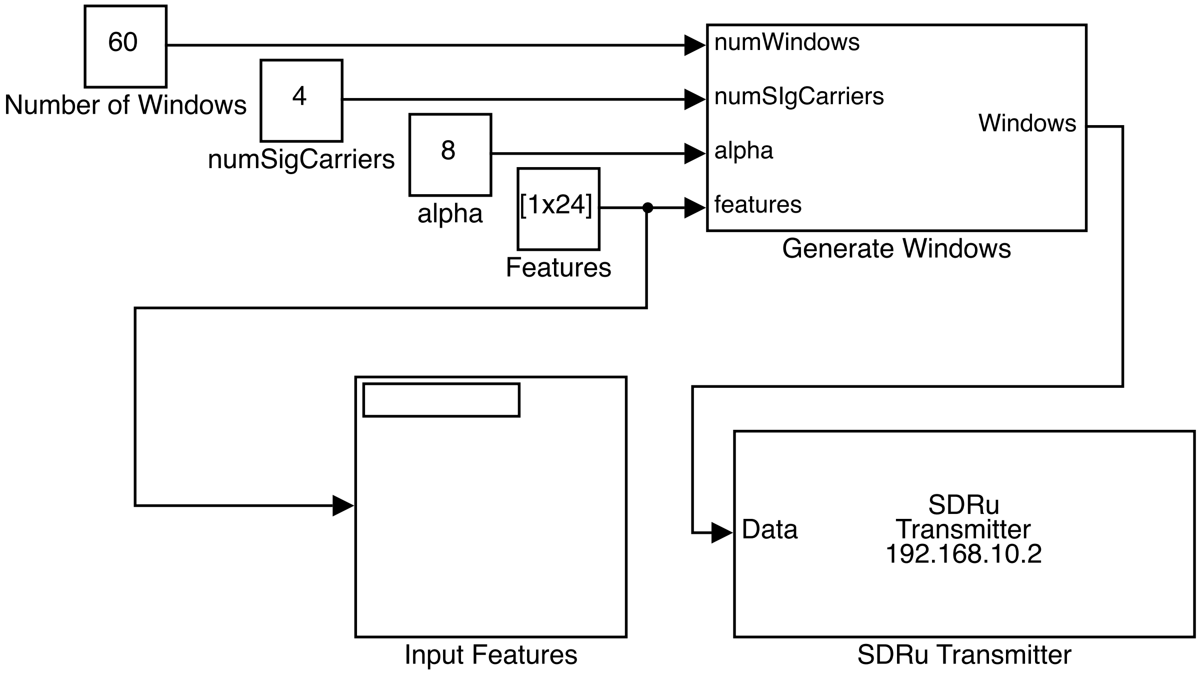


Figure 4.3: Top-level view of `CycloNodesTx` Simulink model

`CycloNodesTX` Generates windows of OFDM symbols with a set of embedded features ready for transmissing to a software defined radio. The top-level model allows key parameters such as the number of windows, subcarriers mapped for each feature, alpha and the features themselves to be configured. The features are also visualized in a display block for easier comparison with the output at the receiver. The Generate Windows subsystem iterates over the number of windows specified and creates the requested amount of OFDM symbols using either random or predefined QAM data symbols.

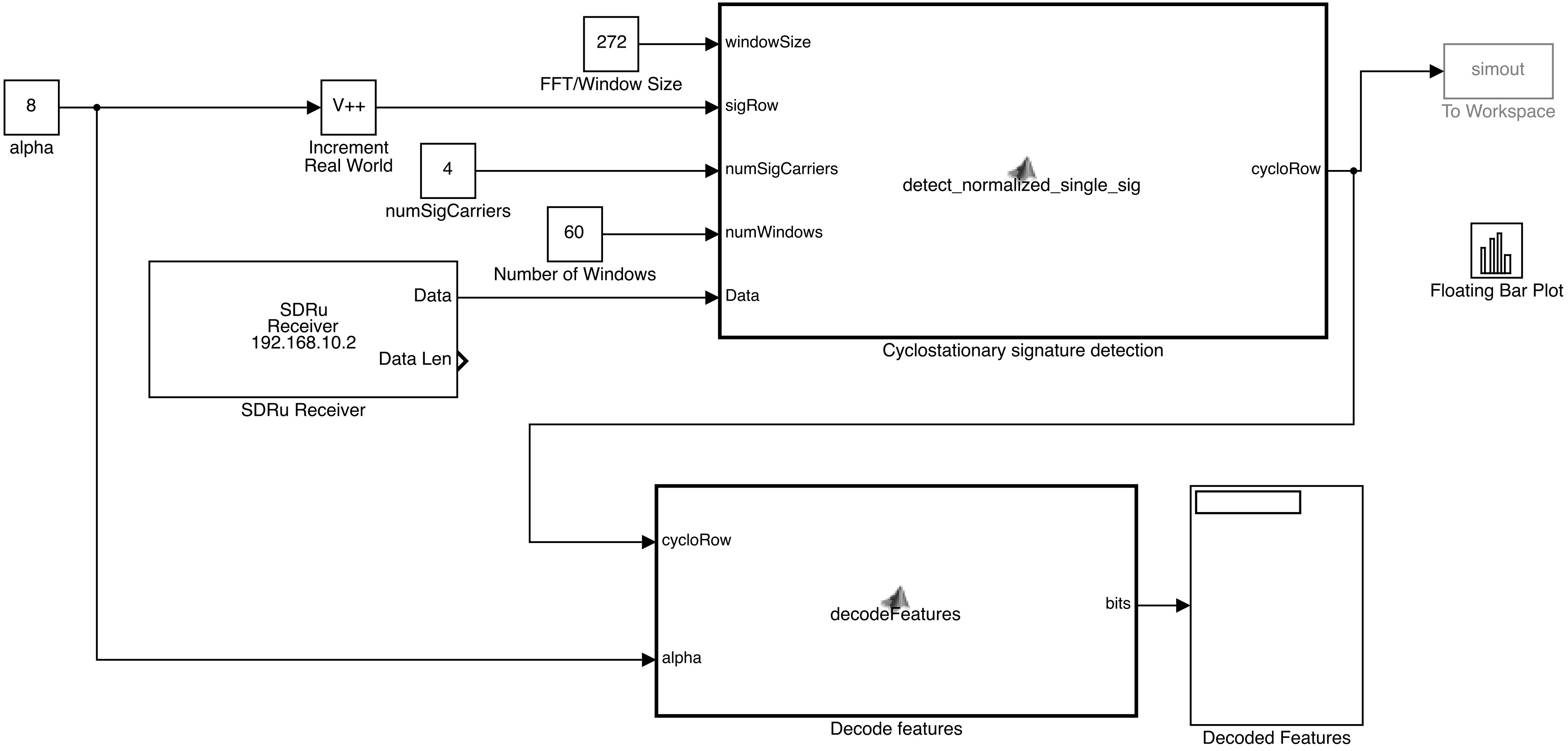


Figure 4.4: Top-level view of `CycloNodesRx` Simulink model

`CycloNodesRX` Processes windows received from the software defined radio based on the parameters specified, such FFT size by detecting cyclostationary signatures and subsequently decoding the features to a bit sequence. A display block is used to visualize the bits decoded for comparison with the sender. The result of cyclostationary signature detection is also passed to the MATLAB workspace for inspection.

Iris

Iris [Sutton et al., 2010] enables the prototyping of software radio designs using a library of pre-defined and custom components and controllers. The Iris implementation of the proposed MAC consists mainly of `OfdmCycloModulatorComponent` and `OfdmCycloDemodulatorComponent` which are adaptations of the existing OFDM (de-)modulator components shipped with Iris.

The adaptations made so far are primarily the introduction of subcarrier mapping depending on a signature parameter set for the modulator and the addition of cyclostationary analysis to the demodulator.

Iris is demonstrated by example in Listing 4.6 which shows the radio configuration used to set up a loopback system which consists of the following hierarchy:

Radios A software radio consisting of engines, links and controllers.

- **Engines** Either a PHY or stack engine containing physical layer or higher layer components respectively.
  - **Components** Individual components within an engine. In the case of the loopback configuration these are a file reader and writer, and a cyclostationary modulator and demodulator pair. Each component has one or more ports which can be named and may have parameters that can be set.
- **Links** Describe connections between component ports defined in an engine above. In the loopback configuration the file reader is connected to the cyclostationary modulator, which is subsequently directly connected to the demodulator and finally ends in the file writer.
- **Controllers** Instantiate controllers of a certain type. Controllers are not linked to components, rather they can respond to events emitted by components, for example by reconfiguring the radio. An Iris port of the architecture used in the MATLAB implementation might use a controller to manage the MAC state machine responding to signalling frames the demodulator emits as events and configuring the modulator to embed an appropriate signalling frame.

Due to the Iris implementation not yielding comparable results to the MATLAB implementation this was left as a stub in order to focus on furthering the working version.

```xml
<?xml version="1.0" encoding="utf-8" ?>
<softwareradio name="CycloLoop">
  <engine name="phyengine1" class="phyengine">
    <component name="filerawreader1" class="filerawreader">
      <parameter name="filename" value="testdata.txt"/>
      <parameter name="blocksize" value="200"/>
      <parameter name="datatype" value="uint8_t"/>
      <port name="output1" class="output"/>
    </component>

    <component name="ofdmcyclomodulator1" class="ofdmcyclomodulator">
      <port name="input1" class="input"/>
      <port name="output1" class="output"/>
      <parameter name="debug" value="true"/>
      <parameter name="numguardcarriers" value="55"/>
      <parameter name="cyclicprefixlength" value="16"/>
    </component>

    <component name="ofdmcyclodemodulator1" class="ofdmcyclodemodulator">
        <port name="input1" class="input"/>
        <port name="output1" class="output"/>
        <parameter name="debug" value="true"/>
        <parameter name="cyclicprefixlength" value="16"/>
    </component>

    <component name="filerawwriter1" class="filerawwriter">
      <parameter name="filename" value="out.txt"/>
      <port name="input1" class="input"/>
    </component>
  </engine>

  <link source="filerawreader1.output1"
        sink="ofdmcyclomodulator1.inputData" />
  <link source="ofdmcyclomodulator1.output1"
        sink="ofdmcyclodemodulator1.input1"/>
  <link source="ofdmcyclodemodulator1.output1"
        sink="filerawwriter1.input1"/>
  <controller name="test1" class="test" />
</softwareradio>
```

Listing 4.6: Iris Loopback Radio Configuration

4.3 Summary

This chapter presented in detail the primary implementation in MATLAB and outlined the challenges faced in attempting to bring the original implementation to the PHY via Simulink and Iris.

Chapter 5

Evaluation

This chapter describes the evaluation which took place in the CTVR Iris Testbed, described in Iris Testbed. The evaluation considers the performance of the Encoding used by the proposed MAC and options for an analysis of the proposed MAC in contrast to IEEE 802.11 in MAC Analysis.

5.1 Iris Testbed

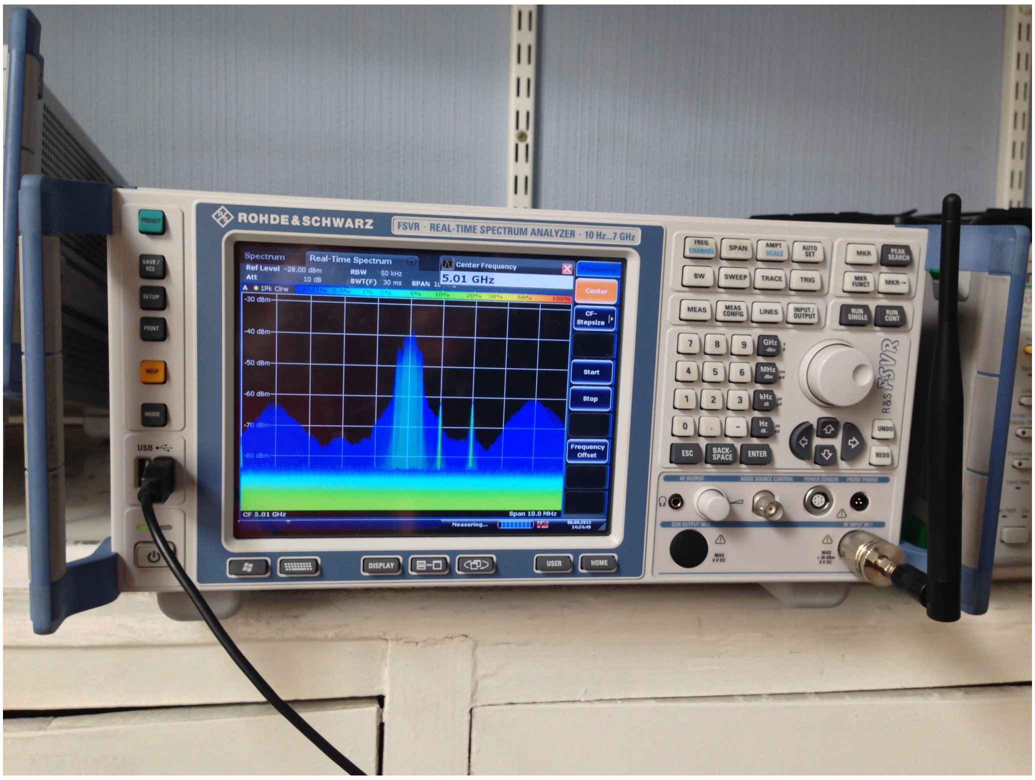
The CTVR Iris Testbed [Doyle et al., 2010] is pictured in Figure 5.1a. The testbed consists of a number of host computers running Iris [Sutton et al., 2010] with Ettus Research USRP N210 [Ettus Research, 2012] software radios (Figure 5.1b) attached to these and a gateway for remote access to the nodes and equipment such as spectrum analyzers like the Rohde & Schwarz FSVR shown in Figure 5.1c.

Figure 5.2 shows the signal transmitted by the Simulink implementation on the spectrum analyzer.

5.2 Encoding

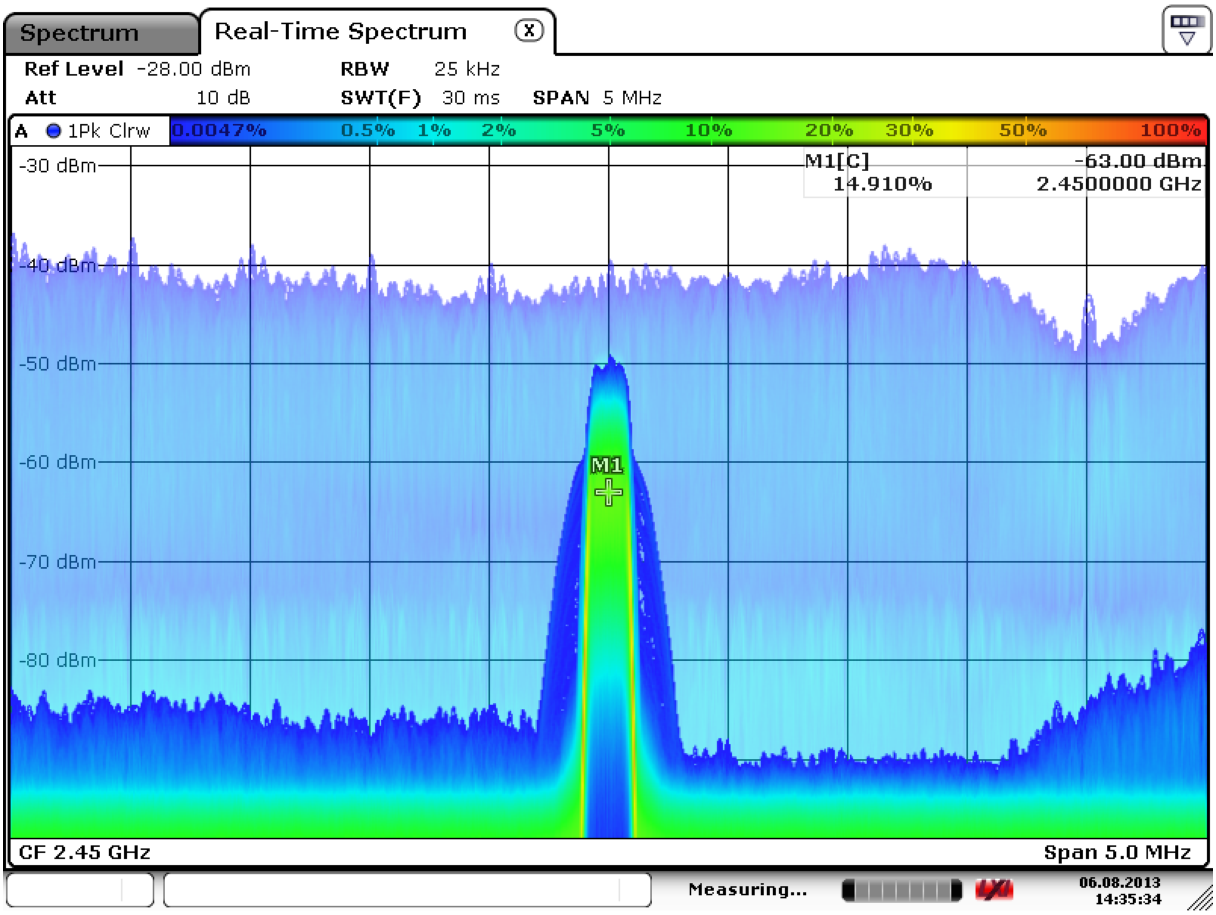
The decoding of cyclostationary signatures was stress-tested using `exerciseCyclostationarySignatures.m`. This function generates 1000 random signalling frames and performs 5 decoding attempts on each as well as recording whether the signalling frame was correctly decoded or not. Data recorded by a sample run of the function yielded a 93.5% successful decoding rate.

(a) Iris Testbed (b) Ettus Research USRP N210



(c) Rohde & Schwarz FSVR Spectrum Analyzer

Figure 5.1: Iris Testbed and Equipment Overview



Ref Level -28.00 dBm RBW 25 kHz
Att 10 dB SWT(F) 30 ms SPAN 5 MHz

M1[C] -63.00 dBm
14.910% 2.4500000 GHz

CF 2.45 GHz Span 5.0 MHz

Measuring... 06.08.2013 14:35:34

Date: 6.AUG.2013 14:35:34

Figure 5.2: Signal generated and transmitted by Simulink implementation

The chances of successfully decoding a signalling frame may however vary depending on channel conditions and can be influenced by altering the threshold used for identifying peaks in the spectral correlation values returned when performing cyclostationary analysis.

5.3 MAC Analysis

Due to the implementation challenges outlined in Alternative Implementation Challenges only a sketch for theoretical analysis of expected performance is presented as no actual measurements or comparisons could be made.

This analysis considers two scenarios which a typical IEEE 802.11 [Hiertz et al., 2010] topology consisting of an access point and several connected nodes as well as a shared backhaul link might be used for:

- Provide Wide Area Network (WAN) access to connected nodes via the access point's backhaul link. In this case the main traffic flows are from the access point to nodes from the WAN and from individual nodes to the WAN.
- Provide LAN connectivity between nodes associated with an access point. In this scenario most traffic is between associated nodes, via the access point.

In terms of radio resources, the 802.11 WLAN should operate using one 20 MHz channel, while the proposed MAC provides 1 MHz each for TX and RX between each pair of nodes in a multi-antenna setup, or 2 MHz using a single-antenna full-duplex radio [Bharadia et al., 2013]. The option for nodes to identify higher bandwidths through mutual spectrum opportunities after a link is established is not considered.

Each scenario should be considered in cases with 1, 3, 5 or 20 associated nodes to observe behaviour variations depending on the number of contending nodes. In the case of the proposed MAC an additional node serves as a replacement for the access point offering backhaul.

It is anticipated that an analysis based on these parameters could be used to determine whether the following hypothesis is accurate:

The proposed MAC delivers performance gains over IEEE 802.11

In contrast to the unproven hypothesis above, the performance of the IEEE 802.11 MAC has been analysed extensively [Bianchi, 2000; Malone et al., 2007] with a key observation which forms part of the motivation for developing the proposed MAC protocol: as the offered load increases towards the PHY capacity, actual throughput reaches a "maximum" level after which it drops and tends asymptotically towards a slightly lower value.
This should provide a good basis for comparison between both approaches.

Similar behaviour as IEEE 802.11 was found to be exhibited [Meditch and Lea, 1983] by bus-based Ethernet systems using Carrier Sense Multiple Access/Collision Detect (CSMA/CD).

Figure 5.3 attempts to illustrate the expected behaviour of the proposed MAC and CSMA/CD or CSMA/CA based networks. Note that this is presented without scale due to the absence of data to establish a precise reference.

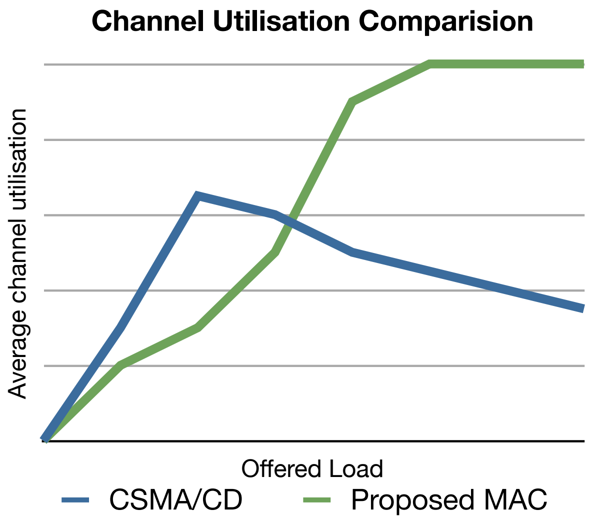


Figure 5.3: Anticipated Channel Utilisation for proposed MAC in comparison to CSMA/CD

5.4 Summary

This chapter described the setup used for stress-testing the Encoding and outlines an approach which could provide the basis for an evaluation when a PHY-level implementation of the proposed MAC is operable.

Chapter 6

Conclusion

This chapter concludes this dissertation by considering the contributions made towards answering the research question posed and enabling Wireless Ethernet as well as identifying future work which remains to be done and some closing remarks by the author.

6.1 Contributions

The key contributions of this dissertation include the development of a basic state machine for a MAC as a basis for dedicated wireless links, a key component of enabling a switched wireless LAN.

As part of the MAC design, the overhead introduced by embedding cyclostationary features is reconsidered as redundancy which may be used to ensure correct data transmission rather than overhead limiting throughput.

6.2 Future Work

The contributions made in this dissertation primarily relate to laying the theoretical groundwork for an implementation of the MAC using a software defined radio. This implementation forms the basis for putting the described bandwidth specification and rendezvous procedures to the test as well as identifying other physical layer issues which could be mitigated through improvements to the proposed MAC.

Beyond an operable physical layer implementation, the behaviour of the MAC when used at scale with the switched topology outlined in comparison with existing IEEE 802.11 networks may merit further investigation.

6.3 Closing Remarks

Designing a wireless MAC from the ground up requires a solid foundation in wireless communications and the issues caused by the PHY. While from a high-level point of view, the Application Programming Interface (API) provided to use the medium such as the addressing scheme and quality of service contracts are of greater interest, when it comes to implementing the MAC a sensitivity is required for exactly how sensitive receivers have to be designed to respond to signals being transmitted.

This is a path that should only be trodden in the company of a well-versed telecommunications engineer or researcher rather than trying to piece together a working system from basic, minimum working examples shipped with development tools which typically fudge their chances of success through use of robust modulation schemes, generous bandwidths and high TX powers to avoid frequency-selective fading, signal loss or difficulties synchronizing to a target frequency.

In the scope of a relatively short project when to do the bulk of the work relying on third parties or collaborators outside your direct research group should also be considered to avoid coinciding with annual holiday periods which may easily overlap with most of the time allocated to working on a dissertation. Inviting a researcher to a meeting in a cosy lab in sub-zero wintery conditions is far more likely to succeed than attempting to coax the same into a roasting hell of workstation and server fans being egged on by direct midday sunlight.

An opportunity to gain a better fundamental understanding of the design and engineering processes involved may have contributed to a success of the experimental implementation and evaluation.

Despite these obstacles, I feel nonetheless that this dissertation has given me the opportunity to explore interesting areas of current research in wireless networking and develop an intuition for the developments to come in the field, as well as providing a minor contribution to potential future work.

`FIN` [Postel, 1981]

Appendix A

MATLAB Implementation Overview

A number of constants and definitions are used throughout the implementation, including:

alpha 8: number of subcarriers between mapped subcarriers

cpLength 16: length of the OFDM cyclic prefix

dataLength 200: number QAM data symbols in each OFDM symbol

fftSize 272: (dataLength+cpLength+numGuards+1)

numFeatures 24: number cyclostationary features to be embedded

numGuards 55: number of OFDM guard subcarriers

qamNumber 64: QAM modulation order (64QAM)

The primary implementation in MATLAB consists of the following files:

Shared These files are shared between the SPMD implementation and the encoding stress test.

- **`charToQAM.m`** Converts 8-bit characters to 16-QAM or 64-QAM
- **`decodeFeatureBits.m`** Returns the bits encoded by a set of cyclostationary features in the results of cyclostationary analysis
- **`detect_normalized_single_sig.m`** Performs cyclostationary signature detection on a received window of OFDM symbols (based on implementation by Paul Sutton)

`gen_wimax_multiple_cyclosig_symbol.m` Performs subcarrier mapping with a given set of QAM data symbols and features to be embedded resulting in an OFDM symbol with the features embedded (based on implementation by Paul Sutton)

`lorem16,lorem64` Input files containing sample data to be transmitted

`QAMToChar.m` Converts 16-QAM or 64-QAM symbols 8-bit characters

`readQamDataFile.m` Reads one of the specifed input files to be used as sample data

`SignallingFrame.m` Class modelling a signalling frame and providing methods for (de-) serialisation to and from bit sequences

`SignallingFrameStatus.m` Enumeration for the status bits contained in a signalling frame

Encoding Test These files are used to run the encoding stress test, the results of which can be found in section 5.2.

`exerciseCyclostationarySignatures.m` Exercises the generation and decoding of signalling frames with 1000 random signalling frames, with 5 runs each. The result of each run is noted and the mean decoding success rate determined.

`simulateCyclostationarySignature.m` Simulates cyclostationary signatures by generating OFDM symbols with embedded features corresponding to a signalling and immediately performs cyclostationary analysis to decode the signal and retrieve the signalling frame.

SPMD Nodes These files are used by nodes running the SPMD implementation.

`IEEE8023wMAC.m` Skeleton class for the MAC.

`IEEE8023wMACState.m` Enumeration for MAC states.

`LaunchWorker.m` Used by individual workers to inspect their worker ID and specialise on a particular role such as MAC, Receiver or Sender.

`LaunchWorkers.m` Launches a MATLAB Parallel Computing Toolbox cluster with three workers and submits a communicating job using the specified MAC profile, destination Internet Protocol (IP) address, node ID and destination ID.

`MAC.m` Executed by the MAC worker and configured by the MAC profile chosen. Responds to received data depending on the signalling frame contained and manages the MAC state machine.

`MACCommunique.m` A MAC Communiqué encapsulates a signalling frame, a description string and payload data for communications between the workers. In particular from the Receiver to the MAC worker, and from the latter to the Sender.

`ReceiveCyclostationarySignature.m` Executed by the Receiver worker. Receives incoming data, performs cyclostationary signature detection and passes the signalling frame to the MAC worker.

`SendCyclostationarySignature.m` Executed by the Sender worker. Receives communiqués from the MAC worker and sends the data given with the signalling frame embedded as a cyclostationary signature.

Glossary

API Application Programming Interface. 46

ARQ Automatic Repeat Request. 15

CSMA/CA Carrier Sense Multiple Access/Collision Avoidance. 2, 43

CSMA/CD Carrier Sense Multiple Access/Collision Detect. 43

CTS Clear to Send. 25, 34

CTVR Centre for Telecommunications Value-Chain Research. iv, 40

DAB Direct Access Based. 9, 28

DC Direct Current. 20

DSA Dynamic Spectrum Allocation. 9, 10

DSA Dynamic Spectrum Access. 2

FFT fast Fourier transform. 7, 30, 37

IP Internet Protocol. 48

LAN Local Area Network. 2, 4, 7, 8, 43

LTE Long Term Evolution. 12

MAC Medium Access Control. v, ix, 1, 2, 6, 7, 9–12, 14, 15, 17, 18, 20, 23, 24, 26–29, 33, 34, 38, 40, 43–46, 48, 49

MIMO Multiple Input Multiple Output. 12

OFDM Orthogonal Frequency Devision Multiplexing. 4, 6, 7, 14, 17, 21, 22, 29, 30, 36, 38, 47, 48

PHY physical layer. 15, 17, 20, 38, 39, 43, 44, 46

QAM Quadrature Amplitude Modulation. 12, 21, 22, 29, 36, 47, 48

RTS Ready to Send. 25, 27, 34

RX Receive. 20, 23, 25, 43

SPMD Single Program Multiple Data. 33, 47, 48

TDD Time Division Duplex. 10

TDMA Time Division Multiple Access. 2

TX Transmit. 20, 23, 25, 43, 46

UDP User Datagram Protocol. 35

WAN Wide Area Network. 43

WLAN Wireless LAN. 12, 43

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