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Literature Review

Wireless communications and networking standards are fast evolving to satisfy the increasing demand for higher speed, more bandwidth, and longer battery life. As this happens, one of the foundations of networking, the layered protocol architecture, is coming under close scrutiny. Although the traditional layered architecture has worked well for wired networks, its applicability to wireless networks is often debated. Researchers are actively looking into an area called the cross-layer design in which protocol design is done by sharing more information across adjacent and non-adjacent layers to obtain performance gains. This is unlike layering, where the protocols at the different layers are designed independently.

If one looks at the state-of-the-art in this area, one will observe that there are several interpretations of cross-layer design [Srivastava and Motani, 2005]. This is probably because the cross-layer design is truly a hybrid area of study, bringing together folks in areas of networking, software, communications, and signal processing. One of the challenges is that these cross layer design ideas do not fully explore all the aspects of wireless media and physical radio environment. Second challenge is that the synergy between the performance viewpoint and implementation concerns is weak. While most proposals focus and elaborate on the performance gains from cross-layer design, there are very few ideas on how cross-layer interactions may be implemented. This results in a situation where the existing protocols focus more on the theory and less on the practical implementation of the proposal. This challenge is even more pronounced for the Medium Access Control (MAC) protocols due to the lack of experimentation systems optimized for this area of research. The objective of this thesis is to provide one possible solution to the above mentioned challenges.

2.1 7-layer OSI Model

The 7-layer Open Systems Interconnection (OSI) model, as shown in Figure 2.1 defines the functionality of each layer and the interface between the adjacent layers. The Physical (PHY) layer deals with the physical characteristics of interfaces and media. It handles various aspects of synchronization between the sender and the receiver. It manages different types of line configurations such as point-to-point or multi-point and the physical topology of the network such as bus, star, ring, or mesh. It also controls various aspects of the transmission mode, which can be either simplex, half or full duplex. The data link layer, also known as the Medium Access Control (MAC) layer, deals with the aspects of framing and flow control. It assigns the physical addresses and manages the access control mechanism. It also deals with the aspects of introducing error codes in the data flow to take care of error control mechanism. While the MAC layer takes care of local addresses, the network layer deals with global addresses, also known as the logical addresses. It also manages the forwarding and routing protocols for the communication system. The transport layer deals with the service-point addressing issues. It also takes care of aspects such as segmentation and reassembly, connection control, flow control, and error control. The session layer deals with the dialog control and synchronization issues. The presentation layer deals with aspects of translation, encryption, and compression. Finally, the application layer deals with enabling users to access the network services and resources.

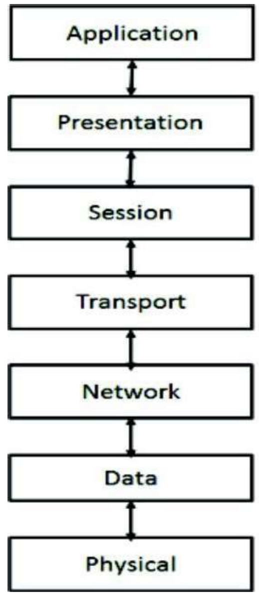

Figure 2.1: 7 Layer OSI Model, Describing the Interconnections between the Different Layers

Following are some of the benefits of a traditional, structured 7-layer approach. First of all, it helps reduce complexity by dividing the processes into groups and implementation of the network architecture is less complex. It fosters compatibility by providing standardized interfaces which allow for "plug-and-play" compatibility and multi-vendor integration. It facilitates modularization as developers can upgrade new technologies at each layer keeping the integrity of the network architecture. It accelerates evolution of technology as developers can focus on technology at one layer, while preventing the changes from affecting another layer. Finally, it simplifies learning as processes can be broken up into groups, which divides the complexities into smaller, manageable chunks.

2.2 Cross Layer Design – State of the Art

Reconfigurability of the MAC is defined as the capability of the system to change from one MAC technique to another according to a defined criteria. Using this approach, significant performance improvements have resulted in wireless networking protocols through a cross-layer interaction between the PHY, MAC and network layers [Shakkottai *et al*, 2003]. The underlying idea is that sharing more information across these layers allows them to make optimal decisions, which offers an improved overall performance. This concept is further illustrated with the aid of an example.

Receiver-based Auto Rate [Holland *et al*, 2001] is a rate adaptive MAC protocol suggested for wireless local area networks (WLAN). WLANs have the ability to offer data rates up to 54Mbps. This is made possible due to the protocol's ability to adapt modulation and coding schemes based on the channel conditions, typically measured using a metric known as Signal to Noise Ratio (SNR). This has resulted in a significant increase in bandwidth efficiency, thus enabling a wide array of new applications. WLANs support different types of modulation and coding schemes starting with the most noise-sensitive Binary Phase Shift Keying (BPSK) to the most bandwidth-efficient 64-Quadrature Amplitude Modulation (64-QAM), as shown in Table 2.1. EDR stands for Effective Data Rate that is achievable with the number of streams and choice of Modulation and Coding rates.

Table 2.1 : Different Modulation and Coding Schemes for WLAN Standard and Effective Data Rates

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Number of Streams	*Modulation Scheme*	*Coding Scheme*	*Effective Data Rate (EDR) MHz*
0	BPSK	½	6.50
1	QPSK	½	13.00
2	QPSK	¾	19.50
3	16-QAM	½	26.00
4	16-QAM	¾	39.00
5	64-QAM	2/3	52.00
6	64-QAM	¾	58.50
7	64-QAM	5/6	65.00
8	BPSK	½	13.00
9	QPSK	½	26.00
10	QPSK	½	26.00
11	BPSK	½	13.00

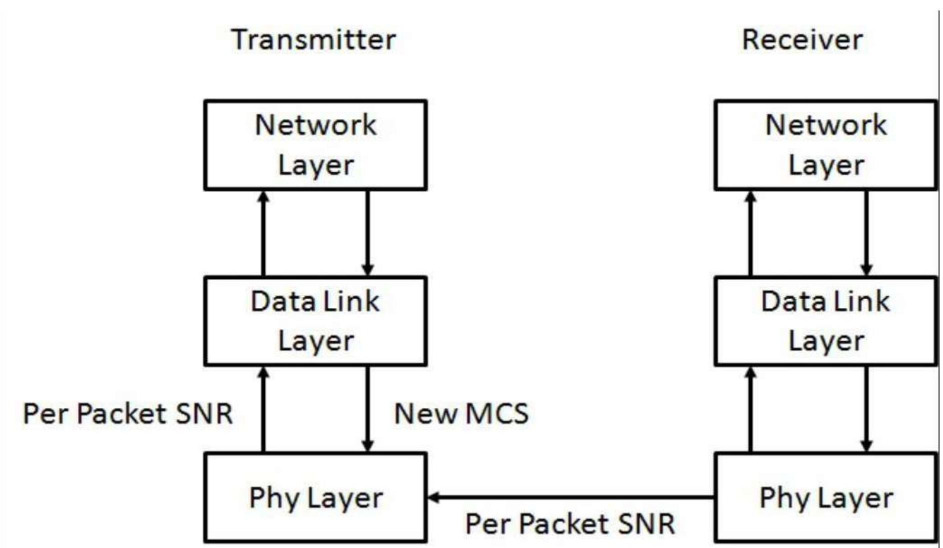

Figure 2.2: Information Sharing between Different Layers in RBAR

The choice of which modulation scheme to use depends on the current state of the transmission channel. The selection of a particular modulation scheme determines the effective data rate. While most devices offer users the flexibility of specifying the data rate to be used, there is also a mechanism for automatically determining the scheme based on the channel conditions.

While automatic rate selection protocols have been studied for cellular networks in the past, [Holland *et al*, 2001] were the first to present the RBAR protocol in which the rate adaptation mechanism was placed at the receiver instead at transmitter. Through their work, they were able to show that RBAR is better because it results in a more efficient channel quality estimation which is then reflected in a higher overall throughput. However, techniques such as RBAR require sharing of information between multiple layers and modifications at the existing layers as well. This is depicted in Figure 2.2.

This type of information sharing is common to most of the cross layer designs described in the literature. One of the challenges is the lack of a common definition language to describe the cross layer design, without requiring the user to read through large amounts of text. To overcome this challenge, this thesis proposes the following notation to describe information exchange between different layers.

$$[\text{[illegible]}] \rightarrow [\text{[illegible]}] \cdot [\text{[illegible]}] \qquad (2.1)$$

This thesis has used the notation Rx_n.PHY to depict PHY layer on Receiver of Channel *n* and the notation Tx_n.PHY to depict the PHY layer on transmitter of channel *n*. So, in a SISO system as shown in Figure 2.2, sending per packet signal to noise ratio (SNR) estimates from Receiver to Transmitter would be denoted as

$$[\text{[illegible]}.\text{[illegible]}] \rightarrow [\text{[illegible]}.\text{[illegible]}] \cdot [\text{[illegible]}] \qquad (2.2)$$

This thesis uses the following notation to describe the modifications done at various layers as part of cross layer modifications

$$[\text{[illegible]}].[\text{[illegible]}] \rightarrow [\text{[illegible]}] \qquad (2.3)$$

There are many cross-layer algorithms described in the literature. A detailed survey of the cross layer design algorithms can be found in the work done by [Fu *et al*, 2014]. A few of these algorithms have been described here. While this is not an exhaustive list of cross-layer algorithms, it serves as a good summary of the various cross layer algorithms

2.2.1 Bit Rate Adaption Protocols

WLANs have the ability to offer data rates up to 54 Mb/s in 802.11a/g standards and several hundreds of Mb/s in the new 802.11n standard. WLANs support different types of modulation and coding schemes, starting with the most noise-sensitive Binary Phase Shift Keying (BPSK) to the most bandwidth efficient 64 Quadrature Amplitude Modulation (64-QAM). The choice of which modulation scheme to use depends on the current state of the transmission channel, typically measured using a metric known as Signal to Noise Ratio (SNR). The selection of a particular modulation scheme determines the effective data rate.

While most devices offer users the flexibility of specifying the data rate to be used, there is also a mechanism for automatically determining the rate based on the channel conditions. Bit rate adaptation protocols usually measure the frame loss rates at various bit rates and operate at the bit rate that is likely to give the highest throughput. However, this mechanism requires sampling multiple bit rates and can be inadequate in fast-changing channels. An alternative approach is to use additional information such as the SNR available at the physical layer of the receiver. RBAR was the first protocol in which the rate adaptation mechanism was placed at the receiver instead of the transmitter. The SNR of received frames is measured at the receiver and conveyed to the MAC layer of the sender, which in-turn maps this SNR to the appropriate modulation and coding scheme. This quick adaptation of rate results in a higher overall throughput. However, techniques such as RBAR require sharing of information between multiple layers and modifications at the existing layers as well. SNR of each packet is shared between the

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Receiver and Transmitter PHY layer. Transmitter PHY layer sends this information to the MAC layer, which uses this information to adjust the MCS (Modulation and Coding Scheme) to perform well for the receivers SNR. This information is then relayed back to the PHY layer which implements the modulation scheme. Likewise, the actual PHY layer has to be modified to replace the hard decision encoder with a soft decision encoder. These sequence of events are denoted in the thesis as

[illegible] → [illegible] · [illegible] (2.4)

[illegible] → [illegible] · [illegible] (2.5)

[illegible] → [illegible] · [illegible] (2.6)

[illegible] · [illegible] → [h[illegible]] (2.7)

SoftRate [Vutukuru *et al*, 2009] technique determines the bit rate using the Bit Error Rate computed from the SoftPhy hints [Jamieson, 2008]. AccuRate [Sen et al, 2010] uses per-symbol dispersions to capture channel behavior. It then replays these dispersions on different rate encodings of the same packet. The replay action can be emulated at the receiver without requiring the transmitter to send the packet at every other rate. This technique then uses the coherence time of the channel to identify the optimal rate of the received packet and uses the same rate on the next packet. This technique predicts a packets optimal rate correctly 95 out of 100 times, when the packet is received correctly. If the packet is received in error, then AccuRate computes the optimal bit rate correctly 93 out of 100 times. All of these bit rate adaption techniques require per-packet SNR estimates and per-bit confidences to be sent from lower to higher layers. Likewise, it needs link layer feedback to be sent from higher layers to lower layers. The PHY and MAC layer needs to be modified to replace a hard decision decoder with a soft decision decoder.

2.2.2 ZigZag Interference Cancellation

Carrier Sense Multiple Access (CSMA) is used in WLAN networks to combat the problem of collisions when multiple nodes transmit simultaneously. This technique fails in case of hidden nodes where senders repeatedly collide or one sender ends up greedily capturing the medium, thus preventing others from transmitting. [Gollakota and Katabi, 2008] have proposed ZigZag decoding as a way to combat hidden terminals in wireless networks. This technique combats the issue of interference by using two instances of collided packets to reconstruct the original message. It relies on the fact that when two packets collide once, they tend to collide again and the subsequent collision results in a transmission with a small jitter. ZigZag uses this opportunity and the MAC address of the sender to partially decode one chunk of packet during the first transmission and other chunks during subsequent transmission. Implementing ZigZag decoding requires the following changes to the 802.11 protocol.

[illegible] → [illegible] · [illegible] (2.8)

[illegible] · [illegible] → [illegible] (2.9)

2.2.3 Error Correction Techniques

The concept of error correcting codes is widely used in wireless transmissions. While this is a great technique, one cannot argue that it increases packet size, thereby reducing application throughput. Most of the transmission schemes retransmit the entire frame, irrespective of the bit error rate. Alternatively, partial packet recovery [Jamieson and Balakrishnan, 2007] proposes calculating per-bit confidence information and retransmitting only those bits that are in error. The SoftPhy technique [Jamieson, 2008] uses SoftPhy hints as confidences to identify bits in error. While this helps in reducing the packet retransmission overhead, it requires modification of the PHY and MAC layers, thus requiring the replacement of a hard-decision decoder with a soft-decision decoder. Likewise, several Unequal Error Protection (UEP) techniques, which change the error correcting algorithms based on the type of the data payload being transmitted, have been proposed in literature [Kim *et al*, 2003]. With UEP techniques, the following cross layer modifications are needed

[[illegible]] → [[illegible]] · [[illegible]] (2.10)

[[illegible]] · [[illegible]] → [[illegible]] (2.11)

2.2.4 CMAP MAC Protocol

Next, the popular Carrier Sense Multiple Access (CSMA) MAC protocol is discussed.

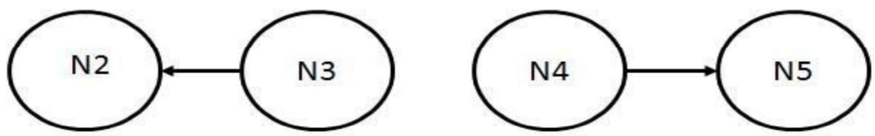

Figure 2.3 : Exposed Node Problem

Consider the system configuration, as shown in Figure 2.3, which uses the CSMA MAC protocol. If Node N3 is transmitting to Node N2 and at the same time Node N4 wishes to transmit to Node N5, CSMA MAC will avoid the second transmission because it senses activity on the channel. Conflict MAP (CMAP) [Vutukuru *et al*, 2008] is a technique that harnesses the power of such exposed nodes. It uses additional information about who is transmitting on the channel. With this information, a CMAP node can send its packets if their transmission will not significantly interfere with the ongoing transmissions. In the above example, N4 can continue transmissions to N5, because it does not interfere with the other transmission. CMAP can be implemented using the following cross layer primitives.

[[illegible]] → [[illegible]] · [[illegible]] (2.12)

[[illegible]] → [[illegible]] · [[illegible]] (2.13)

[[illegible]] → [[illegible]] · [[illegible]] (2.14)

2.2.5 Frequency Aware Protocols

Some designs exploit both time and frequency domain capabilities to utilize channel resources effectively. Frequency aware rate adaptation [Hariharan *et al*, 2009] allocates frequency to each user based on the SNR estimates over various sub-bands, because different users might see different fading effects over a transmission band. Other techniques allocate disjoint frequency bands to different senders to mitigate interference [Gummadi *et al*, 2008; Chandra *et al*, 2008]. Modifications required for this protocol can be described by the following equations

[[illegible]] → [[illegible]] · [[illegible]] (2.15)

[[illegible]] → [[illegible]] · [[illegible]] (2.16)

[[illegible]] → [[illegible]] · [[illegible]] (2.17)

2.3 Radio Front End Impairments

Most of the techniques described above use bit error rate (BER) as a function of Eb/No as an evaluation metric, where Eb/No is energy per bit normalised by noise density of a discrete memoryless channel. However, there are many other front end impairments, such as quadrature skew, gain imbalance, phase noise, and amplifier nonlinearity, that a radio signal experiences in addition to additive white Gaussian noise (AWGN). These impairments are very typical in practical radio transceiver chips, especially on lower cost chipsets. It is important that the impact of such type of impairments are thoroughly investigated and it's impact on the Bit Error Rate is understood. A theoretical analysis of the performance degradation due to quadrature skew and I/Q gain imbalance in multi-carrier direct conversion receivers has been presented by [Windisch and Fettweis, 2006]. The impact of a nonlinear amplifier and phase noise on a quadrature amplitude modulated (QAM) Orthogonal Frequency Division Multiplexing (OFDM) system performance has been studied by [Costa and Pupolin, 2002]. Likewise, a model for performance evaluation of an M-ary QAM OFDM system, in the presence of AWGN and nonlinear distortions due to power amplifier, has been presented by [Santella and Mazzenga, 1995]. Impact of linear radio front end impairments on performance of communication systems has also been studied in literature. OFDM systems are designed to exploit the orthogonality of sub-carriers: any non-orthogonality introduced by the radio front end can severely impact its performance. Effects of physical layer impairments on OFDM systems have been studied by [Cutler, 2002]. The impact of oscillator's I/Q gain imbalance and quadrature skew on a dual band wireless local area network (WLAN) transmitter and how pre-distortion can be used to reduce this impact has been described by [Karagianni *et al*, 2008]. An automatic I/Q imbalance compensation technique for quadrature modulators using feedback from the signal's frequency spectrum has been presented by [Minseok *et al*, 2012).

Although the impact of the radio front end impairments has been studied in detail, how the knowledge of such impairments can be used for system level performance improvement has not been explored in the literature. Typically, the receiver signal processing algorithms have to be optimized to overcome the effect of these impairments. However, as multiple impairments happen at the same time, this significantly increases the complexity of the receiver. In this thesis, a new cross layer protocol using the radio front end impairments, such as gain imbalance and quadrature skew, has been presented. It provides a mathematical derivation which shows how the impact of these impairments can be represented as a closed form equation, which can then be easily implemented with a minimal computation overhead. This thesis also presents a cost and performance analysis which demonstrates that the proposed cross layer algorithm is practical to implement and provides significant performance improvements.