EFFICIENT RATE ADAPTATION IN IEEE 802.11 WIRELESS NETWORKS

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Efficient Rate Adaptation in IEEE 802.11 Wireless Networks

by

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Abstract

IEEE 802.11 is a predominant technology in wireless networks. Though designed to extend local area networks, it has been extended beyond its original infrastructured scope. Three medium sharing aspects must be considered to improve wireless networks throughput. These include higher data rate, power management and channel spatial reuse.

This thesis focuses on the rate adaptation aspect of wireless networks. Though critical, IEEE 802.11 standards do not specify any rate adaptation mechanism which leaves it up to the wireless devices vendors to implement interfaces that utilize PHY multirate capability. A rate adaptation mechanism must accurately estimate the channel condition despite the presence of various dynamics caused by fading, mobility and hidden terminals, and effectively select the appropriate data rate.

Utilizing the diverse information scope in literature, we propose hybrid rate adaptation schemes, **DRA, DRALD** and **DRANLD**, that draw channel quality information from both the sender and the receiver to effectively determine appropriate data rate. Extensive *NS-2* simulations illustrate that these schemes are more adaptive to the dynamic channel conditions and their performance is better than their predecessors.

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Chapter 1

Introduction

Although the PHY layer of IEEE 802.11 Standard family provides a set of different modulation schemes and data rates, the Standard itself does not provide any mechanism to adaptively select among these data rates. Nevertheless, rate selection must be considered to improve wireless networks throughput. This has stirred research interests in wireless networks rate adaptation schemes.

Existing rate adaptation mechanisms can broadly be classified into *"open"* or *"closed"* loop approaches depending on whether the sender or the receiver determines the appropriate data transmission rate. Since either of the two categories have shortcomings, we focus on their strengths and propose efficient rate adaptation schemes that combine different design techniques proposed in literature.

The remainder of this Chapter is organized as follows. In Section 1, we state our research motivation. We then highlight different aspects of IEEE 802.11 wireless networks that are related to our work in Section 2. In Section 3, we discuss the Network Simulator (*NS-2*) and its channel models that we used to implement our work. Lastly, Section 4 highlights the organization of the rest of the thesis Chapters.

1.1 Motivation

The fast evolving bandwidth hungry multimedia applications has pushed the wireless networks capacity to its limit stirring extensive research efforts. On the other hand, IEEE 802.11 wireless technology was developed for infrastructured wireless networks, but its capabilities has been extended to ad hoc wireless networks. This extension comes with diverse limitations which includes need for throughput optimization. To alleviate this limitation, there are several aspects of wireless networks that can be addressed; channel spatial reuse, power management, and data rate selection. We direct our efforts to the data rate aspect allowing IEEE 802.11 wireless devices to adaptively tune their transmission rates to maximize network throughput.

Although IEEE 802.11 PHY specifications provide multi-rate capability, IEEE 802.11 standard (MAC) does not specify any mechanism to utilize this capability which leaves the implementation of rate selection mechanism to chipset vendors [1, 2]. Efficiency of a rate adaptation scheme depends on its adaptability to channel variations and its collision detection and handling mechanism.

Every 802.11 interface on the market should have a rate selection and fallback mechanism. Rate selection helps in upgrading the data rate when the link quality improves whereas a fallback scheme steps down the data rate in response to adverse channel conditions. Most existing rate adaptation algorithms depend on the sender to make rate selection decision based on its own perception of the channel quality. Other algorithms argue that the receiver is better placed in determining the appropriate data rate; thus they depend on the receiver to estimate the channel quality and to communicate this information back to the sender to select the appropriate data rate. There are advantages and disadvantages of using either of the above approaches solely, which mainly revolve around the information scope and the overhead of the mechanism.

In this thesis, we propose rate adaptation mechanisms that combines the sender's and the receiver's capability to determine appropriate data rate which improves overall network throughput.

1.2 IEEE 802.11 Wireless Networks

Wireless local area networks (WLANs) have become an integral part of the modern world since it provides a flexible and economical platform for short and mid-range communication. IEEE 802.11 working group has already developed a family of standards, illustrated in Figure 1.1, for wireless systems which operates in the 2.4GHz ISM band. Proliferating IEEE 802.11-compliant devices have made the WLAN technology the most dominant.

IEEE 802.11 wireless networks operate in two modes; *infrastructured* and *infrastructureless*; with the latter also referred to as *ad hoc* mode. In the infrastructured mode, stations within a group, known as *basic service set* (BSS), communicate directly with the access point. Then the access point forwards the messages to the desired destination within the same group or through the wired distribution system to another access point from which the messages arrive to their intended destination. In ad hoc networks, the stations operate in a peer to peer level with no access point

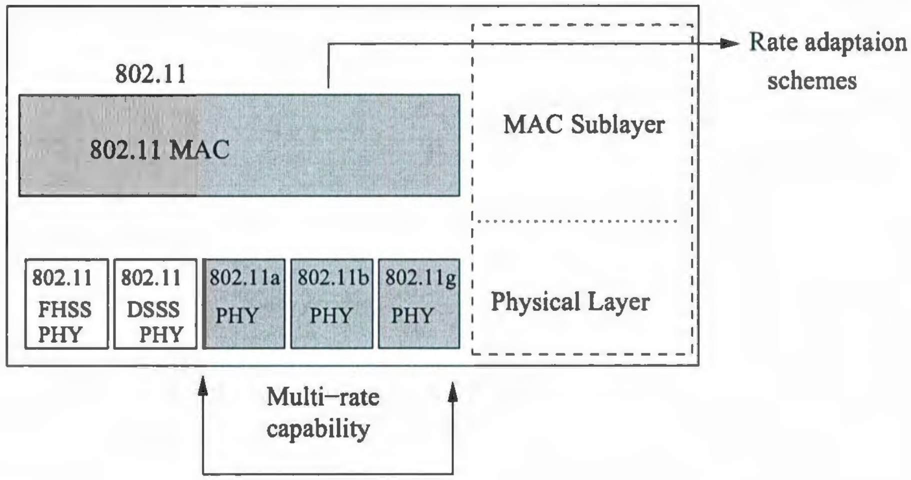

Figure 1.1: IEEE 802.11 family standards

or distribution system.

Wireless networks have fuzzier communication boundaries which poses a prominent challenge, the *hidden/exposed terminal* problem. A hidden terminal is a potential sender in the receiver's transmission range which cannot be detected by the sender but may disrupt the current transmission. An exposed terminal is a node which is prevented from sending to other nodes due to a transmitting node within its range [3]. We can illustrate this problem using Figure 1.2. To prevent interference, IEEE 802.11 allows nodes A and B to use Request-to-Send (RTS) and Clear-to-Send (CTS) frames respectively to notify other stations of their transmissions. Subsequently, exposed sender G will defer its transmission to node H upon receipt of sender A's RTS message. Similarly, hidden sender M will also defer its transmission to node N upon receipt of receiver B's CTS message. From this illustration, it is clear that RTS/CTS mechanism does not solve hidden/exposed receiver problem. Neither sender C nor E is aware of the on-going transmission between nodes A and B. Therefore, sender C's RTS message will collide with sender A's transmission at exposed receiver D, and hidden receiver F will not respond to sender E's RTS since its supposed to remain idle until the ongoing transmission is complete. Xu et al. [4] discusses the effectiveness of RTS/CTS mechanism in solving the hidden/exposed terminal problem. There are other mechanisms proposed in literature [5, 6] that attempt to solve the hidden/exposed terminal problem, however most of them only solves the hidden/exposed sender problem. Chen *et al.* attempts to solve the hidden/exposed receiver problem in [7]. Their work motivates part of our work that is discussed later in Chapter 4.

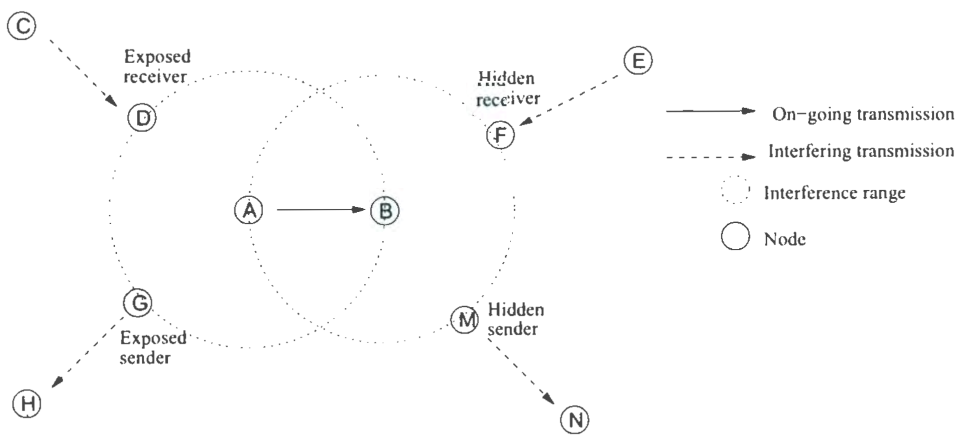

Figure 1.2: IEEE 802.11 hidden/exposed terminal problem

1.2.1 IEEE 802.11 MAC

Similar to the previous IEEE 802.3 standard (Ethernet), 802.11 uses a Carrier Sense Multiple Access (CSMA) scheme to control access to the transmission medium. However, rather than Collision Detection (CSMA/CD) mechanism employed by Ethernet, 802.11 uses Collision Avoidance (CSMA/CA) scheme to avoid wasting transmission capacity detecting collisions. This Ethernet-like CSMA/CA access is provided by the Distributed Coordination Function (DCF). The DCF is a mandatory contention-based channel access function with no centralized controller. There is also an optional polling-based Point Coordination Function (PCF) that offers contention-free medium access through *point coordinators*. In either case, all stations in the network are synchronized to time slots.

Stations sense the medium to determine its availability before any transmission. There are two types of carrier sensing functions, *physical carrier sensing* (PCS) and *virtual carrier sensing* (VCS). In PCS, if a station want to transmit, it first measures the energy in the medium. If the station detects that medium has been idle for more than a time interval called Distributed Inter Frame Space (DIFS), it proceeds with its transmission. Otherwise, the station waits until the channel becomes available, then it defers for an extra DIFS time. If the medium remains idle after the DIFS period, the station selects a random back-off time counter which it decrements while the medium is idle until it reaches zero when the frame is then transmitted. The value of the backoff counter is uniformly selected between 0 and the current Contention Window (CW) size. Interframe spacing coordinates access to the medium. IEEE 802.11 standard defines four different Inter Frame Spacing (IFS) intervals: Short IFS (SIFS), PCF IFS (PIFS), DCF IFS (DIFS), and Extended IFS (EIFS). Apart from EIFS which is used when there is an error in frame transmission, the other three interframe spacing intervals are used for medium access and are illustrated in Figure 1.3. MAC frames are usually protected against errors, caused by transmission errors or collision, by means of a Frame Check Sequence (FCS) field containing a 32-bit Cyclic Redundancy Check (CRC) and a simple send-and-wait Automatic Repeat Request (ARQ) mechanism. If the receiver detects a CRC error, the frame is dropped.

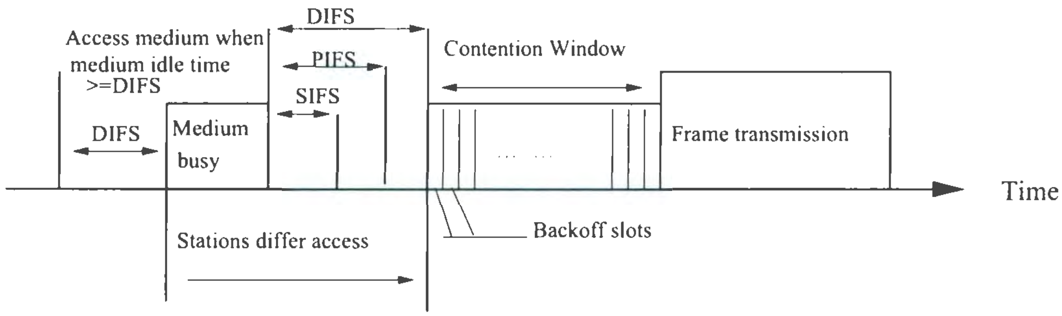

Figure 1.3: IEEE 802.11 interframe spacing

Otherwise the frame is deemed successful and the receiver sends an acknowledgement (ACK) frame back to the sender. The ACK is sent after a SIFS interval of reception. If an ACK is not received within an ACK timeout period the sender doubles its contention window and waits for another backoff period before retransmitting the DATA frame.

An optional VCS mechanism is defined by 802.11 MAC for reserving the medium using the RTS/CTS mechanism. RTS/CTS frames contain a duration field that defines the period of time that the medium is to be reserved to transmit the actual DATA frame and the returned ACK frame. As illustrated in Figure 1.4, all stations within the transmission range of the sender (which sends RTS) and receiver (that sends CTS) sets their Network Allocation Vector (NAV) when they learn of medium reservation. NAV maintains a prediction of how long the medium will be busy based on the duration value. A station should update its NAV upon reception of a new frame even if it is not addressed to it whose duration field has a value greater than its current NAV value. Since RTS/CTS frames increases network overhead, in practice this mechanism is usually turned off [1, 8].

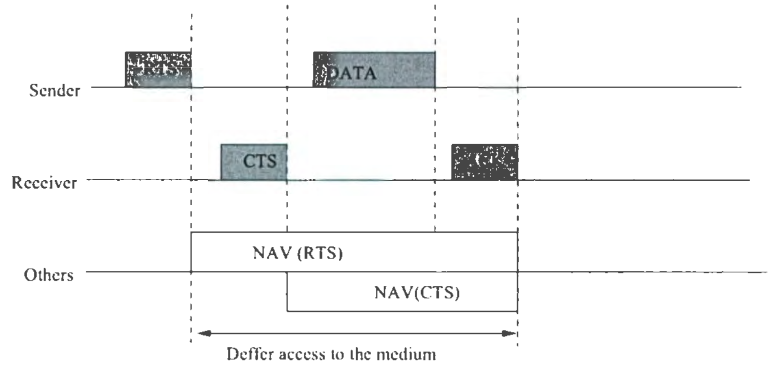

Figure 1.4: Setting NAV for VCS

1.2.2 Physical Layer

Physical layer (PHY) is the interface between the MAC layer and the wireless medium. It transmits and receives DATA frames over the shared wireless medium. The frame exchange between MAC and PHY is controlled by the Physical Layer Convergence Procedure (PLCP) sublayer. Employing different modulation and channel coding schemes enables the 802.11 PHY to provide multiple transmission rates.

The original 802.11 PHY specification was based on Direct Sequence Spread Spectrum (DSSS) with 1Mbps and 2Mbps data rates in the 2.4GHz ISM band. Later on, 802.11b PHY with additional rates of 5.5Mbps and 11Mbps was specified. The spread spectrum technique utilizes more bandwidth for transmission to reduce the impact of localized interference. Thus, DSSS spreads the signal into a larger band by multiplexing it with a signature inorder to minimize noise and interference. The PHY rates 1 and 2 Mbps are based on Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) modulations, respectively. To provide the higher PHY rates, 5.5 and 11 Mbps, IEEE 802.11b defines a Complementary Code Keying (CCK) modulation scheme. CCK is a variation on M-ary Orthogonal Keying Modulation that uses I/Q modulation architecture with complex symbol structures. 5.5Mbps is encoded using 4 bits per word while 11Mbps uses 8 bits per word. However, both rates use QPSK as modulation technique. The spreading maintains the same chipping rate and spectrum shapes as original 802.11 DSSS, hence they occupy the same channel bandwidth. 802.11a PHY was also standardized to utilize 5GHz spectrum and to provide higher data rates ($6 \sim 54$ Mbps). It is based on orthogonal frequency division multiplexing (OFDM), which breaks a wide-frequency channel into several subchannels that are used to transmit data. The slow subchannels can then be multiplexed into a fast channel. A good example of 802.11a chipsets manufacturer is *Atheros communications.* 802.11g PHY has also been standardized to utilize the higher data rates provided by 802.11b while retaining the backward capability. Therefore, 802.11g PHY supports all the twelve rates ($1 \sim 54$ Mbps).

Increasing data rate seems the right choice in maximizing network throughput or minimizing transmission delay. However, there are many factors in which a lower data rate may achieve better throughput. For example, if the distance between the sender and receiver is long, using higher data rates may lead to excessive number of retransmissions due to a lower Signal-to-Noise Ratio (SNR). That is, if the SNR perceived at the receiver is smaller than a minimum SNR threshold, then the transmission cannot be decoded correctly and its considered a failed transmission. There are also many other factors that influence propagation of radio transmissions. Walls tend to decrease and reflect signals, and background noise (thermal noise) creates interference making it difficult to demodulate signals. To overcome these obstacles, vendors define different ranges for their wireless devices. This include: *transmission power*, which is the strength of the emissions. *Sensitivity* is the measure of the weakest signal that can be reliably heard on the channel by the receiver. *Attenuation* is the decrease in the signal strength between the sender and receiver, which is the difference between the transmit power and the sensitivity value. Though increasing transmission power may overcome attenuation, it has its own drawbacks. For battery powered devices increasing transmission power may have a negative effect on energy conservation. In addition, it increases interference with other BSS and reduces *spatial reuse* which is the total number of concurrent transmissions that can be accommodated in a given BSS. When transmission power and pathloss model are fixed, *carrier sense range* can also be defined in wireless devices, which is the minimum distance between two concurrent transmitters. The smaller the carrier sense range, the better the spatial reuse but this increases the interference (hidden/exposed terminal problem) at the receiver. All these factors together with the data transmission rate play a crucial role in the overall performance of a WLAN. One challenge is to identify the optimal values that maximize the aggregate network throughput. There are various thoughts in literature [9, 10, 11, 12, 13, 14, 15, 16] that attempt to solve this challenge through tuning transmit power and carrier sense thresholds.

However, our focus will be how to utilize the PHY multirate capability, given the transmit power and carrier sense thresholds, to achieve desirable network throughput.

1.3 Network Simulation

Here we briefly introduce the simulation environment for our protocol testing. Section 1.3.1 introduces our Network Simulator (NS-2) and Section 1.3.2 the channel models that are incorporated in NS-2. Section 1.3.3 enumerates NS-2 channel thresholds that are tuned for different performances.

1.3.1 NS-2

We implement our work based on NS-2, an open source simulation tool and its wireless extension. NS-2 is an object oriented discrete event simulator written in C++ and OTcl which is an object oriented extension of Tcl from MIT. NS-2 is mostly used to simulate queuing, routing, and transport algorithms, congestion control and also some multicast related protocols in frame switched networks and wireless networks.

NS-2 protocol implementation consist of four steps: (a) Adding or modifying the existing C++ and OTcl code (b) Writing an OTcl script describing the topology, protocols and applications to be simulated, and the desired form of output (c) Running the simulation, by executing the OTcl script (d) Analyzing the trace files that are generated [17].

We extended NS-2.30 to include our multi-rate utilization to compare to some existing benchmark proposals.

1.3.2 Channel Models

NS-2 has implemented three propagation models so far; Two-Ray Ground, Free Space, and shadowing models [18] to predict the signal power received by the receiver. The signal strength determines if the transmitted frame is received successfully. Both Free Space and Two-Ray Ground are large scale path loss propagation models. They both describe the signal attenuation between a transmit and a receive antenna as a function of the propagation distance and other parameters, and represent communication range as an ideal circle. However, Free Space propagation model assumes that there is only one clear Line-of-Sight (LOS) path between the transmitter and receiver whereas Two-ray Ground argues that LOS is not the only means of propagation and considers both direct path and a ground reflection path. This makes Two-Ray Ground more accurate than Free Space propagation model. Shadowing propagation models are also large-scale but they also consider the effect that the received signal power fluctuates due to objects obstructing the path between transmitter and receiver [19, 18].

The signal at the receiver contains not only a direct LOS radio wave, but also a large number of reflected radio waves. Worst still, the LOS is often blocked by different obstacles both man made and natural. A delayed attenuated signal is received by a mobile antenna which adversely degrade the channel. If antenna moves, the channel varies with location and time because the relative phases of the reflected waves change which lead to fading. In a fading channel the received signal is variably weak with high Bit-Error-Rate (BER). A wireless channel must minimize the effects of multipath fading. Rayleigh fading model assumes a received multipath signal to consist of a large number of reflected waves with independent and identically distributed (discrete) inphase and quadrature amplitudes. This model seems to be more representative of a wireless channel which is characterized with fading. Rayleigh propagation model lack the effect of a dominant LOS component [19].

Ricean fading propagation model, assumes that the mobile antenna receives the signal by two different paths and at least one of the paths is changing. Ricean fading occurs when one path dominates the other (usually the Line-of-Sight (LOS)). This propagation model is more appropriate in small sized wireless networks where besides the dominant LOS component, the mobile antenna receives a large number of reflected and scattered waves (multipath fading) [19].

Punnoose *et al.* [20] modelled the effects of small scale fading (Rayleigh and Ricean) within the NS-2 simulator. They pre-compute a dataset, lookup table, containing the components of a time-sequenced fading envelope. This lookup table is used to model a wide range of parameters. The adjusted parameters include: time-averaged power (P), maximum Doppler frequency (f_m), and the Ricean factor (K). Nodes motion causes a Doppler shift in the frequency of the received signal, and the extent of the Doppler shift depends on the relative velocity of the sender and the receiver. f_m denotes the maximum Doppler frequency during the communication between the sender and receiver. The Ricean K factor is defined as the ratio of signal power in dominant component over the scattered, reflected power which is important in understanding the behavior of a short-range wireless channel. It determines the distribution of the received signal amplitude. When $K = 0$ represent Rayleigh distribution since there is no LOS component. For long simulations this dataset is reused for continuity.

1.3.3 NS-2 Thresholds

NS-2 uses thresholds to determine whether one frame is received correctly by the receiver. The carrier sense threshold (CSThresh_) is set to determine whether one frame is detected by the receiver. If the signal strength of the frame is less than the CSThresh_ the frame is not passed on to MAC but is discarded at the PHY. NS-2 also sets the RxThresh_ threshold which determines if the frame is received correctly or not. If the signal strength of the received frame is below the RxThresh_ it is marked as an error and passed on to the MAC where it is discarded. CPThresh_ determines if a frame is received correctly or not. If a node receives multiple frames simultaneously. it calculates the ratio of the strongest frame signal to the signal strength sum of all the other frames and compares it with the CPThresh_ threshold. If this ratio is larger than the CPThresh_ the frame is received correctly and all the other frames are discarded. Otherwise all the frames are said to have collided and are discarded [21, 22].

1.4 Thesis Organization

The rest of this thesis is organized as follows. Chapter 2 reviews rate adaptation protocols related to our work. We then provide a detailed description, implementation, and performance analysis of our light-weight Differential Rate Adaptation (DRA) protocol in Chapter 3. In Chapter 4, we modify DRA to incorporate Loss Differentiation (LD) mechanism, called Differential Rate Adaptation with Loss Differentiation (DRALD), and compare performance of DRA and DRALD. Chapter 5 incorporates negative acknowledgment (NAK) in DRALD to efficiently diagnose causes of frame loss. Last, we conclude our work in Chapter 6 and speculate on some possible future directions in rate adaptation in 802.11 based wireless networks.

Chapter 2

Related Work

Since 802.11 standard [23] and its PHY layer supplements [2, 24] do not specify any rate switching mechanism, it is up to the wireless devices vendors to come up with interfaces to accommodate the multirate capability. The ability to select one out of multiple available transmission rates at a given time is referred to as *rate adaptation* or *link adaptation*. Effectiveness of a rate adaptation scheme affects the overall performance of the network. Therefore, any rate adaptation scheme must have a mechanism to estimate the current channel conditions and a plan that adapts the data rate according to the channel estimation. Whenever multi-rate nodes co-exist in the same IEEE 802.11 network, the average throughput of the network is mainly determined by low-rate nodes instead of the high-rate ones. The low-rate nodes once they capture the channel, stay longer in data transmission than the high-rate nodes. Any rate selection mechanism should ensure channel access fairness by ensuring that all nodes are given the same channel access time. Some work in literature has tried to address this research topic over the years [25], and rate selection mechanisms proposed in this thesis allows each node to access the channel for time required to transmit a single DATA frame at basic data rate and in case of transmission failure, diagnose the cause before any retransmission to avoid channel access domination.

Existing rate adaptation mechanisms can be broadly categorized into two; *open loop* [8] and *closed loop* [26] approaches, depending on the scope of information used by the sender to make rate selection decision. In open loop approaches, the sender make decision based on its own perception of channel condition, such as success or failure of previous DATA transmission or the signal strength of a received ACK. Closed loop approaches depend on the receiver to estimate the channel quality and to communicate this information back to the sender to select the appropriate data rate. This two broad categories can further be classified according to the exact information used by the sender or receiver to estimate the channel quality. Section 2.1 summarizes these techniques used to estimate channel quality in the literature and Section 2.2 reviews some existing rate adaptation schemes that utilize these techniques.

2.1 Applicable Techniques

This section details design techniques that distinguishes existing rate adaptation schemes which include:-

- Transmission history
- PHY information
- RTS/CTS
- Frame burst

- Beacon frame
- Loss differentiation
- Fragment size adjustment
- Contention window control
- Negative acknowledgement

2.1.1 Transmission History

The most obvious way to obtain link level information is by maintaining statistics such as; the Frame Error Rate (FER), number of acknowledged frames, and the achieved throughput for the transmitted frames. Though statistic information guarantee throughput maximization, they have a limitation in that they classify the link quality as either good or bad. This classification provides good information in the direction to take (lowering or upgrading data rate) in rate selection but is not enough to select the actual data rate. This means that statistics-based approaches are slow to adapt to the actual channel changes and may even introduce oscillation in stable channel conditions.

2.1.2 PHY Information

These approaches estimate data rate by analyzing SNR or the signal strength (RSS) of a received DATA frame. They are said to be more adaptive since they offer direct measurements of the link conditions. SNR is directly related to BER and hence FER and therefore it's linked to frame delay, jitter and throughput. Knowledge of current

SNR and its associated throughput would solve the rate selection problem instantly, however most radio interfaces can only provide the Signal Strength Indicator (SSI). On the other hand, optimal rate and SNR is highly variable since the link depends on other factors as well and the sender can only estimate the SNR measurement at the receiver. This makes the SNR-based rate control algorithms uncommon in real life. 802.11h [27] supplement has defined means of communicating the SNR information to the sender, but this specification is not finalized yet.

2.1.3 Use of the RTS/CTS Mechanism

Beyond the basic use of RTS/CTS to alleviate the hidden terminal problem in wireless channels, RTS/CTS mechanism has also been used to assess channel quality and estimate the effective data rate. Though RTS/CTS is usually turned off due to its added overhead, IEEE 802.11 standard recommends its use when the DATA frame length is greater than the RTS threshold (2347 bytes). Some work [28] has also suggested the use of adaptive RTS filter, where RTS/CTS is only turned on after a number of frames are lost. This would prevent 'blind' rate fallback, where the data rate is decreased without distinguishing the actual cause of frame loss.

2.1.4 Frame Burst

These schemes take advantage of good channel quality when it lasts. This means that when a sender captures the medium, it holds it for the duration of time equivalent to the time (t) required to transmit a single frame at the lowest data rate. If the channel quality permits higher data rate than the lowest rate, then the sender can send as many frames as it can at this rate provided it does so within time (t). This prevents some stations from dominating the network by allowing all stations to have equivalent channel access time.

To reflect the dynamic channel conditions, an adaptive rate adaptation mechanism should also adjust its burst length (number of frames sent) to reflect current channel conditions. If channel quality improves during this period of time (t) and a higher data rate is adopted, then the number of remaining frames to be transmitted should also be adjusted. Similarly, if channel quality degrades within this period, the remaining frames to transmit should be decreased. For example, suppose the basic rate is 2Mbps and the initial channel assessments recommends a data rate of 5.5Mbps, which translates to a burst length of 3 DATA frames. If reception of the first DATA frame indicates improved channel quality and the sender adopts 11Mbps rate for the subsequent transmissions, the sender should also adjust the remaining burst length to 4 frames instead of 2. Similarly, if reception of first DATA frame indicates a degraded channel and 2Mbps data rate is adopted for subsequent frames, then the sender can only send 1 more frame instead of 2.

2.1.5 Beacon Frame

A beacon frame is periodically transmitted by an access point to allow mobile stations to find and identify a network. These frames are also used for various network maintenance tasks which may include rate estimation. Since periodic broadcast of a beacon frame is mandatory, it provides a good opportunity to estimate the most appropriate data rate without the overhead of RTS/CTS mechanism.

2.1.6 Loss Differentiation

Most rate adaptation protocols implicitly assume that the loss of a DATA frame is caused by bad channel conditions. Thus they usually fallback to a lower data rate upon DATA loss. However, in dense multi-hop wireless networks, DATA loss can also be caused by collision and DATA loss due to collision does not warrant data rate decrease. Infact, reducing data rate in such a case further degrades the network by increasing both the transmission and the collision time of DATA frame. This is mainly because a lower data rate is used for retransmission and the backoff period doubled, thus all the other nodes must backoff for this period of time before accessing the media again. Rate adaptation schemes that have this capability are said to be *loss differentiating*. A Loss Differentiation (LD) mechanism facilitate fallback mechanism of a rate adaptation protocol.

2.1.7 Fragment Size Adjustment

Long DATA frames (e.g. those that exceed RTS/CTS threshold) are usually fragmented to ensure successful transmission under certain channel conditions. The rationale behind frame fragmentation is that, in collision prone environment the probability of successful delivery of a shorter frame is much higher than that of long frame and in a degraded channel the probability of successful delivery of a shorter frame is not significant to that of longer frame. This inference is useful in distinguishing different causes of frame losses which offers good ground for an informed decision in their retransmission. Chen *et al.* [29] observed that tuning the frame size (through fragmentation) and the channel rate according to the observed interference patterns and noise level at the receiver substantially eliminates starvation in highly interfered networks.

2.1.8 Contention Window Control

Any 802.11 DCF sender will first monitor the channel for a DIFS time before transmission. If the channel is idle for DIFS without interruption the sender chooses a random number R uniformly from the interval (0, CW), and starts a backoff timer that expires after ($RaSlotTime$). CW refers to the current contention window size, and $aSlotTime$ is one slot time which is defined by the 802.11 PHY. The backoff timer will be paused whenever the channel becomes busy, and resumes after the channel has been idle for DIFS without interruption. The sender will then contend for the wireless channel using RTS/CTS when the backoff timer expires. Finally, when the sender gains access to the channel and sends out a DATA frame it waits for an acknowledgment (ACK) for a certain period of time referred to as *ACK timeout period.* If an ACK is not received within this period, the sender doubles its backoff window , an exercise known as *exponential backoff (EB)*, and waits for another backoff period before retransmitting the DATA frame. EB is a collision avoidance mechanism that exponentially increases the CW depending on the number of retransmission retries. An efficient loss differentiating mechanism should only double the backoff window if frame loss is due to collision but freeze the contention window if frame loss is due to link errors which greatly reduces the waiting time before DATA retransmission.

2.1.9 Negative Acknowledgement

A missed ACK frame infer a failed DATA transmission. In such an event the sender can only guess what triggered the frame loss, collision or link errors. Clearly, there is no mechanism for the sender to exactly tell what caused frame loss. Unless the receiver sends back a Negative Acknowledgement (NAK) control frame to the sender to indicate it did not receive the previous DATA frame. The rationale behind this is that, the MAC DATA frame can be partitioned into two functional parts: the header and the payload. The header contains the frame type, source and destination address. If multiple stations transmit at the same time, then both the MAC header and the body of the DATA frame will be destroyed. If there is frame loss due to link errors, then there is a chance that the receiver will receive the MAC header (since it's shorter) but the body will be corrupted. From the header, the receiver can gather the source address and send back a NAK frame indicating frame loss due to link errors. In such a case, the NAK is implemented the same way as an ACK frame the only difference being in the frame type field value, which can easily be adjusted by a single bit. Since NAK frame occupies the time reserved for the ACK frame, its implementation does not necessarily reduce the overall network throughput.

2.2 Existing Rate Adaptation Schemes

In this section we review rate adaptation schemes in each subcategory mentioned in Section 1.3.1.

2.2.1 ARF

Auto-Rate Fallback (ARF) [8], of WaveLAN-II was the first open loop rate adaptation protocol to be commercialized. ARF is a statistic-based rate adaptation scheme which consists of rate probing (rate selection) and a fallback mechanism. After consecutive and successful transmissions (usually 10 transmissions) at a certain data rate, the sender attempts to use a higher rate, if available, to transmit the subsequent DATA frames. Whenever a DATA transmission fails, the sender is allowed one default retransmission at the same rate. If the retransmission fails the sender falls back to the next available data rate to retransmit the DATA frame. If the retrial still fails, a further fallback may be necessary as long as a lower rate is still available. Various statistic-based [8, 28, 30, 31, 32, 33, 34, 35] rate adaptation algorithms have been proposed in literature

2.2.2 CARA

CARA [36] along with LD-ARF [37, 38] (Section 1.3.2.7) introduced LD to rate adaptation protocols. CARA uses RTS/CTS but it only activates it when a DATA frame is lost before its retransmission. If a CTS frame is received but the DATA frame is lost again, then the sender deduces that the frame loss is due to channel conditions and thus reduces the data rate. Else the frame is retransmitted at the same rate. After consecutive successful transmissions at a certain rate, the RTS/CTS is suppressed and a higher rate is probed. CARA also proposes the use of Clear Channel Assessment (CCA) to infer collision. After a DATA frame is transmitted, the sender listens to the channel by invoking the PHY CCA function. If channel is busy and the expected ACK is missing, then the loss is assumed to be caused by collision and the same rate is used for retransmission. Otherwise the loss was due to link errors and a lower data rate is used for retransmission. However, CCA is not easy to implement, its possible that the sender always senses the channel as busy (due to its own transmission) or may even fail to sense a busy medium especially if another sender transmits at the same time or when another transmission is much shorter than its own transmission. Hence, CCA loss inference may further degrade the network. Other rate adaptation schemes which have proposed LD mechanisms include [28, 39, 40, 41].

2.2.3 RBAR

RBAR [42] is a closed loop rate adaptation protocol that utilize PHY information to estimate data rate. RBAR turns on the RTS/CTS mechanism to aid in rate estimation. An RBAR sender always sends an RTS frame before transmitting the actual DATA frame. Upon receipt of an RTS frame, the receiver selects the data rate based on the signal strength of a received RTS and piggy-backs this rate information with the CTS frame. Turning on the RTS/CTS mechanism introduces extra overhead to the network. Pavon *et al.* [43] proposed an open loop protocol that utilizes the Receive Signal Strength Indicator (RSSI) measurements of the received ACK to estimate transmission rate without relying on the RTS/CTS mechanism. There are various other rate adaptation schemes that utilize PHY information to estimate data rate [26, 39, 40, 41], some of which will be discussed below.

2.2.4 OAR

Opportunistic Auto Rate (OAR) [26] was built on top of RBAR to exploit good channel quality through transmission of multiple back-to-back DATA frames. When an OAR sender captures the channel, it holds it for the period equivalent to time t required to transmit a single frame at the lowest data rate (basic rate). If the channel conditions allow for higher rate r than the basic rate, then sender can opportunistically send as many frames at rate r as it can within time t. OAR allow nodes with high channel quality to take advantage of it by transmitting more DATA frames than those with low channel quality while ensuring that all nodes are granted the same channel access time t. OAR improves RBAR significantly by allowing a burst of DATA frames to be preceded by a single RTS/CTS handshake, however it assumes constant channel conditions during the burst transmission time and may not respond to rapid channel changes. OAR has been extended in MAD [25], which is designed to improve throughput by allowing a sender to choose a neighbor that can receive a DATA frame at the highest data rate. Our proposed rate selection mechanisms also extend OAR capability to transmit multiple back-to-back DATA frames using a single RTS/CTS handshake, but also allows per frame rate adaptability when channel quality changes are drastic using an ACK/NAK frame RSS recordings.

2.2.5 LDRA

Saad *et al.* [41] recently proposed LDRA that utilizes the mandatory periodic IEEE 802.11 beacon instead of the optional RTS/CTS mechanism to estimate data rate. In LDRA the data rate is determined through measuring the RSS of occasionally received beacon. Upon frame loss the lowest data rate is used for retransmission. The argument is that if the receiver is still within the range of the sender, retransmission at the lowest rate would guarantee frame delivery in event of frame loss due to link errors. If no beacon is received within a certain interval and retransmission at the lowest rate is not successful then the sender infer the receiver is out of range and halts further transmissions. If transmission at lowest rate is not successful and a beacon has recently been received (within the interval) then the sender infer collision. Though this scheme seem to overcome the overhead introduced by RTS/CTS its accuracy highly depends on the beacon interval. The smaller the interval the more accurate this scheme would be, however beacon interval can be affected by nodes mobility among other factors. On the other hand, falling back to the lowest rate available is a pessimistic approach since retransmission at the next available lower data rate could have been successful as well.

2.2.6 OTLR

OTLR [40] is a recent version of OAR that does not require RTS/CTS frames to determine the initial transmission rate, but uses an intermediate data rate for initial transmission. If transmission at an intermediate rate fails, retransmission is done at the next lower rate. If retransmission at lower rate fails too, a lower rate is adopted for next retransmission and this continues until successful. The signal strength of a received ACK frame is used to assess the channel quality and determine the appropriate data rate. This scheme taps the advantages of an opportunistic rate adaptation scheme (transmits a burst of frames if data rate is higher than basic rate) and at the same time differentiate causes of lost frames and take appropriate action. To diagnose the cause of failed transmission, OTLR uses DATA fragmentation. The lost frame is fragmented into two unequal fragments; one short fragment of length *frag threshold* and the remaining fragment with the remaining data. The shorter fragment is transmitted at the current rate r and if its retransmission is successful then the DATA loss was due to collision, otherwise the loss was due to link errors. Probability of successful delivery for a shorter frame is higher in a collision prone environment than in a degraded channel. If frame loss is due to link errors OTLR lowers the data rate, freezes the contention window, and adjust the burst length. If frame loss is due to collision, the contention window is doubled and retransmission is done at the same rate. Though this scheme has been reported to perform better than OAR, incase of adverse channel conditions such that initial transmission cannot be successful at the intermediate rate, then this scheme ends up wasting the network bandwidth that it was trying to maximize by turning off RTS/CTS mechanism.

2.2.7 LDARF

Soung *et al.* proposed a Loss differentiating ARF (LD-ARF) in [37, 38]. After probing for higher data rate an LD-ARF sender may fallback to a lower rate if they guess that the DATA loss was caused by channel errors, otherwise they retransmit at the same rate. LD-ARF uses two LD methods depending on whether RTS/CTS is enabled or not. If RTS/CTS was enabled and CTS was successfully received but the ACK frame is missing, then the DATA loss is said to be caused by bad channel conditions, and a lower rate is used for retransmission. However, if CTS is missing then the DATA loss was due to collision and the same data rate should be used for retransmission. If RTS/CTS is disabled (usually disabled in IEEE 802.11 networks), a garbled DATA frame triggers the receiver to transmit a negative acknowledgement (NAK) if the MAC header of the DATA frame can be reconstructed correctly. The argument behind this is that even if the channel conditions were so bad that the DATA frame could not be decoded still the MAC header can be recovered since it's smaller in size. Using NAK control frame to infer bad channel conditions may also be misleading since it assumes that the a sent NAK frame will always be received. In event that the ACK/NAK frame is lost, LD-ARF would assume the DATA frame was lost, and the loss was due to collision which would lead to doubling of the contention window and retransmission at the same rate. This would further waste network bandwidth.

Table 2.1 summarizes design techniques of the rate adaptation schemes discussed in this section and those of our proposed schemes which will be discussed in the following chapters.

Table 2.1: Characteristics of the discussed rate adaptation schemes

Scheme	Open/ Closed loop	RTS/ CTS/	Stati- stic based	PHY Infor- mation	Burst Frames	Loss Differ- entiation	Beacon Frame	Negative Acknow- ledgement	Fragment Size Adjustment	Congestion Window Control
ARF	Open	No	Yes	No	No	No	No	No	No	No
LDRA	Open	No	No	Yes	No	Yes	Yes	No	No	Yes
LD-ARF	Open	Yes	Yes	No	No	Yes	No	Yes	No	No
CARA	Open	Yes	Yes	No	No	Yes	No	No	No	No
RBAR	Closed	Yes	No	Yes	No	No	No	No	No	No
OAR	Closed	Yes	No	Yes	Yes	No	No	No	No	No
OTLR	Open	No	No	Yes	Yes	Yes	No	No	Yes	Yes
DRA	Hybrid	Yes	No	Yes	Yes	No	No	No	No	No
DRALD	Hybrid	Yes	No	Yes	Yes	Yes	No	No	No	No
DRANLD	Hybrid	Yes	No	Yes	Yes	Yes	No	Yes	No	No

Chapter 3

Differential Rate Adaptation

Though the overhead of open loop rate adaptation approaches is small in terms of bandwidth consumed, their information scope is limited. Their constant attempt to transmit at higher data rate can degrade the network performance. Closed loop approaches are more responsive to channel changes. They tend to make more informed decisions since the receiver is usually better placed in determining the most appropriate data rate. However the cost of transferring information from the receiver to sender increases the overhead in protocol implementation.

In this Chapter, we propose an adaptive rate selection protocol that adjusts data rate and burst frames accordingly in event of rapid channel changes with a small overhead. Our protocol, Differential Rate Adaptation (DRA) which is based on OAR, takes advantage of good channel quality when they occur by transmitting multiple back-to-back DATA/ACK frames which are preceded by a single RTS/CTS exchange. Each ACK contains in its header a bit (0 or 1) to indicate to the sender if the next higher data rate is recommended or not based on the signal strength of the previously received DATA frame. If higher rate is recommended, the sender transmits the next frame at the next available rate and adjusts the remaining frames to transmit accordingly. Otherwise the same rate is used for subsequent transmissions. The rationale behind this per frame rate adaptation approach is to allow multiple back-to-back DATA frames to be preceded by a single RTS/CTS exchange and then adjust remaining frames to transmit based on most current channel quality. This is based on our assumption in this thesis that channel quality changes rapidly and as such data rate need to be adjusted accordingly. We show that DRA achieves a throughput gain of up to 25% compared to OAR.

3.1 Protocol Description

DRA [44] uses a single RTS/CTS frames exchange to precede a burst of DATA/ACK pairs. The RTS/CTS exchange is a closed loop design technique that is used by the receiver to provide the relevant information for rate selection, whereas the DATA frame transmission and rate probing are in line with open loop approaches. DRA probes for a higher data rate with an effective differential compensation, using a single bit in an ACK frame header, ensuring that the rate selection is in line with the current channel conditions. This is done without any extra overhead and with little modification to the IEEE 802.11 standard. The use of a single bit in the ACK header ensures rapid channel changes are captured during the burst length, whereas the RTS/CTS exchange captures the initial channel quality. This makes DRA more adaptive to the changes in channel quality previously estimated using RTS/CTS which becomes obsolete as the burst goes on. A schematic comparison between DRA

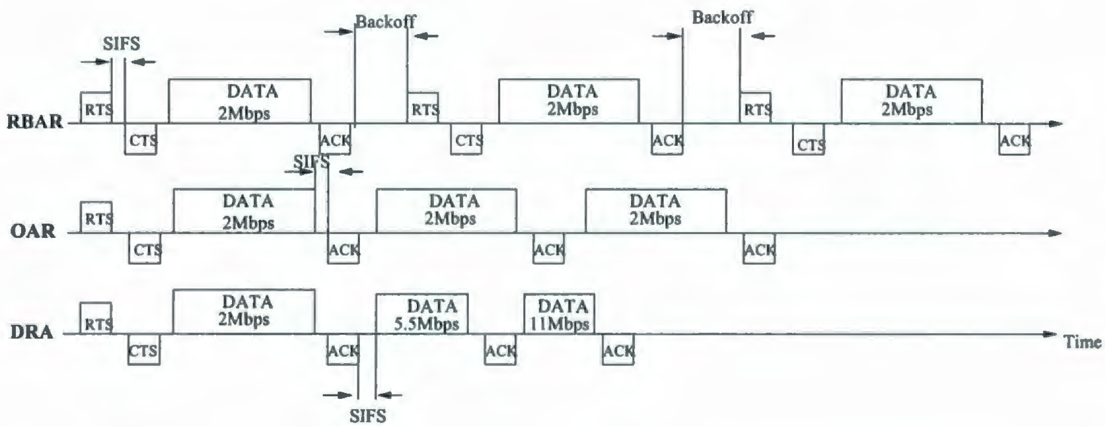

Figure 3.1: DRA design

with OAR and RBAR is show in Figure 3.1.

3.1.1 Data Rate Estimation and Feedback - Receiver's Story

DRA entrusts the receiver to communicate the channel quality information to the sender. Upon reception of the RTS or the DATA frame the receiver records the SNR (or the Signal Strength) of the received frame. Based on the recorded SNR, the receiver can select the supported data rate from a precomputed lookup table. The receiver then communicates this data rate in the CTS frame so that the sender can adopt this rate in the subsequent burst of DATA frame. When the sender receives the CTS together with the data rate information, it computes its burst length, which in our implementation is equivalent to the time required to transmit a single frame at the basic rate. Its possible that channel conditions changes during this burst length which could mean change in SNR and consequently supported data rate. DRA captures this channel changes by piggy-backing a single bit in the ACK from the receiver to indicate if the next higher data is feasible for the next DATA frame in the burst.

Similar to RBAR and OAR a DRA receiver needs to communicate the initial data rate back to the sender via a CTS frame. Since the CTS frame does not have a rate field we need to modify its MAC header "duration" field so as to carry the data rate and the size of the data frame. In the Specification the duration field is a standard 16-bit field of a data or control frame. The value is the amount of time needed before the subsequent ACK is received in milliseconds. This is used to set the NAV of a node that overhears the frame to accomplish the VCS. We change this field into two subfields, *rate* and *length*, of 4 and 12 bits, respectively as shown in Figure 3.2. The rate subfield is sufficient to address 16 different rates, to accommodate all the data rates for either the original 802.11, 802.11b, or 802.11a/g. The length subfield contains the size of the MSDU (actual frame) in bytes. The 12 bits in this subfield can accommodate a maximum 4096 bytes which is greater than the maximum body size of 2346 bytes. During construction of a CTS frame the receiver copies the length value from the incoming RTS frame in the CTS length subfield and puts in the data rate r_i in the rate subfield. To indicate if a higher data rate should be adopted for the

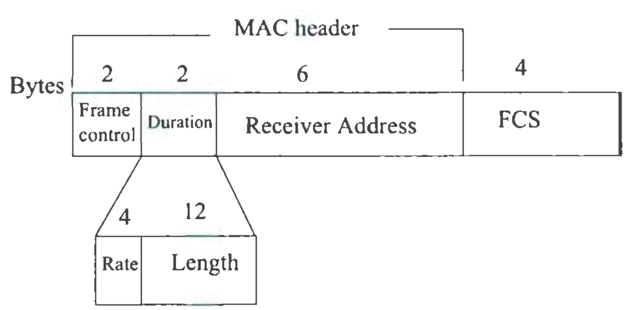

Figure 3.2: Format of a CTS frame in DRA

subsequent DATA frames, the receiver utilizes frame control field of the MAC header, as a *retry* flag, since it's redundant in an ACK frame as illustrated in Figure 3.3. If the measured SNR of a received DATA changes as the burst continues, then it's important for the sender to adopt to the rate that is supported by the new SNR. Upon reception of a DATA frame, the receiver compares the SNR of the moment to the current data rate, if this SNR supports a higher data rate the retry flag is set to 1, else it's set to 0.

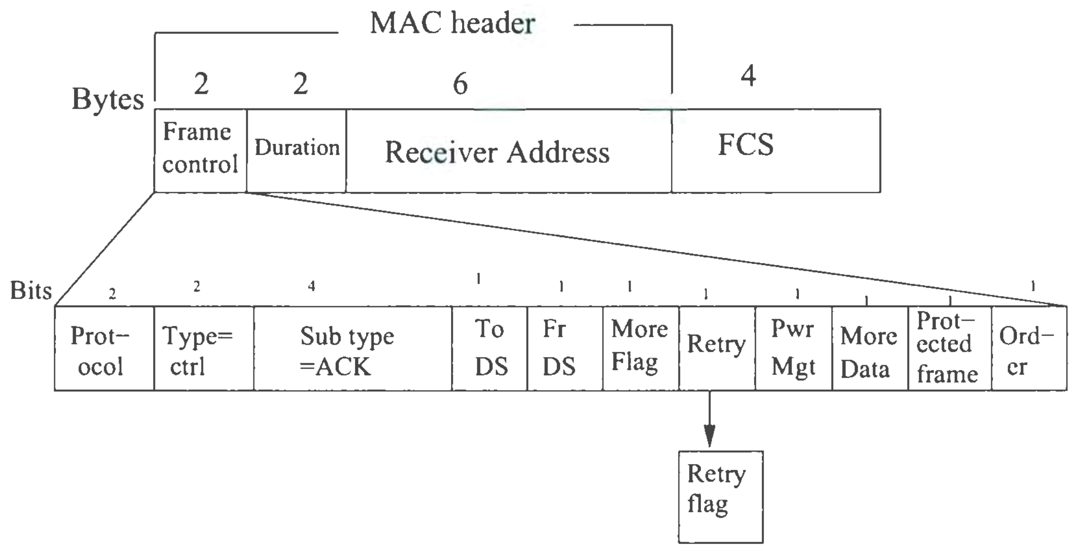

Figure 3.3: Format of an ACK frame in DRA

3.1.2 Rate Change -Sender's Story

To avoid collision, the sender contends for the channel before exchanging RTS/CTS with the receiver. Then, a burst of DATA/ACK pairs will be transmitted. The inter-frame space between each of these consecutive frames is SIFS so that the consecutive DATA transmission (burst) is not interrupted. This burst of DATA/ACK frames is responsible for adapting to the changing channel conditions and for retransmission of lost/garbled DATA frames. Figure 3.4 illustrates the state transition of a DRA sending agent. Usually, the initial data rate $R = r_i (1 \leq i \leq k)$ is determined by the value set in the "rate" field of the received CTS frame. The sender then constructs the DATA frame and transmits it at RMbps, and waits for an ACK frame which indicates if a higher data rate is recommended or not. If the ACK frame is not received, then the sender retransmits the same DATA frame at the current rate. If the received ACK frame recommends a higher data rate, i.e if the retry flag is equal to 1, R is set to $r_{\min\{k,i+1\}}$ which is the next available higher data rate. If the the retry flag is set to 0 or if there is not higher data rate available, then the next DATA frame is transmitted at the current rate R.

To utilize the good channel conditions when they last, DRA adjusts the temporal length of the burst to be considerably longer than needed to complete a single RTS/CTS/DATA/ACK at the basic rate. This new burst length is denoted by T_b. This means that, as long as the sender has more DATA frames (queue is non-empty), it keeps transmitting them after SIFS of receiving an ACK until the end of T_b. The challenge comes in choosing T_b which should ensure fairness in transmission. In DRA, we ensure that our choice of T_b satisfy that, during this time the channel condition at the receiver can be compensated by our rate adaptation mechanism. Thus, in our implementation we set $T_b = 50ms$) which is approximately the time to transmit slightly over two DATA frames of maximum size, 2346 bytes, at the basic rate 1Mbps. We verify this calculation using OAR calculation of T_b which is set at 20ms to accommodate one DATA frame at basic rate where coherence time is about 122.88 (24.57, 12.28, 6.14, resp)ms for a center frequency of 2.4GHz at mobile speed of 1 (5, 10, 20, resp.) m/s. After the T_b time is over and the sender has more frames to send

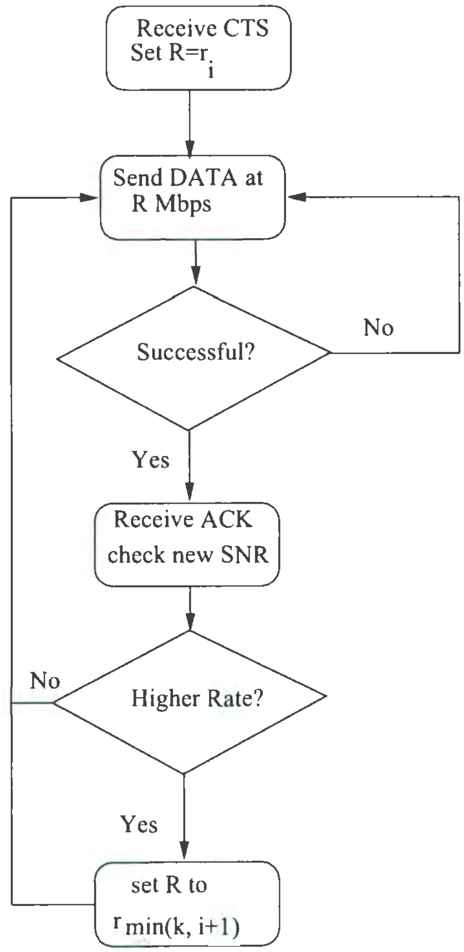

Figure 3.4: State transition of a DRA sender

then it must contend for the channel again.

3.1.3 Setting the Network Allocation Vector (NAV)- Other Nodes' Story

DRA embeds the duration information in each type of frame to avoid hidden terminal problem. All the other nodes must refrain from sending frames during this time. As noted earlier, DRA redefines its duration field into two subfields, the rate and the payload size subfields. The MAC and PHY layer headers are all transmitted at the basic rate. Thus, the only variables that determine the transmission time of a DATA frame are the data rate r_i and the size of the payload S, we then denote the time needed to transmit the PHY (RTS, CTS, DATA and ACK) header by $H_p(H_r, H_c, H_d,$ and H_a respectively. The NAV is then set as follows:

- On overhearing an RTS, the NAV should be set to $SIFS + H_p + H_c$ which is up to point A in Figure 3.5
- When overhearing the CTS the NAV should be reset to $SIFS + H_p + H_d + 8 \times \frac{S}{r_i}$, point B.
- On overhearing the DATA frame, other nodes should reset their NAV to $SIFS + H_p + H_a$, until point C.
- Finally on overhearing the ACK, the NAV should be reset to $SIFS + H_p + H_d + 8 \times \frac{S}{r_i}$, point D.

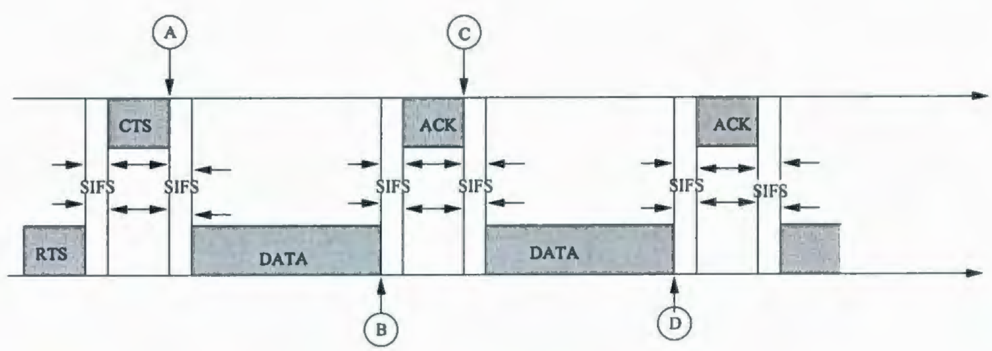

Figure 3.5: Setting the network allocation vector

3.1.4 Performance Evaluation

To evaluate the performance of DRA, we implemented it using NS-2. Our focus was to study the throughput gain of DRA in a highly dynamic channel with or without hidden terminals. We used a Ricean distribution model and its precomputed dataset to simulate a rapidly fading channel. To achieve this, we vary the value of Ricean K parameter to take values between 0 and 5 so as to achieve different levels of contribution of the line-of-sight component in the received signal. Since DRA is an extension of OAR, we compared these two protocols' performance in the same changing channel conditions. We initially set mobility speed to 2.5m/s with the receiver travelling to and from the transmitter as described in [42, 26], which is equivalent to setting the maximum Doppler frequency f_m to 30Hz. Our preliminary results showed that with this speed DRA offers slightly high throughput than OAR. This indicates that OAR succinct design is fairly effective for low to medium mobility rate whereas DRA's per-fragment rate adaptation achieves higher throughput even if the channel conditions are changing rapidly. We verified this using our experiments below, setting maximum nodes mobility to 25m/s and increasing the frame bursts to reduce control overhead.

3.1.4.1 Experiment Setup and Results

We tested DRA using two scenarios, with and without hidden terminals. In each scenario we set the burst length to 6ms and 50ms to find out the effect of longer burst lengths. Apparently, longer bursts alleviate RTS/CTS overhead but renders the data rate estimated by a received CTS obsolete. In our experiment we observe how DRA benefits from its adaptiveness to longer burst lengths. In our first scenario, we deploy two CBR flows (A to B and D to C) as shown in Figure 3.6(a). The distance between sender and receiver is set to 100m to ensures that data rate oscillates between 1Mbps and 11 Mbps (the four rates supported by 802.11b PHY). Since most of the nodes are within 100m radius, they can decode all the control frames (RTS, CTS, DATA and ACK) and the header of DATA frames and thus are fully connected. We start the

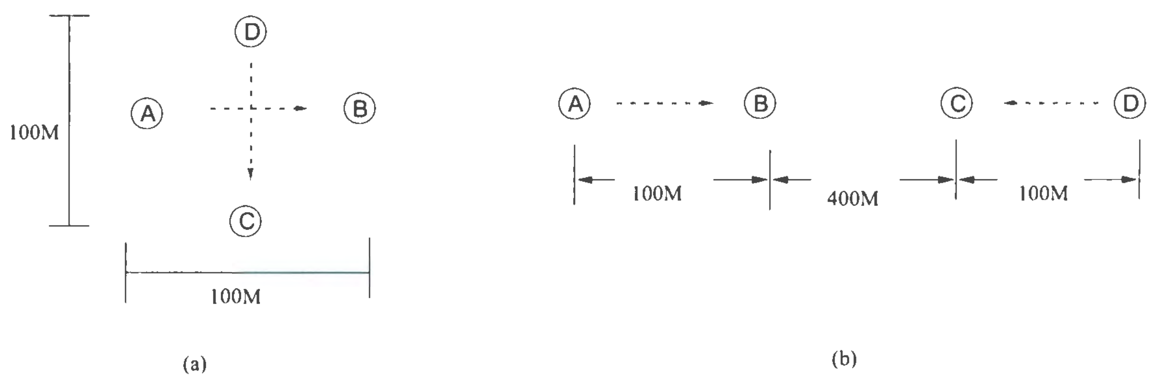

Figure 3.6: Experiment scenarios

two flows simultaneously for a duration of 50ms, repeating each experiment 10 times for each K ($K = 0$ to $K = 5$) value for the two burst lengths (6ms and 50ms). For every K value we plot the total throughput, which is the number of received frames within the simulation period, for each protocol burst length as shown in Figure 3.7. From the plot, we can see that throughput increases as line of sight becomes stronger (until $K = 5$, when it plateaus). We achieve an average throughput of 4% for a shorter burst length (6ms) and up to approximately 28% for longer burst length (50ms) since DRA's adaptiveness improves with longer burst. Figure 3.8 shows the DRA's throughput percentage gain for both shorter and longer burst lengths.

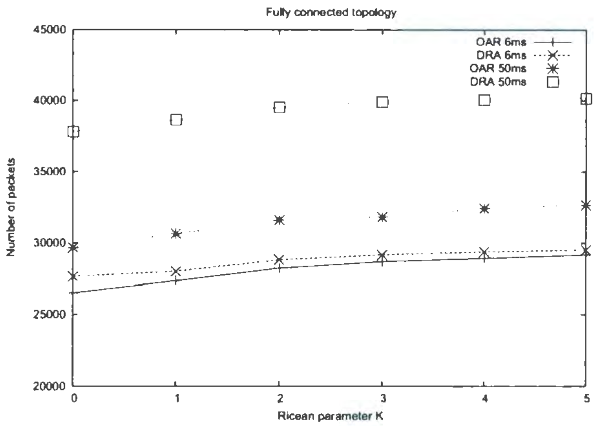

Figure 3.7: Fully connected topology

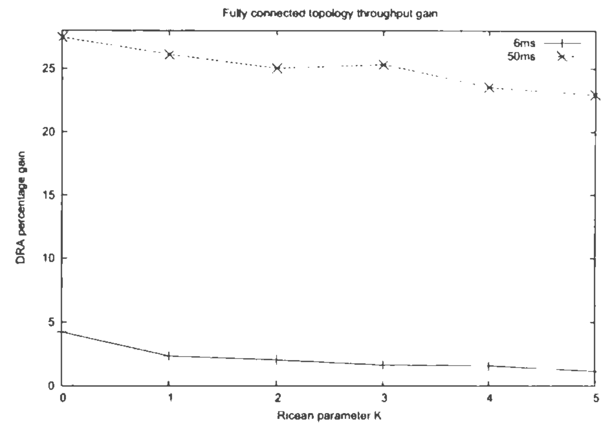

Figure 3.8: Connected flows throughput

In the second scenario, shown in Figure 3.6(b), we also deployed two CBR flows (A to B and D to C). However in this scenario, we separate these two flows fairly far away such that two receivers B and C are 400m apart and the senders A and D are 600m apart. As a result of the NS-2 default settings the two senders are hidden from each other but their receivers are still within the Carrier Sensing (CS) range of each other. Ideally in this case, the two flows should be effectively distant transmitter, there will not be a 100% parallelism. The results from this scenario are plotted in Figure 3.9. The results indicate that the effect of hidden flows is minimized and throughput is nearly doubled. The 6ms burst length achieves an average throughput gain of up to 3% and 50ms up to ≈28%. Figure 3.10 summarizes DRA's throughput percentage gain for both shorter and longer burst lengths in a scenario with hidden flows.

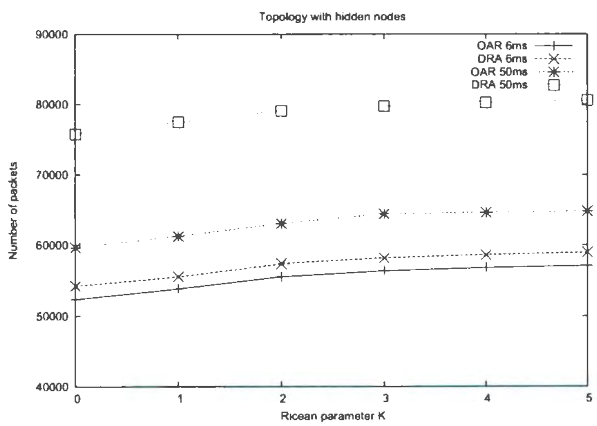

Figure 3.9: Hidden flows

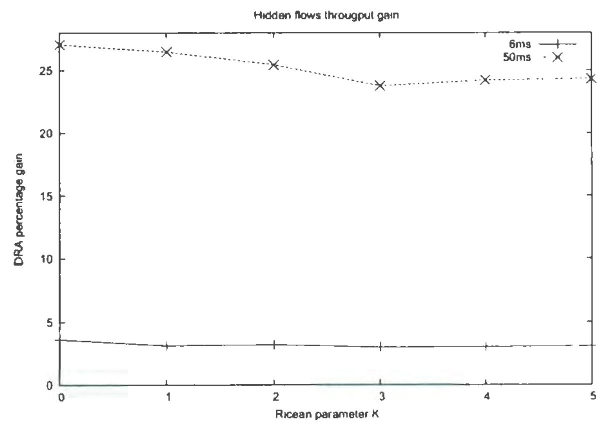

Figure 3.10: Hidden flows throughput gain

Chapter 4

Differential Rate Adaptation with Loss Differentiation

The aim of an efficient rate adaptation scheme should be to improve channel performance through selection of optimal data rates that suits current channel conditions. OAR and DRA assumes gradual changes in channel conditions and fails to factor in subsequent frame losses caused by rapidly deteriorating channel quality and collision due to multiple transmitters. These schemes (OAR and DRA), incorporates neither a fallback mechanism nor a loss differentiation mechanism in their designs.

However, WLANs are dynamic in nature which makes it difficult to estimate channel coherence time. It is therefore misleading to assume that all transmitted frames will be successfully acknowledged. If a rate adaptation scheme incorporates neither a fallback nor Loss Differentiation (LD) mechanism then a sender can only keep retransmitting unacknowledged frame until it is successfully acknowledged or its allowed retry limit is exhausted. This wastes network bandwidth.

A mere fallback to a lower data rate upon transmission failure assumes frame loss is due to link errors. However, when a WLAN has a number of active stations frequent collision is possible, which negates such an assumption. On the other hand, opportunistic transmission of back-to-back frames (as is the case in OAR and DRA) not only increases throughput but also collision probability. When losses are due to collision, reducing data rate certainly reduces throughput since DATA frame transmission and collision time are both escalated. Thus, an LD mechanism enables the sender to diagnose cause of frame loss and make an informed decision on retransmission rate.

In this Chapter we incorporate a simple but powerful RSS-based LD mechanism into DRA to form Differential Rate Adaptation with Loss Differentiation (DRALD) scheme. Our LD mechanism is motivated by the observation in [7, 4], that the Receive Signal Strength (RSS) at the sender and receiver are strongly correlated. This means that a sender can use its RSS measurements to make channel quality judgement at the receiver. In DRALD, a sender differentiates frame losses caused by deteriorating channel quality to those caused by collision by storing CTS/ACK's RSS value. Based on this value the sender can then decide the appropriate retransmission rate.

We first discuss DRALD design details in Section 1, then compare its performance to its predecessors (OAR and DRA) in Section 2 below.

4.1 Loss Differentiation Mechanism

Our LD mechanism, dubbed DRALD, incorporates two issues in its design.

1. **Loss diagnoses**. Distinguishing causes of frame loss and assessment of channel conditions to recover from the loss.

2. **Loss recovery**. Adjusting both data rate and remaining frames to transmit depending on the diagnosis.

Note that DRALD initial rate estimation and upgrading aspect is carried out as in DRA and its LD mechanism is only effective upon frame loss.

4.1.1 Frame Loss Diagnosis

A DRALD sender stores two variables that helps to distinguish the cause of a lost DATA frame.

- RSS measurement (RSS_{value}), of a previously received CTS or ACK frame and
- a boolean value (*isdeteriorating*) that checks if the channel quality is deteriorating or not.

Different data rates are supported by different RSS thresholds (RSS_{thresh}). Therefore, like OAR and DRA, each node should store a lookup table that maps different RSS thresholds to available data rates. Every time the sender receives a CTS or ACK frame it records the RSS_{value} of the moment and updates *isdeteriorating* variable. The sender adapts the retransmission rate depending on RSS_{value} and is *isdeteriorating* value. Changes in the recorded RSS value indicates conditions in the wireless link between sender and receiver are changing and it might be necessary to adapt transmission rate (R) accordingly. Hence, *isdeteriorating* variable indicates when these conditions are deemed as deteriorating.

If RSS_{value} is lower than the RSS_{thresh} for the current data rate R, or if it is lower than the previously recorded RSS value, *isdeteriorating* is set to *true*.

Otherwise it is $false$. Upon an ACK frame timeout, the sender checks recorded RSS_{value} and $isdeteriorating$ value. If RSS_{value} is lower than RSS_{thresh} or/and $isdeteriorating == true$, the sender concludes that the wireless link has deteriorated and sets R to $r_{max\{1,r-1\}}$, which is the next available lower data rate. Otherwise, the sender concludes the loss is due to collision and a retransmission is done at the current data rate R. DRALD's LD mechanism can be illustrated by the flowchart in Figure 4.1.

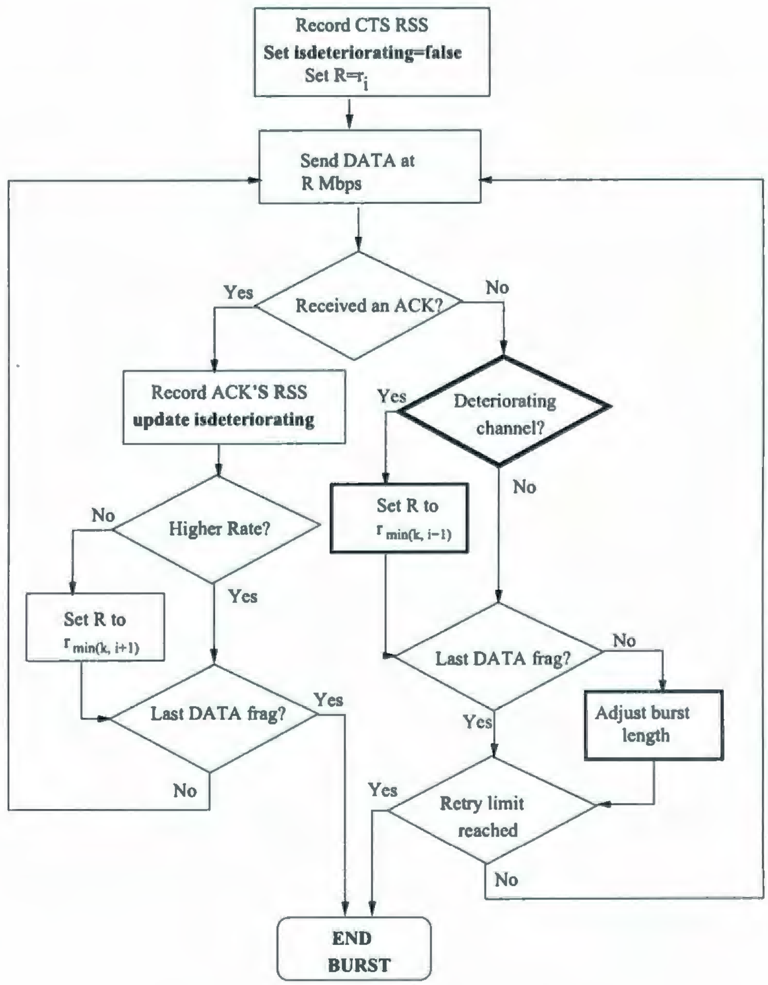

Figure 4.1: DRALD design

The *isdeteriorating* value enables the sender to keep track of channel fluctuations even if the changes may not be large enough to warrant a lower data rate. In event of a lost DATA frame the sender combines this information with the previously recorded RSS value to determine if a lower data rate should be used. This rarefy the disadvantage of using outdated RSS information to distinguish cause of frame loss which may be misleading in selection of the retransmission rate.

4.1.2 Loss Recovery

Once a DRALD sender has diagnosed the cause of a lost DATA frame, then it must not only adjust the data rate accordingly but also the number of remaining frames to transmit. We propose two reactions upon different frame loss diagnoses that ensure network performance is improved.

- **Frame loss due to link errors:** If frame loss due to channel fading occurs before transmission of the last frame in the burst length, the sender lowers its retransmission rate and adjusts its remaining frames to transmit accordingly. For example, if the sender was initially allowed to send 3 DATA frames at 5.5Mbps, the sender can only send one more frame at 2Mbps. This ensures that a sender with bad channel quality does not dominate the network with its retransmissions and gives network access to nodes with better channel quality.

- **Frame loss due to collision:** If frame loss is due to collision, retransmission should be done at the same rate since a lower data rate does not alleviate collision. Infact, lowering data rate in such a case could further degrade the network by increasing both transmission and collision time of the DATA frame.

4.2 Performance Evaluation

This section evaluates the effectiveness of incorporating loss differentiation into DRA. Section 4.2.1 details our experiment setup and Section 4.2.2 discusses the results.

4.2.1 Simulation Setup

Similar to DRA, DRALD is simulated with 802.11b (with data rates 11Mbps, 5.5Mbps, 2Mbps) using NS-2. All experiments are carried out on a fast fading channel that follows Ricean distribution. The Ricean Parameter K is varied between 0, which represents a more fluctuating channel with no Line-of-Sight (LOS), and 5, which depicts a more stable channel. We conduct experiments in two UDP traffic scenarios, whose topologies are similar to the hidden flows topology in Chapter 3 Figure 3.6 (b), but we vary nodes' mobility speed and distance between the flows. This enables us to investigate the effects of multiple transmitters and rapidly fading channel

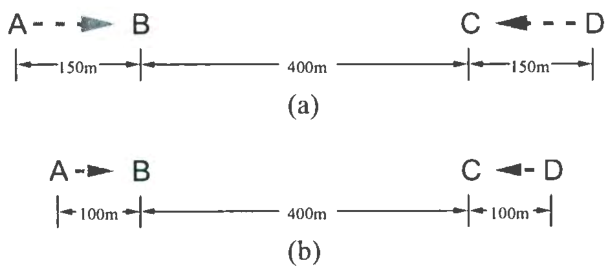

Figure 4.2: Simulation topologies

Scenario 1: slow changing channel conditions. In the first scenario, shown in Figure 4.2(a), we set maximum nodes' mobility speed to $2.5m/s$ and distance between each flow to $150m$. These settings ensures a more stable channel with data rate fluctuating between 2Mbps and 5.5Mbps.

Scenario 2: rapidly changing channel conditions. The second scenario, shown in Figure 4.2(b) assumes rapid fluctuations in channel quality, by setting nodes' mobility speed to $15m/s$. The distance between each flow is set to $100m$ such that the data rates fluctuates between all the three rates (11Mbps, 5.5Mbps, 2Mbps).

The simulation time for both scenarios is 50 seconds and the simulation repeated 10 times for each value of K. The aggregate number of received frames for each value of K is plotted for the three protocols. Results obtained from the two scenarios verifies our earlier findings that DRA performs better than OAR when the channel fluctuates more rapidly and performs similar to OAR in low or medium mobility rate. Additionally, we observe that in both cases DRALD benefits from its capability to adjust its transmission rate and frame burst.

4.2.2 Results Analysis

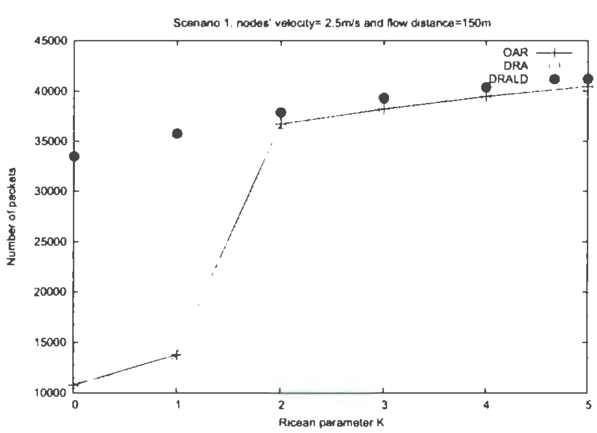

Figure 4.3: Hidden flows each 150m apart

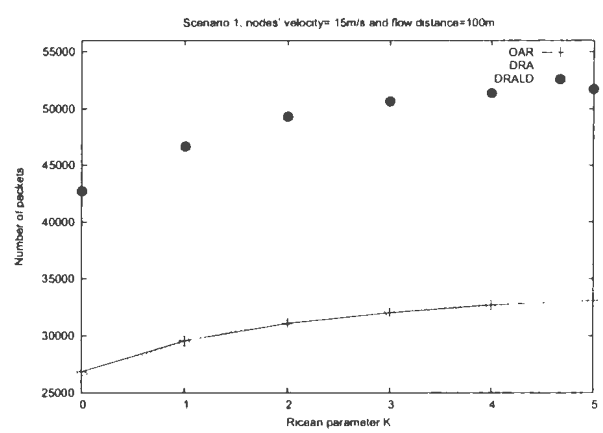

Figure 4.4: Hidden flows each 100m apart

We plot the cumulative frames received in each scenario for each protocol (OAR, DRA and DRALD) for all the values of K and present the results in Figures 4.3 and 4.4. We observe that all the three protocols perform better with stronger LOS signals (greater K values). In both scenarios DRALD is able to transport more data than DRA and OAR. The gain is more significant with small K and high mobility (Figure 4.3). To further find out the cause of this gain, we investigate the number of packets that nodes B and C receive over the simulation time and plot them as time series for $150m$, $2.5m/s$ and $K = 0$, 1 in Figures 4.5, 4.6 4.7, and 4.8. The following sections discuss our findings in details.

4.2.2.1 Scenario 1: 150M Apart

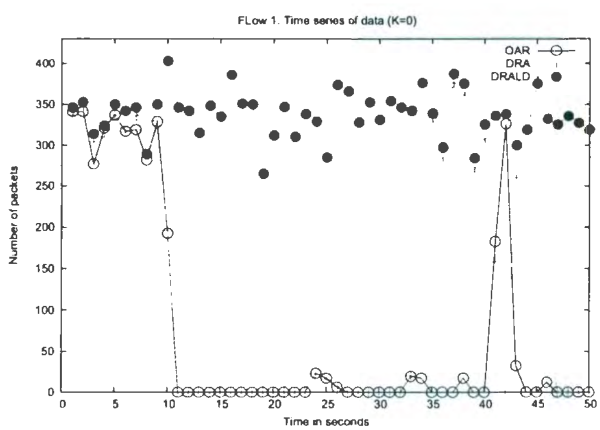

Figure 4.5: Flow1 time series of data for $K = 0$

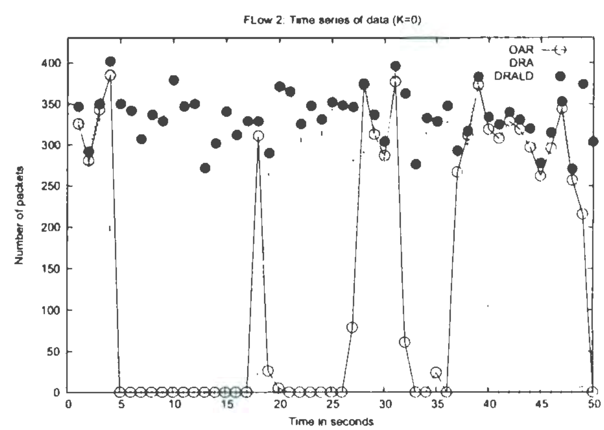

Figure 4.6: Flow2 time series of data for $K = 0$

From Figures 4.5 and 4.6 OAR and DRA, records a significant drop in cumulative frames received between $10 - 35$ and $5 - 15$ seconds in each flow respectively. Most of the transmitted DATA frames are lost due to the rapidly fading channel and both

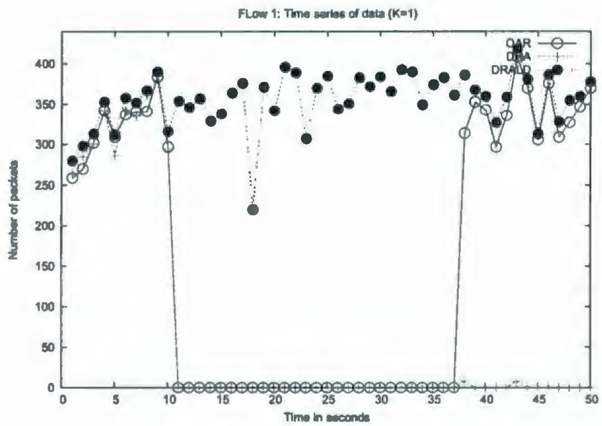

Figure 4.7: Flow1 time series of data for $K = 1$

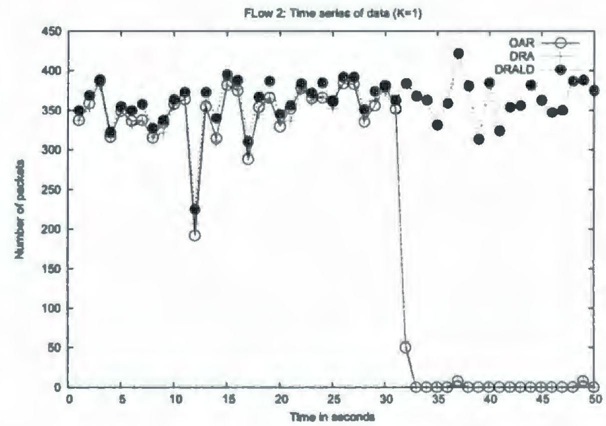

Figure 4.8: Flow2 time series of data for $K = 1$

OAR and DRA are not able to respond with appropriate data rate. Between $30 - 50$ and $25 - 50$ in Figures 4.5 and 4.6 respectively, DRALD and DRA senders benefit from the improved channel quality by increasing both data rate and burst length compared to OAR which records improved performance for just a short period of time due to its shorter burst length.

In Figures 4.7 and 4.8, for $K = 1$, DRA performs slightly worse than OAR between $35 - 50$ seconds. Rapid channel fluctuations oftenly occur for $K = 1$. As such, if the channel quality improves rapidly, DRA is triggered to adjust both data rate and burst length. When the channel fades, after 10 seconds, then DRA performs poorly for the rest of the simulation time since increasing burst length means ensuring that all the transmitted frames are successfully acknowledged. In event of lost DATA frame(s), a DRA sender holds on to the channel until retransmission is successful, or the allowed retransmissions for all the remaining frames in the burst are exhausted. During this period, OAR which assumes certain channel coherence time, outperforms DRA for its shorter burst lengths. DRALD recovers from frame losses (caused by either collision or fading channel) by adjusting both data rate and remaining frames to transmit to match the current channel quality. Therefore, DRALD records steady performance growth even for $K = 0$ or $K = 1$.

4.2.2.2 Scenario 2: 100M Apart

Figure 4.4 represents the performance of the three protocols when distance between each flow is set to $100m$ and $maxVelocity$ is set to $15m/s$. Since nodes' mobility changes the channel coherence time [26], setting the nodes speed to $15m/s$ means that the channel quality fluctuates rapidly than when $maxVelocity = 2.5m/s$. On the other hand, the set distance between each flow ($100m$) strengthens the received signals which fluctuates the data rate between $2Mbps$, $5.5Mbps$, and $11Mbps$. DRA and DRALD benefit from these settings since they have capability to increase data rate and hence the burst length when the channel quality is good. In event of a fading channel, DRALD outperforms both DRA and DRALD through its LD mechanism that ensures successful retransmission by lowering data rate.

Chapter 5

Negative-Acknowledgement-Aided Loss Differentiation

Chapter 4 incorporated an LD mechanism (DRALD) in DRA [44] that records received CTS/ACK RSS value to differentiate causes of frame losses. We showed that DRALD outperforms DRA and consequently OAR. In this chapter, we propose a more efficient LD mechanism, dubbed Differential Rate Adaptation with NAK-Assisted Loss Differentiation (DRANLD), that combines DRALD's LD mechanism and Negative Acknowledgement (NAK) control frame to yield a more efficient LD mechanism. Introducing NAK as an LD mechanism in DRANLD not only provides means for the receiver to communicate its channel quality perception to the sender but also alleviates the possibility of using outdated CTS/ACK's RSS value to infer link errors or collision.

The remaining sections of this Chapter are organized as follows; first we discuss how NAK frame can assist in rate estimation in Section 5.1, then we discuss how we incorporated NAK in our rate adaptation scheme for effective loss differentiation in Section 5.2. Section 5.3 evaluates performance improvement due to our NAK-assisted loss differentiation, DRANLD.

5.1 Negative Acknowledgment and Loss Differentiation

Constructing NAK control frame to aid in loss differentiation was introduced in [37, 38] but implementation and exploration of this idea has remained fallow. This work assumes that the DATA frame can be partitioned into two functional parts namely; the header and the payload. The header part contains the frame type, source and destination address to distinguish the DATA frame and the payload contains the data. The structure of a NAK frame is similar to that of an ACK and its transmitted at the same data rate. Therefore, introduction of a NAK frame causes minimal overhead since its transmission time is similar to that occupied by an ACK frame.

In event of frame loss due to collision, both the header and the payload are usually corrupted. That is, the receiver does not decode any part of the DATA frame. However, if frame loss is due to link errors, then the receiver is likely to receive the header correctly since the header is much shorter than the payload. In such a case, the receiver checks from the header the sender and recipient address and sends back a NAK frame signifying it could not decode the DATA frame. Reception of a NAK frame indicates link errors at the receiver and DATA retransmission should be at a lower rate. On the other hand, failure to receive an ACK nor NAK frame implies there were multiple senders and the frame was lost due to collision. Table 5.1 summarizes the use of NAK to differentiate causes of frame loss.

Table 5.1: Loss differentiation using NAK

	Both header and Payload decodable?	send ACK/NAK?	Transmission successful?
Receiver	Yes	ACK	Yes
	Header decodable	NAK	No
	No	None	No
	Received ACK?	Received NAK?	Diagnosis
Sender	Yes	No	Successful
	No	Yes	Link errors
	No	No	Collision

Use of only NAK frame to diagnose frame losses assumes it will always be received by the sender. However, such an assumption is misleading since there is a possibility for a NAK frame to be lost as well. In such a case, the sender receives neither an ACK nor NAK frame. Ultimately, the sender concludes the DATA frame was lost and the loss was due to collision. Table 5.2 summarizes the possible outcomes whenever a sender sends out a DATA frame. The last two entries in the table can wrongly be diagnosed if NAK control frame is solely used as a loss differentiating mechanism.

Therefore, we propose per frame rate adaptation mechanism that uses NAK frame and the recorded CTS/ACK's RSS value to effectively diagnose frame loss causes. We adopt this per frame approach to ensure quick adaptation in a rapidly changing

Table 5.2: Possible outcomes when a DATA frame is sent

Both header and Payload decodable?	send ACK ACK/NAK	Receive ACK/NAK
Yes	ACK	ACK
Header decodable	NAK	NAK
No	None	None
Yes	ACK	None
Header decodable	NAK	None

channel quality. Otherwise, time window information based rate adaptation may be more robust where the channel quality does not change too rapidly.

5.2 DRANLD Design

To effectively diagnose frame loss causes;

- DRANLD sender probes the receiver to send back a NAK control frame to signify frame loss due to link errors.
- Similar to DRALD, records RSS value of received CTS/ACK frame to assess link quality between sender and receiver

If a NAK frame is received then the sender can easily infer DATA loss was due to link errors. Similarly, if neither ACK nor NAK frame is received and the recorded RSS value shows deteriorating channel quality, then the loss is due to link errors. Only when neither ACK nor NAK is received and the channel quality has not been deteriorating does the sender infer frame loss due to collision.

5.2.1 DRANLD Receiving Side

In DRANLD the structure of the NAK frame is similar to that of an ACK (and other controls frames). The only difference is that of the frame type field which must have a one-bit difference to that of ACK. Since RTS frame type field is set 1011, CTS to 1100 and that of an ACK to 1101, we suggest that the frame type field of a NAK frame be set to 1110 (as shown in Figure 5.1). IEEE 802.11 specifies an Extended Inter-Frame Space (EIFS) that any receiving station receiving erroneous frame must wait before its backoff timer starts to count down. EIFS includes SIFS, ACK and DIFS. However, since NAK occupies the same time as an ACK, its duration field can similarly be set as that of an ACK frame. That is, the DURATION field of NAK is set to $SIFS + T_{frag} + SIFS + T_{ACK} + SIFS$.

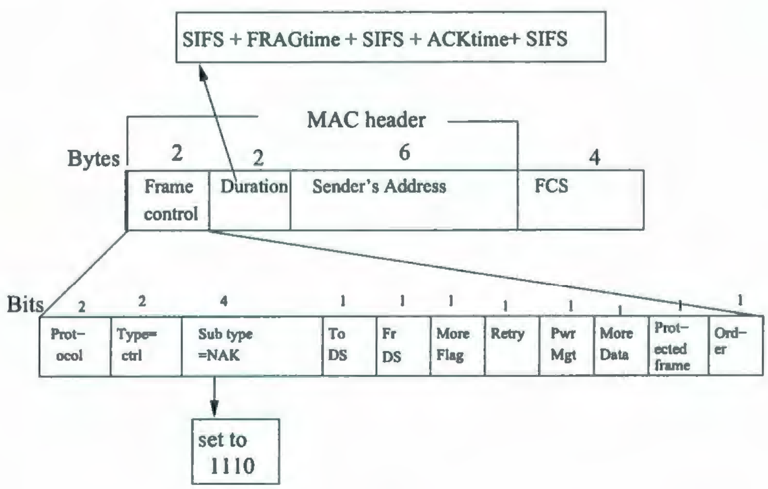

Figure 5.1: Format of an NAK frame in DRANLD

Its not obvious that in case of erroneous DATA frame, the receiver captures the address details of the transmitter. A station that sends out a DATA frame should remain in *promiscuous mode* waiting for an ACK from its intended receiver. If the receiver is not able to decode the header for sender's address, then receiver's address field of the constructed NAK frame should be replaced with its own address (sender's address) so that a node in promiscuous mode can know it is the intended recipient of the NAK frame. A node in promiscuous mode would have to listen to all the frames sent on the network rather than just the frames addressed to it.

5.2.2 DRANLD Sending Side

When the sender sends out a DATA frame it awaits acknowledgment from the receiver. Similar to DRA (discussed in Chapter 3), if an ACK frame is received, the sender checks if the retry bit (known to us as *higher rate bit*) recommendeds a higher rate or not for subsequent transmissions. DRANLD then adjusts the data rate and the remaining frames to transmit accordingly. Additionally, DRANLD also records the RSS value (defined in Chapter 4 as RSS_{value}) of the moment and updates the $isdeteriorating$ variable.

In event of a lost DATA frame and the sender receives a NAK frame from the receiver, the receiver easily infers frame loss due to link errors, sets data rate R to $r_{max\{1,r-1\}}$, which is the next available lower rate, and retransmits the same DATA frame.

However, if the sender receives neither an ACK nor NAK frame it diagnose the loss using sender's channel assessment information (similar to DRALD). If the channel quality has been deemed as deteriorating (i.e $isdeteriorating == true$), and/or the previously received CTS/ACK RSS value does not support the current data rate

$(RSS_{value} < RSS_{thresh})$, then the sender assumes the loss was due to link errors and sets R to the next available lower rate $r_{max\{1,r-1\}}$ to retransmits the same DATA frame. When a lower rate is adopted for retransmission, then the burst length should also be adjusted accordingly so that the sender does not dominate the medium. Otherwise, if $(RSS_{value} >= RSS_{thresh})$ and $isdeteriorating == false$ then the sender infers collision and retransmits at the current data rate R.

Figure 5.2 summarizes the loss recovery strategy for a DRANLD sending agent.

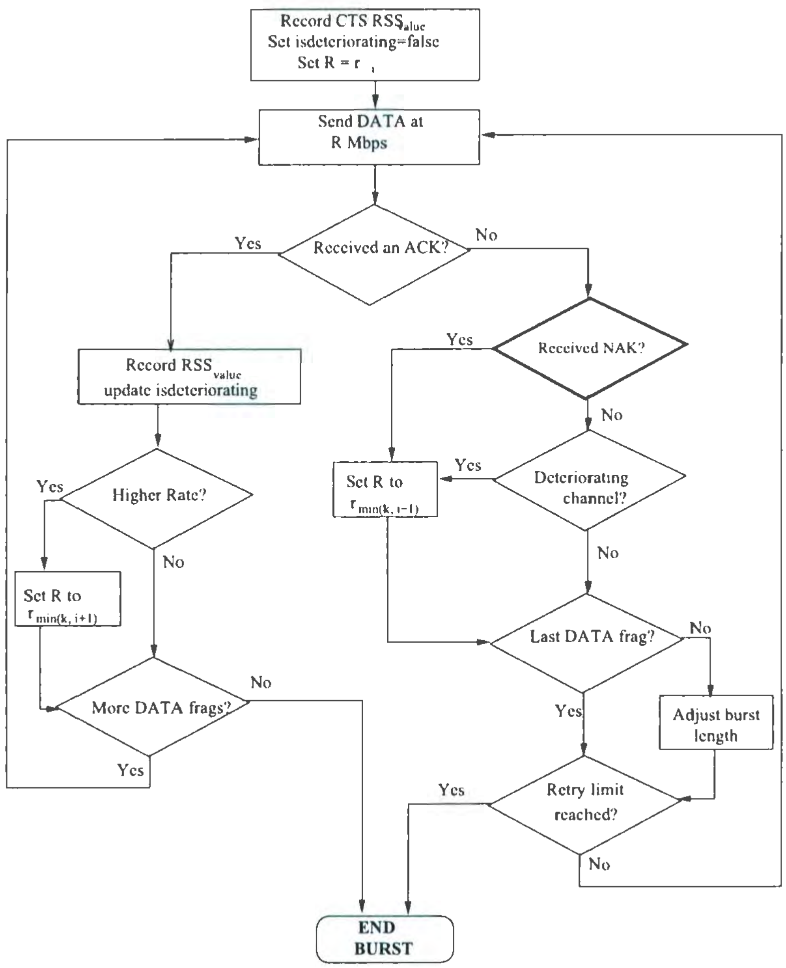

Figure 5.2: DRANLD rate estimation and loss recovery strategy

5.3 Performance Evaluation

In this section, we mainly evaluate the advantage of our NAK-aided loss differentiation mechanism (DRANLD) in slow and fast fluctuating channel over our previous loss differentiation mechanism (DRALD) that we presented in Chapter 4. Our experiment configuration, discussed in the next section, introduces frame loss from both transmission collision and channel fading. DRANLD achieves a throughput gain (over 2%) in a rapidly fluctuating channel than in a slow fluctuating channel.

5.3.1 Simulation Configuration

We evaluate the performance of DRANLD over a more representative UDP scenario with multiple hidden terminal flows, as illustrated in Figure 5.3, which exhibit both path loss and interference. From the figure, nodes D, F, G and J are outside transmission range of sender A and receiver B but within their interference range. Therefore, RTS/CTS exchange between A and B prohibits nodes G and J from transmitting. However, nodes C, E, H and K are outside transmission and interference range of sender A and receiver B. Thus, C's and E's transmission interferes with legitimate transmission between nodes' A and B.

The distance between individual flows is $\approx 140m$ and that between different flows is $\approx 450m$. Nodes mobility speed is varied between $2.5m/s$ and $15m/s$. These settings enable us to observe effects of path loss and collision in rapid and slow channel fluctuations.

Similar to our previous experiments in Chapters 3 and 4, we run the experiments for 50 seconds for all values of K between 0 and 5. We show the benefit of a NAK-

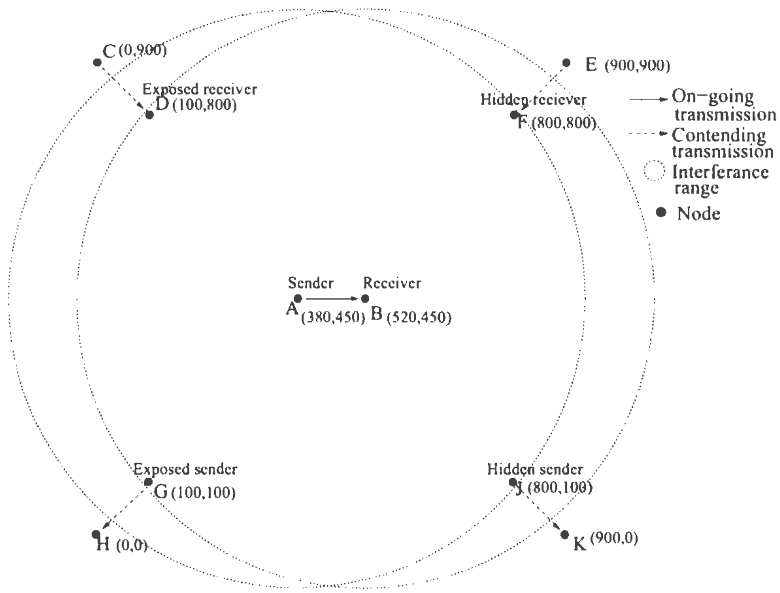

Figure 5.3: DRANLD simulation topology

aided loss differentiation by plotting and comparing the average number of frames received for each K value for both DRALD and DRANLD.

5.3.2 Results Analysis

Figures 5.4 and 5.5 plot DRANLD throughput gain, over DRALD and DRA, in slow and fast fluctuating channels respectively.

Both DRANLD and DRALD can predict the channel quality at the receiver by recording the signal strength (RSS_{value}) of a received CTS/ACK frame which they then use to determine if the quality is deteriorating or not. In a slow fluctuating channel, the channel quality can only steadily improve or deteriorate. As such, the recorded RSS value, at the sender, does not become obsolete quickly and can effectively predict the channel quality at the receiver by itself. Thus, as shown in Figure 5.4 DRANLD performance is similar to that of DRALD since additional reception of a

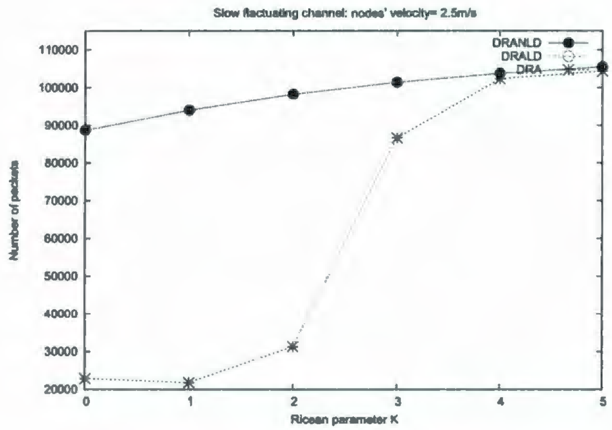

Figure 5.4: Nodes mobility speed= 2.5m/s

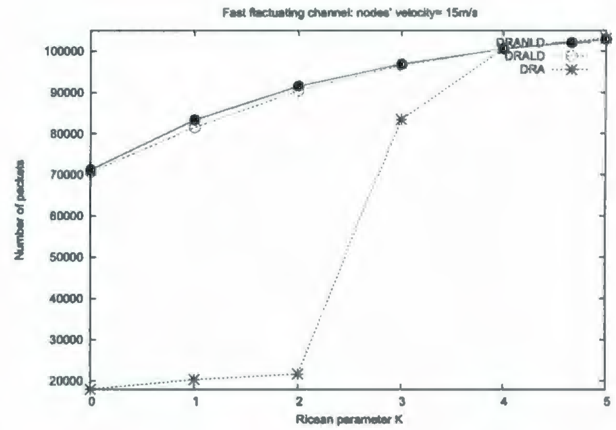

Figure 5.5: Nodes mobility speed = 15m/s

NAK frame only confirms the channel quality already predicted using only RSS-based LD mechanism.

However, Figure 5.5, shows that DRANLD performs better than DRALD when channel conditions fluctuates more rapidly. The recorded RSS value quickly becomes obsolete in this scenario and may not predict the receiver's channel quality accurately. As such, the more timely reception of NAK frame better indicates a fading channel at the receiver and the data rate is reduced as a result. Appendices A and B show DRANLD and DRALD RSS recordings and how they adjust their retransmission rates in a fast fluctuating channel. In Appendix A, DATA frame transmitted at time 15.306 is dropped since the $RSSValue$ (15.971) is less than RSS_{thresh} (usually 16) for the current data rate ($11Mbps$). However DRALD previously recorded $RSSValue$ (when CTS frame was received at time 15.3059) is greater than RSS_{thresh}, i.e 16.016 > 16. DRALD deduce that frame loss was due to collision and retransmits the DATA frame at the current rate, $11Mbps$. However, frame loss was due to fading channel quality at the receiver and retransmission should have been done at a lower rate. Thus, retransmission fails since DRALD is not able to capture the receiver's deteriorating channel quality with its obsolete RSS recordings. Appendix B shows how DRANLD handles such a scenario with its NAK-aided LD mechanism. Although the previously recorded $RSSValue$ at time 5.76837 imply that the retransmission of the DATA frame should be done at the current rate ($11Mbps$), reception of NAK frame at time 5.76959 indicates deteriorating channel quality at the receiver, and a successful retransmission is done at a lower rate ($5.5Mbps$).

Chapter 6

Conclusion and Future Research

This thesis presented three incremental data rate selection mechanisms for IEEE 802.11 wireless devices; **DRA, DRALD, DRANLD**.

DRA, utilizes a feedback mechanism provided by the receiver to adapt to channel quality changes. Based on the signal strength of a received DATA frame, the receiver may recommend a higher data rate using the retry bit of an ACK frame. If the retry bit of a received ACK frame is set to 1, then the sender adopts higher data rate for subsequent transmissions. Our simulation results indicated that DRA achieves a throughput gain of over 20% compared to its ancestor OAR for longer burst lengths in fast channel fluctuations.

Upon frame loss, DRA blindly retransmits a DATA frame using the current data rate. Thus, we proposed DRALD which incorporates a loss differentiation mechanism that records the signal strength of a received CTS/ACK frame to diagnose the cause of frame loss before selecting the retransmission rate. The RSS recordings enables the sender to predict the channel quality at the receiver. DRALD's ability to diagnose cause of frame loss improves network performance significantly compared to its predecessor DRA.

Although DRALD records performance efficiency compared to DRA and OAR, it suffers from use of obsolete RSS recordings in channel quality predictions. This is especially possible in rapidly fluctuating channels. As such, we presented a NAK-aided loss differentiation mechanism, DRANLD, that builds on the LD mechanism proposed in DRALD. Reception of a NAK frame indicates a fading channel and a lower retransmission rate should be used. However, if neither an ACK nor a NAK frame is received by a DRANLD sender, the channel prediction is based on the previously recorded RSS value (similar to DRALD). Only when the channel is not deemed as deteriorating does the sender conclude that the frame loss is due to collision and the current data rate is used for retransmission. DRANLD, records a throughput gain of over 2% in a rapidly fluctuating channel.

This work used RTS/CTS frames to determine the initial burst lengths and data rates. However, various works have shown that use of RTS/CTS increases the overall network overhead. Future work may involve exploring possibilities of using cross layer information in rate selection mechanisms and using other techniques to determine the initial burst length and data rate for our rate adaptation mechanisms.

Appendix A: DRALD Obsolete RSS Readings in Fast Fluctuation Channel

```
15.3054  sendRTS():

15.3057  recvRTS():           RSSValue:  16.039

15.3057  sendCTS():

15.3059  recvCTS():           RSSValue:  16.016

15.306   sendDATA():

15.3069  recv_timer():        RSSValue:  15.971

15.3072  RetransmitDATA():    RSSValue:  16.016  oldrate: 1.1e+07

 newrate: 1.1e+07   pkts: 5

15.3073  sendDATA():

15.3083  recv_timer():        RSSValue:  15.502

15.3086  RetransmitDATA():    RSSValue:  16.016  oldrate: 1.1e+07

 newrate: 1.1e+07   pkts: 5

15.3097  sendDATA():

...

...
```

Appendix B: NAK-aided RSS based LD in DRANLD

```
5.76414  sendRTS():

5.76441  recvRTS():          RSSValue:   16.917

5.76442  sendCTS():

5.76467  recvCTS():          RSSValue:   17.016

5.76472  sendDATA():

5.76567  recvDATA():         RSSValue:   17.094

5.76568  sendACK():

5.76593  recvACK():          RSSValue:   17.156

5.76594  sendDATA():

5.76689  recvDATA():         RSSValue:   17.124

5.7669   sendACK():

5.76715  recvACK():          RSSValue:   16.823

5.76716  sendDATA():

5.76811  recvDATA():         RSSValue:   16.691

5.76812  sendACK():

5.76837  recvACK():          RSSValue:   16.005

5.76838  sendDATA():

5.76933  recv_timer():       RSSValue:   15.766

5.76934  sendNAK():

5.76959  RetransmitDATA():  RSSValue:   14.648    oldrate: 1.1e+07

 newrate: 5.5e+06   pkts:  1

5.76959  recvNAK():          RSSValue:   14.648
```

5.7704	sendDATA():		
5.77211	recvDATA():	RSSValue:	12.959
5.77212	sendACK():		
5.77237	recvACK():	RSSValue:	9.003

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Index

ACK- Acknowledgement, 7

ARF- Auto-Rate Fallback, 23

BER- Bit-Error-Rate, 12

BPSK- Binary Phase Shift Keying, 8

BSS- Basic Service Set, 3

CARA, 23

CCA- Clear Channel Assessment, 23

CCK- Complementary Code Keying, 8

CRC- Cyclic 0 Check, 6

CS- Carrier Sensing, 40

CSMA- Carrier Sense Multiple Access, 5

CSMA/CA- CSMA with Collision Avoidance, 5

CSMA/CD- CSMA with Collision Detection, 5

CTS- Clear-to-Send, 4

DCF- Distributed Coordination Function, 6

DIFS- Distributed Inter Frame Space, 6

DRA- Differential Rate Adaptation, 14, 30

DRALD- Differential Rate Adaptation with Loss Differentiation, 14, 43

DRANLD- Differential Rate Adaptation with NAK-Assisted Loss Differentiation, 52

DSSS- Direct Sequence Spread Spectrum, 8

EB- Exponential Backoff, 21

EIFS- Extended Inter Frame Space, 56

EIFS- Extended Inter Frame Spacing, 6

FCS- Frame Check Sequence, 6

FER- Frame Error Rate, 17

IFS- Inter Frame Spacing, 6

LD- Loss Differentiation, 14, 20, 42

LD-ARF- Loss differentiating ARF, 27

LDRA, 25

LOS- Line-of-Sight, 12, 47

NAK- Negative Acknowledgement, 22, 52

NAV- Network Allocation Vector, 7, 36

NS-2- Network Simulator, 10

OAR- Opportunistic Auto Rate, 25

OTLR, 26

PCF- Point Coordination Function, 6

PCS- Physical Carrier Sensing, 6

PHY- Physical Layer, 8

PIFS- PCF Inter Frame Spacing, 6

PLCP- Physical Layer Convergence Procedure, 8

Promiscuous mode- A node listens to all frames rather than just the frames addressed to it, 57

QPSK- Quadrature Phase Shift Keying, 8

RBAR, 24

RSS- Receive Signal Strength, 17, 43

RSSI- Receive Signal Strength Indicator, 24

RTS- Request-to-Send, 4

SIFS- Short Inter Frame Spacing, 6

SNR- Signal-to-Noise Ratio , 9

SSI- Signal Strength Indicator, 18

VCS- Virtual Carrier Sensing, 6

WLAN- Wireless Local Area Networks, 3