A Survey of Rate-Adaptation Schemes for IEEE 802.11 Compliant WLANs

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Abstract

The IEEE 802.11 compliant stations can transmit at multiple transmission rates. Selection of an appropriate transmission rate plays a significant role in determining the overall efficiency of a communication system. The technique which determines the channel state information and accordingly selects an appropriate transmission rate is called rate-adaptation protocol. The IEEE 802.11 standard does not provide standard specification for implementing a rate-adaptation protocol for its multi-rate capable wireless stations. Due to the lack of standard specification, there is a myriad of rate-adaptation protocols, proposed by industry and various research institutes. This paper surveys the existing rate-adaptation schemes, discusses various features which contribute significantly in the process of rate-adaptation, the timing constraints on such schemes, and the performance gains in terms of throughput, delay and energy efficiency; which can be gained by the use of rate-adaptation. The paper also discusses the implication of rate-adaptation schemes on the performance of overall communication and identifies existing research challenges in the design of rate-adaptation schemes.

Keywords: Multi-rate, IEEE 802.11, Rate-adaptation, WLAN, Loss-differentiation

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1. Introduction

The IEEE 802.11g standard [1] compliant, wireless communication devices have the ability to communicate at multiple transmission rates. The lowest transmission rate supported by the standard is 1 Mbps while the highest transmission rate (in the approved extensions of the standard) is 54 Mbps. Transmission rate holds a great significance in determining the overall efficiency of a communication system. Generally, it is always desirable to use the highest transmission rate because it can yield highest throughput, lower medium occupancy and power consumption. However, because of the underlying modulation schemes, transmissions at higher rate require higher signal-to-noise ratio (SNR). Therefore, higher rate transmissions are prone to erroneous reception as compared to lower rate transmissions. On the other hand, lower transmission rates cause rate-anomaly [2, 3] and affect the performance of the other stations in a Basic Service Set (BSS). Owing to the variable channel conditions, the transmission rate is required to be adjusted so as to select the best possible transmission rate at any given time. Inappropriate rate selection can put a communication system in either of two states: (i) *a transmitter operates at lower than optimum rate, thus the chances of transmission failures (and thus retransmissions) are minimized while reducing communication efficiency*, or (ii) *a transmitter uses an inappropriately selected higher rate, which minimizes the chances of successful transmissions causing retransmissions*. Every communication system pays a high price when it suffers from transmission failures. In case of the IEEE 802.11 standard, a station waits for '*ACK-timeout*' after sending a frame before it concludes that frame has failed to reach the destination. After a transmission failure, the *contention window* is incremented, which essentially means that the station would have to wait for a longer time before accessing the medium for retransmitting the frame. Moreover, selection of an inappropriate transmission-rate not only misuses the shared medium and cause delays, it also causes overhead in terms of energy, in the battery powered mobile terminals. A set of procedures that monitor the channel state and adapt the transmission rate, constitute a rate-adaptation scheme.

There are several challenges associated with the design of rate-adaptation scheme, particularly, in a network composed of IEEE 802.11 stations. For instance, the foremost design decision is whether to use frame-success/frame-loss statistics or SNR as a measure to determine the channel state. Both choices have their own efficiency and complexity issues. Rate adaptation schemes are also constrained by timing [4]. Frequent monitoring of the channel state increases the complexity and may result in reaction to short-lived channel variations – affecting the performance. Any decision other than the optimum results in selection of higher or lower transmission rate than actually required at a given time. Although, rate-adaptation technique is inherntly applied at the medium acces control (MAC) sub-layer, the effects of rate-adaptation decisions can be seen in the performance of higher layer protocols. For instance, in routing protocols for Mobile Adhoc Networks (MANETs), route discovery process consists of broadcast frames. According to the IEEE 802.11 standard, broadcast frames are sent at lower transmission rates so as to enable broadcast frames reach a longer distance. Thus, nodes discovered through broadcast frames are included in the routing tables while when the actual data-frames are sent (at higher transmission rates), those neighbouring nodes may not be reachable [5]. Although, rate-adaptation protocol is of significant importance, the IEEE 802.11 standard does not provide standard specification for a rate-adaptation technique. The standard, however, specified mandatory rules for devising a rate adaptation scheme. As a result of the lack of standard specification, a number of rate-adaptation techniques have been proposed by manufacturers of the standard compliant devices and by various independent researchers.

Since the early release of the IEEE 802.11 standard, there are numerous approaches for rate-adaptation. It is pertinent to survey the previously published literature and summarize the key design challenges and factor that influuence the performance of rate-adaptation scheems. This paper surveys various rate-adaptation techniques proposed for IEEE 802.11 compliant stations. The paper categories the rate-adaptation schemes into two major classess (1) *Frame statistics based rate-adaptation schemes* that uses success or failure statistics of previously transmitted frames and approximates channel quality and (2) *SNR based rate-adaptation* schemes. The SNR based schemes are further categoriesed into SNR-based open loop and SNR based closed loop systems. The paper presents detail design considerations and challenges associated with rate-adaptation schemes and their effects on communication efficiency. The key contribution of the paper is then to highlight and summarize future design steps which will help improve the performance of rate-adaptation schemes.

The paper is organized into five major sections; section-2 discusses the multi-rate capability of IEEE 802.11 compliant stations and various rules and operational procedures relevant to rate-adaptation as mandated by the standard, section-3 gives an in depth review of various frame-statistics based rate-adaptation schemes, section-4, discusses the significance of frame-loss differentiation mechanisms, its importance and survey of various schemes in the available literature, section-5, discusses SNR-based (open and closed-loop) rate-adaptation schemes and finally, section-6 presents the lessons learnt during the survey and gives recommendations for future research.

2. IEEE 802.11: Multi-Rate Operation

2.1 Multi-rate Support

In a Basic Service Set (BSS), a station (STA) which starts the BSS designates a set of transmission rates which should be supported by all STAs in a BSS; this set is called BSSBasicRateSet. A STA communicates its multi-rate capability in the form of a parameter called Supported rates. The Supported rates parameter is also included in association request, re-association request and probe request frames. The Supported rates parameter includes all the operational rates at which a STA can transmit and receive. The supported rates parameter is a superset of rates represented in the BSSBasicRateSet. This parameter can hold information for only eight operational rates; for STAs which support more than eight operational rates an Extended supported rates parameter is used in all relevant frames (such as the association/re-association/probe request frames). The supported rate parameter is encoded as one to eight octets, where each octet represents an operational rate. For an operational rate which is also a part of the BSSBasicRateSet, the first bit of the octet is 1, while the rest of 7 bits are used to encode the operational rate. For example, for an operational rate of 2 Mbps which if a part of the BSSBasicRateSet, the octet representing this rate would be 1000 0100 (132 decimal). Likewise, as an example, for operational rate of 6 Mbps, which if not included in the BSSBasicRateSet would be encoded as 0000 1100 (12 decimal).

Therefore, management frames (beacon, association response, re-association response and probe response) include the supported rates parameter to convey the operational rates and the BSSBasicRateSet to STAs. STAs also convey their operational rates to an AP by including the supported rates and the optional extended supported rates in various management frames such as the association/re-association and probe request frames. Association can be denied within a BSS if the OperationalRateSet of a station does not include the transmission rates included in the BSSBasicRateSet.

2.2. Multi-rate Operation: Mandatory Rules

Protection mechanism frames including Request to Send, Clear to Send (RTS/CTS) and , CTS-to-self are used to propagate medium usage information across the BSS and to establish the virtual Carrier Sensing (CS) mechanism. These frames should be transmitted at such a rate so that Extended Rate PHY (ERP) and non-ERP STAs can interpret them and know about the duration of medium usage. For this purpose the standard mandates that such frames should only be sent at one of the mandatory transmission rates of the Direct Sequence Spread-Spectrum phyiscal layer (DSSS PHY of the IEEE 802.11), or the High-Rate DSSS (HR/DSSS of the IEEE 802.11b) so that all STAs within a Basic Service Area (BSA) can decode the transmission and update their corresponding Network Allocation Vectors (NAVs) for the duration of transmission. With an exception of the frame types mentioned in the above paragraph and Block acknowledgment request/Block acknowledgment frames, all other control frames should be sent at one of the rates in the BSSBasicRateSet. Broadcast/multicast frames should also be sent at one the rates in the BSSBasicRateSet. Frames for polling stations for example the Contention-Free Poll(CF-Poll) generated within a Contention Period (CP) should only be sent at the one of the rates in the BSSBasicRateSet. This condition is not required if the protection mechanism (e.g. the RTS/CTS) is used before generating the CF-Poll. In situation when the supported rate set of the receiving STA is not known, the transmitting STA should only use rates specified in the BSSBasicRateSet or should transmit at a rate at which it received frames from the receiving STAs. In a normal frame exchange, a transmitting STA needs to inform other STAs in a BSS about the duration of medium usage by using the duration field in frames. This value in the duration field includes the time for transmission of a corresponding acknowledgement (ACK) frame and the inter-frame spaces. To calculate the duration field value, a transmitting STA knows about everything apart from the duration of ACK/CTS; because it is up to the receiving STA to select a certain transmission rate for sending the ACK/CTS frame. Therefore, to enable the transmitting STA to calculate the value of the duration field, the standard mandates that a receiving STA (which would send an ACK/CTS frame) should send an ACK/CTS frame at the highest rate in the BSSBasicRateSet which is less than or equal to the rate at which the transmitting STA sent the latest frame in the frame exchange sequence (which can be RTS or data frame). However, if the transmitting STA sent the frame which is not in the BSSBasicRateSet (and thus the condition outlined in the above paragraph could not be met), then a receiving STA should send the ACK/CTS frame at the highest mandatory rate of the phyiscal layer (PHY) which is less than or equal to the rate at which the transmitting STA sent a frame.

The rules mandated by the standard for devising a rate-adaptation strategy essentially mean that transmissions should only be done at rates which could be successfully decoded at the receiver, and at the same time the selection of transmission rates should not disrupt the distributed medium access control (MAC) protocol operations in the BSS.

2.3. Received Signal Strength Measurement and Representation

An IEEE 802.11 compliant transmitter uses transmit power at roughly 20 dBm (100 mW) and a standard receiver can receive power all the way to -96 dBm (2.511 x 10-10 mW). To represent and measure the received power at a receiver, the IEEE 802.11 standard defines an optional parameter called Received Signal Strength Indicator (RSSI). This value is measured by the PHY to represent the power observed at the antenna of a receiver while receiving the current PHY Protocol Data Unit (PPDU). RSSI measurement is performed between the beginning of the Start Frame Delimiter (SFD), in the PHY Layer Convergence Protocol (PLCP) preamble and the end of Header Error Check (HEC), in the PCLP header. The standard represents the RSSI with a 1 byte numeric value giving the RSSI an allowable range of 0 to 255. However, no vendor has reported to use the complete 0-255 range of the RSSI; so each vendor has a specific maximum RSSI value represented by RSSI Max in the standard. Cisco uses 101 different levels for the RSSI, the RSSI Max of Cisco is 100 [6]. RSSI Max values used by Symbol and Atheros are 31 and 60 respectively.

The standard does not provide mapping between the RSSI levels and any particular power levels as measured in mW or dBm. It is left to manufacturers to map the energy values in mW to RSSI levels, decide the granularity and thus the total range of the RSSI values [6]. Most of the vendors use tables for mapping the RSSI values with corresponding dBm values; the highest RSSI is usually mapped to -10 dBm or below. Any value of received power higher than -10dBm is mapped to the RSSI Max. The reason for mapping the RSSI Max to -10 dBm or lower value of the received signal power is that it is below -10 dBm that fluctuation in the received power can affect the transmission rate and other MAC functions of an 802.11. Therefore, every vendor tries to map the finite number of RSSI levels to the performance-sensitive part of the dBm graph (which starts usually at or below -10 dBm). Another justification for using such mapping is that RSSI is used for performing Clear Channel Assessment (CCA) and determination of Roaming Threshold. Both of these procedures require sensitivity of a receiver to very low energy levels which requires that there should be appropriate RSSI mapping to represent such low energy levels. As an example of mapping the RSSI values to various dBm values by one of the vendors of IEEE 802.11 compliant wireless communication stations, Cisco [7], consider **Table 1**, which shows the correlation between the dBm rating and the corresponding RSSI value for the Cisco 7920 Wireless IP Phone.

Table 2. Comparison of dBm and RSSI Values for Cisco 7920 Wireless IP Phones.

RSSI	5	10	15	20	25	30	35	40	45	50	55	60	65	70
dBm	-98	-97	-89	-83	-79	-75	-67	-61	-57	-49	-44	-41	-38	-34

3. Rate-Adaptation through Frame Success/Failure

The statistics related to the transmission-status of transmitted frames provide an estimation of the channel quality. Generally, when the number of successfully transmitted frames is higher in a particular estimation window, it reflects the possibility of a future successful transmission. Such estimations form the basis of statistics-based rate adaptation schemes. In the statistics based rate-adaptation schemes, the channel estimation and rate-selection are performed by the sender and therefore such schemes are also called sender-side rate-adaptation schemes.

3.1. Auto-rate Fallback (ARF)

It is commonly agreed that the first known rate-adaptation scheme for IEEE 802.11 compliant wireless communication devices was published in [8] for Wave-LAN® -II in 1997. The rate-adaptation scheme was called Auto Rate Fallback (ARF) and it is one of the highly cited publications on rate-adaptation. The ARF scheme keeps track of a timing function and uses statistics related to the status of most recent frame transmissions. The default transmission rate selected by the ARF is 2 Mbps. ARF reduces the transmission rate to 1 Mbps after 2 consecutive frame failures, indicated by missing ACK frames at the transmitter. When an ACK is missed for the first time following an earlier successful transmission, the first retry is made at 2 Mbps. In case of another, consecutive frame loss, marked by missing ACK the ARF lowers the transmission rate to 1 Mbps and all the subsequent retries and frame transmissions are performed at 1 Mbps.

After reducing the transmission rate a timer is started to track successfully transmitted and/or lost frames. When either the timer expires or the number of successfully transmitted frames reaches 10, ARF increases the transmission rate back to higher rate (2 Mbps). The next frame transmission, which can be called a probe transmission, is performed at the higher rate. If the transmission at the higher rate (when using the probe transmission) fails, the ARF immediately reduces the transmission rate again to 1 Mbps. This process is repeated in a similar fashion and ARF attempts transmission at higher rates after 10 successful transmissions or timer expiry. The ARF's rate change boundary is given in Fig. 1, which depicts that when transmitter and receiver are close enough they would experience very few frame losses and as the distance increases the number of frame losses will increase and ARF would switch between the two transmission rates based on the number of frame losses. It is pertinent to note that the ARF as developed for 1 and 2 Mbps WLANs is simple and may have been suitable for bi-rate wireless transmitters, however, the simplicity of ARF is not practical for multi-rate wireless transmitters with capability to transmit and receive at 2, 5.5., 9, 11, 36, 48 and 54 Mbps. Many research studies, as discussed below, proposed modification to the ARF.

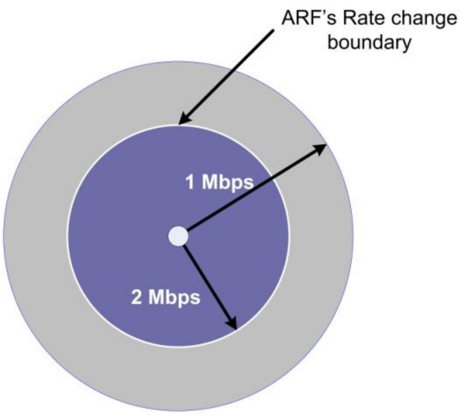

Fig. 1. ARF rate change boundry [8]

3.2. Adaptive-ARF (AARF)

The authors in [9] proposed Adaptive ARF (AARF), by introducing binary exponential backoff (BEB) to ARF's higher threshold. According to AARF, if the first rate-up attempt after 10 successful transmissions fails, then the next rate-up attempt should be made after 20 frames. If the situation persists, this threshold should be doubled every time a transmission fails; the highest limit that a threshold can reach as a result of the BEB is set to 50 frames. AARF essentially minimizes the frequency of rate-up attempts as proposed for ARF. AARF would logically perform well in long term channel variations, because it would not attempt higher-rate transmissions and thus avoid frame failures. However, at the same time, it slows down its responsiveness to sudden variations in the channel conditions.

3.3. Sample Rate

The ARF and AARF react sequentially to improvements in the channel quality. In order to improve the responsiveness, SampleRate [10], randomly selects transmission rates. SampleRate sends frames at a transmission rate which would provide the highest throughput. Initially when the transmitter starts sending the packets, it uses the highest possible transmission rate. It stops using that transmission rate if it experiences 4 successive losses. It will keep on decreasing the transmission rate until it finds a rate value which can successfully transmit frames. Every 10^{th} frame, it randomly selects a rate value which it believes would provide better throughput than the current one. It does not try a transmission rate if (operating at) that rate causes 4 successive frame losses or if it's lossless transmission time is more than the average transmission time of the current rate. It uses a 10 seconds window for calculating the average transmission time. Estimation (decision) windows (in terms of time) used by various rate-adaptation schemes is given in **Table 3**.

3.4. Multi-Rate Retry (MRR) of MADWIFI

Multi-rate retry (MRR) is a rate-adaptation scheme used in the Multiband Atheros Driver for WiFi (MADWIFI) [11]. MADWIFI is a Linux driver for Atheros based chipsets used in the IEEE 802.11 standard devices. MADWiFi is a semi-open-source driver. It hides the hardware specific functionalities using a binary only Hardware Abstraction Layer (HAL). Transmissions are handled with the help of transmission descriptors. The transmission descriptor shows the transmission and receiving status of frames. It also has a pointer to the next descriptor and to the data buffer which is to be transmitted and an ordered set of 4 pairs of rate and transmission count fields (r_0/c_0, r_1/c_1, r_2/c_2 and r_3/c_3). The transmission status structure also indicates the transmission rate at which the frame was transmitted.

According to the MRR scheme, the frame transmission starts at r_0 but if transmissions fail c_0 times the rate is decreased to r_1 and c_1 attempts are made at this rate. This process is repeated until either a frame is successfully transmitted or when transmission at r_3 is repeated c_3 times, after which the packet is discarded and the transmission status is updated in the descriptor. The MADWIFI driver periodically changes the value of r_0/c_0, r_1/c_1, r_2/c_2 and r_3/c_3 according to the transmission status. This periodic duration is 0.5 to 1 second. Therefore, short term channel variations are handled by switching from r_0 to r_1 to r_2 and finally to r_3, while for long term variations it periodically updates the values of r_0/c_0, r_1/c_1, r_2/c_2 and r_3/c_3.

3.5. Adaptive Multi-rate Retry (AMRR)

As a second contribution, [9], introduces binary exponential backoff procedure to the original MADWIFI rate-adaptation mechanism. This is called Adaptive MRR (AMRR). The idea behind AMRR is that it adaptively changes the length of the period after which the values of the rate/count pairs (used for rate-adaptation in the original MADWIFI driver) are changed. To ensure responsiveness of the algorithm to short-term channel variations AMRR uses c_0=1, c_1=1, c_2=1 and c_3=1 where as the MADWIFI used c_0=4, c_1=2, c_2=2 and c_3=2. The value of 'r_3' is always set to the lowest available value of transmission-rate while r_1 and r_2 are set to consecutively lower rates than r_0. AMRR increases the transmission-rate if less than 10% of transmitted frames fail during the previous period. In this case, it updates the whole set of rates from r_0 to r_2. The algorithm also checks if the information is not too old and the success rate crosses a success threshold. On the other hand, if 33% of transmitted frames fail during a previous period, the algorithm doubles the success threshold for next interval.

3.6. ONOE

ONOE [11] is a credit based algorithm and works by incrementing/decrementing credits for a particular transmission rate if the frame loss percentage is lower/higher than 10 percent in a periodic fashion with a default period of 1second. A higher transmission-rate value is selected if the number of credits crosses a specific threshold (10 or more). If no packets are successfully transmitted, the transmission-rate is reduced to the next lower value. The credits are reset to zero each time a new transmission-rate value is selected. ONOE is dependent on the initial bit-rate and the initialization parameters and performs poorly even with slight variations in the channel quality [12].

3.7. Cross-Layer Rate-Adaptation (CLRA)

A very common trait in the design of all rate-adaptation schemes is that they have an inherent tendency to select the highest transmission rate. In many cases it is not always a requirement to operate at the highest transmission rate [13]. According to the authors, this tendency is one of the major reasons for causing higher retransmissions. A method to identify the prevailing requirements and the underlying communication constraints can define an instantaneous limiting value which can be used by the rate-adaptation scheme as the highest transmission rate. By doing so the rate-adaptation scheme can essentially be limited to avoid unnecessary attempts of transmission at higher rates and thus potential retransmissions can be avoided which are highly likely to occur at higher transmission rates. The authors in [13] formulated a mechanism to calculate at run-time, the higher layers traffic requirements and the underlying MAC sublayer's constraints. A limiting value for the transmission rate is then calculated using such constraints and requirements, and is passed on to the statistical rate-adaptation scheme. The statistical rate-adaptation scheme uses this dynamic limiting value for selecting a suitable transmission rate. However, in case of higher station density and/or higher outbound traffic requirements the on-demand incremental strategy indicates the highest transmission rate. In this case, the rate-adaptation is then dependent on the statistics based rate-adaptation scheme.

3.8. Miscellaneous Approaches

Opportunistic Auto Rate (OAR) [14, 15] protocol aims at exploiting the duration of high-quality channel conditions. The core idea of OAR is to send back-to-back data packets whenever the channel conditions are good. OAR works in coordination with another rate adaptation algorithm (Receiver-based auto-rate (RBAR) [16], and optionally with ARF). Primarily, the rate adaptation algorithms are responsible for determining a suitable transmission value, and the OAR then maintains the selected transmission rate for successive transmissions when the channel conditions are good. A similar approach is used in OSAR [9]. An enhancement to ARF is proposed in [17]. According to authors in [17] ARF doesn't reflect the current contention levels and as a result if the contention for medium usage increases, there are higher chances of frame losses. Their argument is based on the findings in [18], which has shown with the help of Markov chain analysis of ARF, that the rate distribution of ARF is mainly distributed on low transmission rate when the number of contending stations increases. In their opinion, the fixed thresholds used by ARF are not optimum in such a scenario and ARF would decrease the transmission rate with increase in contention even if the frame error rate remains stable. So, their design philosophy is that the probability of increasing and decreasing the transmission rate of a transmitting station should not depend on the number of contending stations if the channel error rate is stable. Therefore, according to their proposed scheme for rate adaptation, the rate-up and rate-down thresholds are updated every time the backoff-counter reaches zero to include the effects of medium contention. However, simply using ARF with the proposed enhancements still suffers from the unnecessary back and forth rate selection; therefore, to minimize this effect they used further enhancement which is similar to AARF.

To avoid using fixed, predefined thresholds, a machine learning technique, stochastic learning automata, is applied to rate-adaptation in [19], to randomly select a rate for a transmission and dynamically update the decision based on the ACKs feedback. A semi-Markovian framework for analyzing the performance of ARF and AARF is presented in [20], shows the neither of the two rate-adaptation schemes consistently outperform each other in all conditions. While ARF responds relatively quickly to improved channel conditions when compared with AARF, the later is better in long term channel variations. The authors in [21], analyzed various rate-adaptation algorithms using a testbed in variety of test scenarios. According to their findings SampleRate and ONOE experience drop in packets when the number of transmitters increase. One of the reasons of poor performance in the case of SampleRate is that in situations of higher node density, it frequently samples various available rates and then it has few samples for accurate estimation of transmission time. ONOE and SampleRate can also show performance improvements with use of RTS/CTS mechanisms for minimizing losses due to hidden nodes.

Rate-adaptation schemes have been broadly placed in two categories according to their inherent design for rate-adaptation in [22]: throughput-based rate-adaptation schemes which include [23], [24] and [25], and error-based rate-adaptation schemes like [26] and [27]. The authors proposed the use of appropriate rate-adaptation scheme on per-frame basis according to the type of frame e.g. frames which are associated with throughput demanding applications should use throughput-based rate-adaptation while on the other hand loss sensitive applications should use rate-adaptation schemes which are cautious in terms of frame losses.

There are a number of approaches which have modified the existing rate-adaptation schemes (mainly the ARF), however, quite unfortunately the assumptions on which these schemes are based prevent the practical realization of such rate-adaptation schemes. For instance, [27] proposed a rate-adaptation scheme for downlink, where a station overhears the transmission from Access Point (AP) to other stations and if the AP uses higher transmission rates for other stations than this station, then this station provides a feedback to the AP for increasing the transmission rates. This scheme is based on a number of assumptions, for example, there has to be a number (which in itself is unknown) of stations in the vicinity and there has to be downlink traffic from the AP. Similarly, in order to keep the overheard information as fresh as possible, there has to be a higher level of medium contention. Practically, none of these assumptions can be guaranteed.

Rate-adaptation schemes are widely studied from different perspectives [28]-[34]. An analysis of the impact of various rate adaptation protocols on routing protocols for multi hop wireless networks is presented in [35]. The authors discussed ARF, RBAR and the rate adaptation mechanism as described in the 802.11n draft. In their opinion receiver based rate adaptation mechanisms which they term as closed loop approaches are better than statistical (open loop) approaches. However, in the non- 802.11n WLANs, the receiver based systems would require modification to the standard frame formats and therefore were not considered a workable option. The 802.11n draft defines a new control field called HT (high throughput) for this purpose and therefore, according to their findings the rate adaptation mechanism for 802.11n draft performs best when compared to rest of approaches. However, the 802.11n rate adaptation scheme performs poorly in some scenarios because it does not consider MAC Protocol Data Unit (MPDU) length which is difficult to estimate as a number of MPDUs can be aggregated to form a single Aggregated-MPDU (A-MPDU).

Table 4. Estimation windows used by various statistics based rate-adaptation schemes

Rate Adaptation Scheme	Estimation window
ARF	10 frames
AARF	Min: 10 frames, Max: 50 frames
SampleRate	10 frames or 10 seconds
Multi-Rate Retry (MRR) for MADWiFi	0.5 to 1 second
ONOE for MADWiFi	1 second
CLRA	Dynamic
Miscellaneous approaches [10], [12]	Adaptive

4. Types of Frame Losses and its Impact on Rate-Adaptation

The decisions of most of rate adaptation schemes, presented in the previous section, are based on the statistics related to the status of frame transmission. Loss of frame is indicated when a sender STA does not receive ACK for a previously transmitted frame. However, when carefully examined, such losses can occur because of two different reasons and requires a different action from the rate adaptation scheme.

4.1. MAC Level Losses (Frames losses because of collisions)

Collisions occur when two or more STAs simultaneously transmit frames so that an intended receiver is unable to decode the transmission and thus unable to ACK back to the sender. Simultaneous transmissions can occur because of: (a) failure of the MAC protocol in highly congested BSS or (b) because of operation of hidden nodes in the vicinity of a transmitter and (c) because of MAC buffer overflows. Such losses are indicative of the fact that the (PHY) channel conditions are supportive and unchanged and the transmission is corrupted due to a failure at the MAC layer; therefore, such losses of frames are called MAC level frame losses [36].

4.1.1. Collisions in Highly Congested Networks

In a highly congested BSS the percentage of frame losses because of simultaneous transmission of stations is reported to be as high as 30% [37]. The scenario reported in [37], used network-traffic's traces from the network which was setup for the 67th Internet Engineering Task Force (IETF) meeting, in 2006. In this scenario, if ARF, AARF, SampleRate or any other rate-adaptation scheme which relies on frame success statistics would decrease the transmission rate. For instance, 30% loss implies that 3 frames out of every 10 frames have to be retransmitted. ARF and AARF increase the transmission rate only when the number of successfully transmitted frames reaches 10 or more (in the case of AARF), therefore, in this scenario, there is no possibility of increasing the transmission rate if ARF/AARF is used in the client stations. On the other hand there are higher chances that out of 3 frames failures in every 10 frames there would have been 2 consecutive frame failures. ARF and AARF both, lower the transmission rate when two consecutive frame losses occur. Therefore, it is highly likely that if the frame-loss rate as reported in this scenario persists, ARF like rate-adaptation schemes would ultimately reduce the transmission rate to the lowest. Similar observations are reported in [21], where the authors recorded that 73% of the total frames were transmitted at the lowest rate. Similar studies such as [38], [39], have reported that most of the rate-adaptation schemes do not perform well in highly congested wireless networks. Rate adaptation schemes which do not use a frame-loss differentiation mechanism wrongly associate such frame losses to channel quality deterioration. Reducing the transmission rate, at times of high medium congestion causes further performance deterioration.

4.1.2. Collisions because of Hidden Nodes

Frame losses can also occur because of simultaneous transmissions of frames as a result of presence of hidden stations. The phenomenon of hidden stations arise when a receiver in the middle of two transmitter receives two frames from both transmitters and is unable to receive either, thus drop the frame and none is acknowledged back to the sender. The senders in this scenario are out of the each other's coverage areas and thus their Clear Channel Assessment (CCA) mechanism cannot detect busy medium condition even when one of the two senders has acquired the medium. In case of such losses, reducing the transmission rate further deteriorate the communication efficiency.

4.2. PHY Level Losses

4.2.1. Corrupted Frames

During frame transmission, a frame can be corrupted due to reduction in signal quality e.g. lower Signal to Noise Ratio (SNR), as received by a receiver. The Cyclic Redundancy Check (CRC) field in the PHY Protocol Data Unit (PPDU), in this case indicates that the frame contents are wrongly received and not as sent by the sender. Such frames are discarded with no ACK or feedback to the original sender.

4.2.2. Totally lost, Undetected Frames

In this case, the energy level of the received signal at the receiver is lower than the receiving threshold of a receiver, rendering a receiver unable to detect transmission and decode contents of a PPDU. Such transmissions are completely lost and the receiver has no knowledge and thus cannot provide any feedback to the transmitter.

4.3. Loss-Differentiation

MAC level frame losses need to be differentiated from PHY-level frame losses as they require a different action (more specifically no action) from the rate-adaptation scheme. In case of no loss-differentiation, a rate-adaptation scheme would generally associate every frame loss with deteriorated channel conditions, which in many cases would require the rate-adaptation scheme to lower the transmission rate. If the frame losses are because of simultaneous transmissions (i.e. MAC level losses) then reducing the transmission rate would further deteriorate the overall performance. Therefore, it is important to devise a mechanism to differentiate frame losses before a rate-adaptation mechanism takes action.

A number of loss-differentiation mechanisms are proposed in the literature, most of which deal with differentiation of MAC level losses from PHY level losses [40-52]. The authors in [40] evaluated the effectiveness of loss-differentiation mechanisms in various scenarios with varying networks load. An analysis of the effect of contention on the performance of rate-adaptation schemes is presented in [41]. The transmission characteristics are affected by a number of factors, each of which has to be considered while devising a rate-adaptation strategy [53]. According to the method proposed by the authors in [42], a consecutive failure count 'n' is compared with probe activation threshold 'P_{th}' and consecutive failure threshold 'N_{th}'. When n reaches P_{th} , the next data frames will be sent with RTS/CTS frames and when n reaches N_{th} the next data frames will be sent at a lower rate. The default values for P_{th} and N_{th} are 1 and 2 respectively. This scheme uses a threshold of 10 for successful transmissions and after that the next transmission is done at a higher rate. Using those values for the three different thresholds; this scheme is essentially like the ARF with only one change that after the first frame loss, it will use RTS/CTS and after the second frame loss it will reduce the data-rate. A mechanism to identify frame losses using the Clear Channel Assessment (CCA) is given in [39]. This is done in a scenario when a station sends a data frame and waits for ACK and while it is waiting, the CCA indicates busy channel. In such cases the station concludes that a collision has occurred. In this case, the station would retransmit without increasing the failure count or reducing the transmission rate. This mechanism would not work if there is a simultaneous transmission from other stations and their transmission ends before or after the transmission of a station under consideration. An RTS threshold is used in [36] to activate RTS/CTS handshake when the duration of a data-frame crosses the RTS-threshold. A similar RTS/CTS technique is used in [45], with ARF. To improve over the trial based or threshold-based usage of RTS/CTS, authors in [46] proposed probabilistic approach for activating the RTS/CTS procedure for loss differentiation. An RTS-probability parameter is maintained, whose value is calculated by using the collision probability of transmitted frames using a mathematical model.

The use of RTS/CTS causes an overhead especially when the MAC Service Data Unit (MSDU) size is small and this overhead can affect the performance while transmitting Voice over IP (or other real time traffic) [54],[55]. As an alternative of using RTS/CTS for loss-differentiating [34], suggests the use of lowest transmission rate right after a frame loss. According to [34], if the receiver is still within the range, then transmission at lowest rate would make it possible that the receiver would receive the transmission and send back an ACK. This condition would indicate that transmission failure was because of channel quality deterioration. On the other hand, if the transmission at the lowest rate is lost (not acknowledged) however, the sender can still receive beacon frames (which are also sent at a lower rate, as mandated by the standard); then this condition would indicate that frame losses are due to collisions.

5. Signal-to-Noise Ratio based Rate-Adaptation Schemes

Changing the transmission rates essentially change the underlying modulation techniques. For decoding transmissions a receiver requires a certain level of Signal-to-Noise Ratio (SNR). Therefore, once the existing SNR is known, a suitable modulation technique (and thus a transmission rate) which can be decoded at the existing SNR can be selected [16, 17, 24, 41,]. SNR-based rate-adaptation schemes uses SNR measurements to estimate the quality of channel and such measurements are utilized for selecting a suitable transmission rate. SNR-based rate-adaptation schemes can provide very accurate channel state information (CSI) when compared to other schemes where the sender estimates CSI from the delivery-success rates of previously transmitted frames [61].

Ideally, in SNR-based rate-adaptation schemes a transmitter should know about the SNR levels of its transmission at the receiver, however it is not the case. To make it happen various proposed solutions provide runtime feedback about the SNR levels to the transmitter.

5.1. Receiver-side, Closed loop, SNR-based Rate-adaptation Systems

Rate-adaptive framing (RAF), [62] is a closed loop rate-adaptation scheme in which a receiver analyzes the SNR and provides a feedback to the transmitter about an appropriate frame size and transmission rate. In RAF, a receiver piggybacks the optimal transmission rate and frame size in the ACK frame. In order to incorporate the rate and frame size in the ACK frame, RAF, modifies the duration field in the ACK frame. In a single frame transfer when no fragmentation is used, the ACK field is set to zero to indicate the end of busy medium condition. In the case of a fragment burst, when second and following fragments of an MAC Service Data Unit (MSDU) are sent right after receiving ACK for previous fragment, the duration field contains the time in microseconds in which the current frame transfer would complete. RAF divides the 16-bit duration field into two subfields, one 4-bit Channel Rate subfield and the other 12-bit Frame Length subfield. SNR-guided rate-adaptation (SGRA) [63] uses probe frames in combination with SNR-feedback. SGRA defines two states: interfered state and interference-free state. While in the interference-free state, the rate-adaptation is solely done on the SNR feedback while in the interfered state the SNR feedback is only used as guide and actual decision is made using probe frames. The reason for not using SNR to estimate Frame Delivery Ratio (FDR), in the interfered-state is that SNR values over estimate the FDR while the actual FDR is lower because of interference. Various network application have different requirements in terms of transmission rate, delay and loss tolerance, this information when communicated to the rate-adaptation module, can help it take an intelligent decision [26]. The authors in [26] proposed a scheme which essentially relies on RBAR with a modification that a sender has to specify the loss tolerance of the transported traffic in order that the receiver uses both this information and the current channel estimation to select the appropriate transmission mode. The loss-tolerance information is conveyed to the receiver in RTS frames, by using two bits in the standard headers.

Full Auto Rate (FAR) [64], proposed the use of RTS/CTS procedure before every frame exchange sequence. The transmission rate for these frames is selected using ARF like rate-adaptation schemes, where as for the actual data-frames, FAR proposed the use of RBAR. As proposed in this scheme, while sending the RTS frame, the sender is unaware of the transmission rate of the data-frames that it would send and thus does not know the duration for which it would reserve the medium. Therefore, the medium reservation which is done through the RTS frame by the sender is fundamentally flawed.

5.2. Sender-side SNR-based Open Loop Rate-Adaptation Systems

The initial research which proposed the SNR based rate-adaptation schemes required modification to the standard frames, thus discouraged further research on the better possibilities for SNR-based closed loop rate-adaptation schemes. But nevertheless SNR based CSI is accurate and rate-adaptation schemes relying on SNR are relatively more robust. To avoid using feedback information from a receiver, SNR levels of ACK frames from a receiver are used to estimate the channel quality at a sender [65-69]. Such rate-adaptation schemes are thus sender-side SNR-based open loop systems. A United States patent [65], proposed the use of SNR of ACK frames at the sender side to approximate the SNR at the receiver and select appropriate transmission rate. Inspired from SampleRate and SNR-based approaches, authors in [66] combine frame statistics information with SNR of ACK frames to select a transmission rate which gives highest throughput. A similar approach is used in [67], which uses SNR of beacon frames to estimate the channel conditions and select an appropriate transmission rate thereafter. The authors in [68], proposed the use of frame error rate information for rate adaptation in conjunction with SNR information. Inherently this scheme uses logic similar to SampleRate; where it periodically sends probes channel conditions by sending frames at higher and lower rates. The authors believe that by doing so, without the SNR consideration, can penalize the overall performance in a sense that in case of good channel conditions the frames sent at lower rates causes poor performance and in the case when the channel quality is not supportive, probing with higher transmission rates can cause frame looses and retransmissions. To cope with this issue, they use SNR information which guides while probing at lower and higher data rates. When the channel conditions are good reported by higher SNR then the channel will be probed with more number of frames sent at higher rate and less with lower rate. Conversely, when SNR is low, a smaller fraction of frames is sent at higher rates thus reducing the number of frame losses and delay. The authors in [60] proposed a rate adaptation scheme called MutFed, wherein SNR based feedback is provided by a receiver by sending the 10th ACK frame or the by sending the ACK after expiry of 80ms estimation window at the suggested transmission rate. The receiver's feedback is interpreted by the transmitter in different ways to identify the reason of previous frame losses.

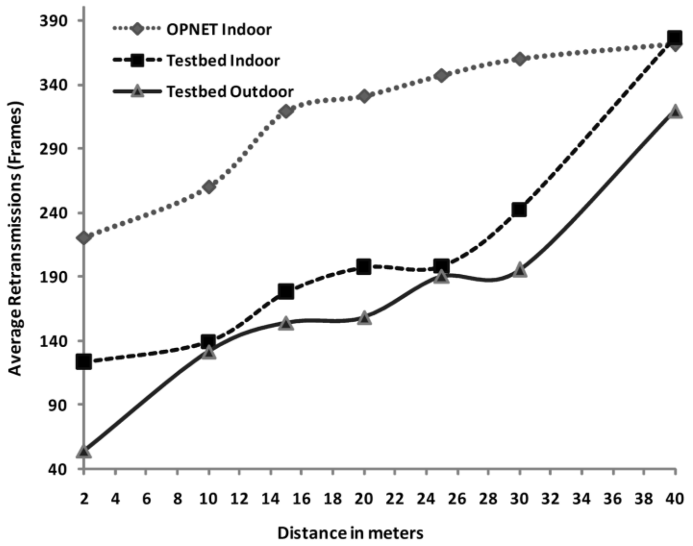

Fig. 2. Comparison of average number of retransmissions in Simulator and Testbed

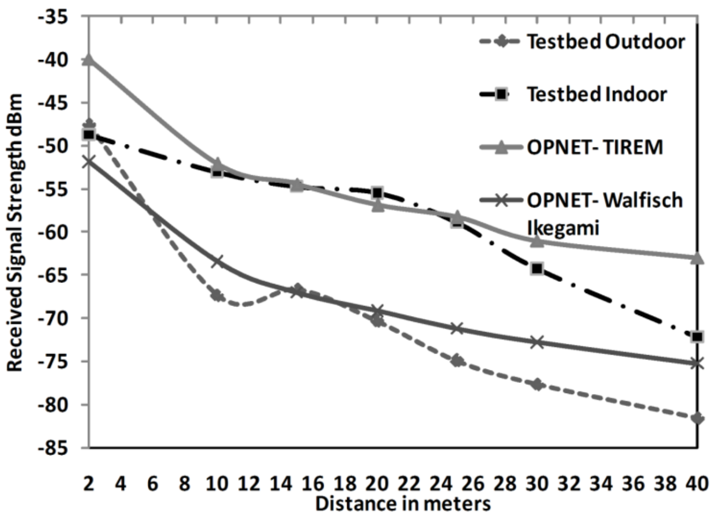

Fig. 2. Comparison of received signal strength in Simulator and Testbed

6. Lessons Learnt and Identified Challenges

Analysis of various frame-statistics based rate-adaptation schemes, as discussed in section-3 shows that such schemes mostly use the following design guidelines:

(1) *Reduce the transmission rate in case of transmission failure [4]*. As discussed in the section-4, there are several reasons of frame losses especially in a distributed-coordinated medium access environment. Transmission failure may not always be indicative of lower SNR and thus blindly reducing the transmission rate further affects the performance.

(2) *Use probe frames to assess the suitability of a newly selected higher rate*. As discussed in [4], that the loss-rate of the most immediate higher rate is usually less than 50%, which implies that the probe frames have higher chances of successful transmission (more than 50%). However, with that loss rate, the overall throughput of the immediately higher rate is lower than the current rate. The authors presented interesting analysis to verify the effects of such design flaws.

(3) *Sequentially increment/decrement the transmission rate*. For statistics-based rate-adaptation schemes, it is practically impossible to be highly responsive and not to use the sequential rate-adjustment, owing to the very nature of estimation of channel state. In contrast, SNR-based rate-adaptation schemes do not need to use the sequential rate-adjustment and can directly switch to any rate suggested by a receiver.

(4) *Use long-term, frame-window to smooth the channel quality variation*. The authors in [4] have shown that mutual information given by two frames spaced by more than 150 ms duration becomes negligible. According to their findings, using a sampling window for a duration of more than 150 ms conveys no information about the actual channel quality and the information may be corrupted by the past samples taken before 150 ms, suggesting an alternate design strategy.

Transmission success or failure is one of the key decision parameters of statistics based rate adaptation schemes, however, as discussed in section-4, a transmission failure may be caused by either: (1) a collided data-frame, (2) collided ACK-frame, (3) corrupted data-frame, (4) corrupted ACK-frame, (5) totally lost data-frame or (6) totally lost-ACK frame. Using the same rules which formed the fundamentals of most of the rate adaptation schemes and which can be stated as '*transmission at lower rates makes frame more robust to corruption*'; we can assume that out of the six likely reasons of frame losses, the corrupted-ACK frame is least likely to occur; because ACK frames are always sent at comparatively lower transmission rates. However, the other five are equally likely to occur. As a general trend in most of the related research literature, it is assumed that collisions are only because of hidden-nodes and as a result RTS/CTS frames are used before actual data-frame exchange to differentiate between PHY losses and MAC losses. However, as reported in [37], the percentage of frame collisions because of simultaneous transmissions increases as the station density increases in a BSS. In such cases, even if the loss-differentiation mechanism identifies and associates the reason of frame loss to be because of collisions; it doesn't always imply that the collisions are because of hidden-nodes. Therefore, after loss-differentiation, simply using RTS/CTS for collision avoidance is not the correct strategy and would cause extra overhead. A great deal of research follows the same direction and relies on the use of RTS/CTS procedure for performing loss-differentiation. The use of RTS/CTS itself is an overhead and quite unfortunately it requires several frame exchanges (with and without RTS/CTS) between the sender and a receiver to arrive at the final conclusion. This overhead is pronounced in case of real-time multimedia traffic with smaller packet sizes. To address this issue various techniques presented in [56-60], can be used in conjunction with a rate-adaptation scheme to estimate the proportion of frame losses, without the use of RTS/CTS exchange.

Closed-loop SNR based rate adaptation schemes provide a better estimate of the CSI and such a rate-adaptation scheme clearly performs better than those schemes which purely rely on 'hit-and-trial' based, sender side schemes. Closed-loop systems are robust and converge quickly to the channel conditions faster than sender side schemes. However, the persistent problem in all (to the best of our knowledge so far) Closed-loop rate-adaptation schemes is the method through which a receiver conveys its feedback to the transmitter. The existing closed-loop rate-adaptation scheme which rely on feedback from a receiver require necessary changes to the original IEEE 802.11 frames specification, e.g. the RBAR requires changes to the MAC data-frame, the RTS/CTS frame and PLCP header. Similarly, RAF changes the duration field in the ACK frames. Incorporating changes in the standard frames renders such rate-adaptation solutions (e.g. like the RBAR and others relying on run-time feedback from the receiver) incompatible to co-exist with the legacy stations in a BSS.

Various assumption are involved in designing sender-side SNR-based open loop systems, e.g. it is assumed that the SNR levels recorded for the ACK frames (at the sender side) are equal to the SNR levels that are experienced by data-frames at a receiver. However, this assumption is not always true and can possibly lead to wrong estimation of channel quality due to the following reasons:

1. The transmission rates used for actual data frames are different from that of ACK frames.
2. The size (and thus the transmission duration) of the data frames and the ACK frames are also different.
3. There is a possibility of uneven SNR levels at the two ends because of the presence of hidden terminals or other sources of interference at either of the two sides, which would result in wrong assumptions of the SNR levels at the other end of communication.
4. Such estimation would also be wrong when different transmission powers are used by a transmitter-receiver pair of stations.

Therefore, sender-side SNR-based rate-adaptation schemes can avoid the use of feedback delivery by a receiver and thus avoiding changes to the standard frames. However it is done using the above assumptions which can be wrong due to either of the aforementioned reasons.. Finally, it is learnt that a larger percentage of the published literature on rate-adaptation schemes, use network simulators to establish proof-of-concept; including NS2, NS3, OPNET, OMNeT++ and QualNet. Rate-adaptation schemes, whether SNR-based or frame-statistics based, both rely on the channel state information mainly determined through SNR and frames retransmission count. Network simulators also lack realism to varying degrees especially for modeling propagation effects [70-72]. **Fig. 2** shows comparison of the average number of retransmissions collected from a MADWiFi based test-bed in a 90 meters corridor on the ground floor of our academic building. The outdoor measurements were collected in a grass ground. The same indoor scenario was simulated using the OPNET's TIREM-4 propagation model. The number of average retransmissions collected from the actual test-bed and those from the simulator vary significantly. This serves as a good evidence that frame-statistics based rate-adaptation schemes implemented in simulators may deviate to varying degrees from the actual implementation. Similarly, **Fig. 3** shows the comparison of the 'received signal strength' in dBm collected from the test-bed and the simulation. Simulated SNR-based rate-adaptation schemes would lack realism as compared to the test-bed implementation.It is recommended that rate-adaptation schemes be implemented on test-beds e.g. the MADWiFi, to improve the confidence in the research.

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