RAAR: A RELAY-BASED ADAPTIVE AUTO RATE PROTOCOL FOR MULTI-RATE AND MULTI-RANGE INFRASTRUCTURE WIRELESS LANS*

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Abstract Auto rate adaptation mechanisms have been proposed to improve the throughput in wireless local area networks with IEEE 802.11a/b/g standards that can support multiple data rate at the physical layer. However, even with the capability of transmitting multi-packets with multi-rate IEEE 802.11 PHY, a mobile host (MH) near the fringe of the Access-Point's (AP's) transmission range still needs to adopt a low-level modulation to cope with the lower signal-to-noise ratio (S-NR), Thus, it can not obtain a data rate as high as that of a host near AP in most cases. According to the characteristics of modulation schemes, the highest data rate between a pair of mobile hosts will be inversely proportional with the transmission distance. Considering these factors, we here demonstrate a Relay-Based Adaptive Auto Rate (RAAR) protocol that can find a suitable relay node for data transmission between transmitter and receiver, and can dynamically adjust its modulation scheme to achieve the maximal throughput of a node according to the transmission distance and the channel condition. The basic concept is that the best modulation schemes are adaptively used by a wireless station to transmit an uplink data frame, according to the path loss condition between the station itself and a relay node, and that between the relay node and AP, thus delivering data at a higher overall data rate. Evaluation results show that this scheme provides significant throughput improvement for nodes located at the fringe of the AP's transmission range, thus remarkably improving overall system performance.

Keywords: Relay-based MAC protocol, Multi-Rate and Multi-Range, Wireless LANs

1. Introduction

In both wired and wireless networks, adaptive transmission techniques are often used to enhance the transmission performance. These techniques generally include varying the transmission power, packet length, coding rate/scheme, and modulation technology over the time-varying channel. Related research in

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cellular networks indicates that throughput would be improved by permitting a mobile station near the center of a cell to use a high-level modulation scheme, while those near the fringe of a cell should use a low-level modulation to cope with the lower signal-to-noise ratio (SNR).

In wireless local area networks (WLANs), the same issue is also considered. Providing that the new high-speed IEEE 802.11a MAC/PHY is adopted, MHs can vary their modulation schemes to transmit packets with different data rates ranging from 6 to 54 $Mbps$. Given such capabilities, all MHs should insist on using the highest-level modulation scheme to obtain the maximal channel utilization. However, as in cellular networks, such insistence is not reasonable because the data rate is inversely proportional to the transmission distance between a pair of MHs, and a high-level modulation scheme requires a higher SNR to obtain the same bit error rate (BER) when compared with that of a lower-level modulation scheme. Thus, without increasing the transmission power to decrease the lifetime of a node, the maximal data rate can be obtained only when the transmitter and receiver are close enough, and a lower data rate should be adopted if the distance is larger. For reference, the expected data rates of IEEE 802.11a (802.11b, and 802.11g) at different ranges measured in [1] are shown in Fig. 1.

Given that, we consider the infrastructure WLAN (IWLAN) defined in IEEE 802.11. In such networks, an AP can provide MHs the access to the Distribution System (DS) and relay packets for all MHs in its transmission range. At the same time, a MH, if equipped with a multi-rate wireless interface such as IEEE 802.11a, can deliver packets to an AP with a suitable data rate based on its distance to AP. These constitute a so-called Multi-rate, Multi-range IWLAN (MMI-WLAN).

In the MMI-WLAN, several auto rate adaptation mechanisms have been proposed to exploit the capability of multi-rate IEEE 802.11 physical layer. Among these, a so-called Opportunistic Auto Rate (OAR) rate adaptation scheme [2] opportunistically grants channel access for multiple packet transmissions in proportion to the ratio of the achievable data rate over the base rate. Similar to OAR, the authors of [3] provide an Adaptive Auto Rate (AAR) protocol that can also transmit multiple packets when the channel conditions are good. For this, AAR carries additional information in each ACK or CTS to indicate the transmission rate of the next data packet, and thus can adapt very quickly to the change of channel quality.

The capability of transmitting multiple packets in a basic slot-time let these methods have the potential to solve the anomaly problem [4] if MHs are located near AP. However, if MHs are located far from AP, these methods still require a low-level modulation to cope with the lower signal-to-noise ratio (SNR), as indicated in the very beginning. This can be an even more serious problem in the MMI-WLAN because, in such networks, if two neighboring MHs desire to communicate to each other, their packets have to be relayed by an AP no matter how close they are. In this environment, it becomes a challenge that how a MH can use a data rate as high as possible to obtain the maximal throughput, without increasing transmitting power and the overall interference in the network.

One possible solution is to deliver data packets through relay nodes. However, even recently, few studies have focused on the issue of directly using IEEE 802.11 MAC to realize a relay mechanism so that the system throughput can be improved [5]. This task is not trivial because unlike TDMA, IEEE 802.11 Distributed Coordination Function (DCF) MAC protocol has the 4-way handshake of RTS/CTS/DATA/ACK, and requires that the roles of sender and receiver should be interchanged several times between a pair of communication nodes.

To provide higher throughputs for MHs not close to AP in the MMI-WLAN, in this work we propose a Relay-Based Adaptive Auto Rate protocol (RAAR) as an enhanced protocol for the MMI-WLAN. RAAR slightly modifies the IEEE 802.11 MAC protocol by introducing a new message exchange procedure for a relay node between a pair of communication nodes. The core idea of RAAR is that after the 4-way handshake of a pair of communication nodes, the relay node should not compete for the channel again, wasting the valuable bandwidth, because the channel is already reserved by the original communication nodes. Our analysis and simulation show that the throughputs of MHs at the fringe of the AP's transmission range can be significantly improved if a suitable relay node can be obtained.

2. Relay-Based Adaptive Auto Rate Control protocol (RAAR)

In this section, the proposed RAAR is introduced in terms of protocol principles and major operations. Before this, the system model of MMI-WLAN under consideration is summarized as follows. Given M different modulation schemes, the MMI-WLAN can be logically segmented into M concentric circles surrounding AP as shown in Fig. 2. This network can be further divided into M disjoint regions: the innermost circle (R_1) and a number of $M - 1$ 'doughnut' like regions which are numbered as R_2, R_3, ..., R_M from inner to outer. The data rate that can be obtained in R_i is denoted as TR_i. For simplicity, we consider only upstream traffic in the MMI-WLAN, i.e., traffic from MHs to AP. This is because, in contrast to MHs having a battery as the usual power supply, AP is fully power-supported, and thus it can choose the data rate more flexibly for transmitting data to MHs. However, this model can be also applied to a general WLAN if the transmission condition over wireless channel is symmetrical.

Transmission of Multiple Back-to-Back Packets

The first aim in RAAR is to keep the channel for an extended number of packets once the channel is measured to be of sufficient quality to allow transmission at rates higher than the base rate. For this, RAAR allows the same time to be granted to a sender as if the sender is transmitting at the base rate. For example, if the IEEE 802.11a interface is adopted in the MMI-WLAN, the base rate is 6 Mbps and a node, MH_i, is located in the innermost region, R_1, wherein 54 Mbps data rate is achievable with 64-QAM modulation scheme. This node is granted a channel access time to send $\lfloor 54/6 \rfloor$ or $\lceil 54/6 \rceil$ (= 9 in both cases) packets to AP conservatively or aggressively. In the former case, the unused time quantum can be released while the latter, the original time quantum should be extended to complete the last packet. This method provides temporal fairness for all MHs in each region. That is, if $\phi_i(t_1, t_2)$ is defined as the service time that a flow in R_i receives during (t_1, t_2), the measure of fairness of RAAR with equal weights for different regions, R_i and R_j, is considered as

$$|\phi_i(t_1, t_2) - \phi_j(t_1, t_2)| \tag{1}$$

This ensures that RAAR provides near base-rate time shares for all MHs in different regions. As indicated in [2], the temporal fairness is more suitable for multi-rate networks than the throughput fairness [6, 7] since normalizing flow throughputs in the latter would cancel the throughput gains available from a multi-rate physical layer.

Relay Node Selection

The second aim in RAAR is for nodes near the fringe of AP's transmission range to transmit packets at a higher rate. For this, RAAR introduces a suitable relay node between the sender and AP to segment the long distance between the communication ends into two shorter pieces. According to the characteristics of modulation schemes, the highest data rate between a pair of mobile hosts will be inversely proportional with the transmission distance. Consequently, even with the same noise level, the reduced path length, and hence the reduced path loss, lead to the sender being able to transmit its data packets through the relay node to AP with a higher rate.

To this end, whenever a MH wants to communicate with an other node, AP should find a suitable relay node, and guide the sender to deliver its data via this node. This can be done because, in the MMI-WLAN, AP has the capability of collecting all MHs' location information, as well as their modulation schemes now adopted [8]. AP can collect such information from periodical status reports or routing information exchanges between MHs and the AP. When a suitable relay node is found for a MH, such information can be delivered from the AP to this node and the relay node just found with the same mechanism of periodical reports or routing exchanges. Consequently, if a mobile host, say MH_i, can find a relay node suggested by AP, it will not deliver its data to AP directly. Instead, MH_i will try transmitting its data via the relay node, say MH_j, to obtain a higher data rate. Otherwise, the transmission will be direct.

This is exemplified in Fig. 3, where the transmission ranges with corresponding data rates are drawn based on the measure data given in Fig. 1. In this figure, MH_i at the fringe of MMI-WLAN is the sender while the destination may be AP, or some other node in the network (not shown). In Fig. 3(b), MH_i, uses MH_j as its relay node to AP, which provides a higher overall data rate. Whereas, in Fig. 3(a), MH_i directly transmits data to AP at only 6 Mbps data rate without the aid of a relay node.

Control Message Flow

Fig. 4 illustrates the RAAR time-line for transmission of data packets. In principle, this is the IEEE 802.11 fragmentation mechanism extended for the incorporation of relay nodes. As the IEEE 802.11 standard, each frame in RAAR contains information that defines the duration of the next transmission. The duration information from the RTS/CTS frame is used to update the NAV to indicate that the channel is busy until the end of ACK0. Both DATA/FRAG0 and ACK0 also contain information to update the NAV to indicate a busy channel until the end of ACK1. This continues until the last fragment which carries the duration ending at the last ACK. The ACK for the last fragment has the duration field set to zero.

As shown above, the control flow indeed follows the same principle of the IEEE 802.11 fragmentation mechanism, and eliminates unnecessary RTS/CTS exchanges to improve the network throughput. That is, in contrast to the direct implementation of IEEE 802.11 4-way handshake, we let the relay node, MH_j, forward DATA/FRAGs from the sender, MH_i, to AP without the exchange of RTS/CTS in advance. This can improve the network throughput because at the very beginning, MH_i and AP have reserved the channel using RTS/CTS transmitted at the base rate. Consequently, the relay node, MH_j, has no need to reserve the channel for MH_i and AP again, which obviously would waste bandwidth for the same transmission.

Traffic and Channel Conditions. There are some issues which arise while using the RAAR protocol. These issues mainly revolve around the behavior of the sender, MH_i. In general, MH_i should calculate the overall transmission time based on its own data rate, TR_s, and the relay node's data rate, TR_r, suggested by AP, to determine whether or not this transmission should go through the relay node. If so, MH_i will estimate the distance between itself and the relay node using information provided by AP, and select a modulation scheme for error free transmission to the relay node.

However, such estimation may be incorrect due to mobility or channel condition change, and consequently, with the modulation scheme just chosen, the data frame could be received incorrectly by AP. In this case, when expecting a new arrival from the relay node after RTS/CTS exchange, AP estimates its ACK time for this frame as well, and if the time expires without receipt of the expected frame, AP can send a NACK to explicitly inform MH_i of this failure. As a result, after obtaining the negative acknowledgement, MH_i sends the following frames to AP directly, with data rate TR_s, and the protocol reverts back to a degraded version of this method, as discussed in the next section.

3. Throughputs of IEEE 802.11 MAC, RAAR and D-RAAR

In the MMI-WLAN, multiple nodes located in multiple regions, using the common wireless channel of IEEE 802.11 PHY are usual cases. In this environment, we first examine the performance anomaly problem of IEEE 802.11 MAC indicated in [4]. Then, we show how this problem can be solved with a degraded version of RAAR. Finally, we demonstrate the capability of RAAR that can further increase the system throughput beyond the solution of D-RAAR. These analytical results are further verified with the simulation results of GloMoSim [9], which is a scalable simulation environment for wireless and wired networks based on PARSEC [10].

IEEE 802.11 performance anomaly

Consider that in a M-region MMI-WLAN, N_j mobile hosts in each region j are ready to transmit an uplink frame with l-bytes UDP data payload using PHY mode m_j with transmit power P_{tx}. In this environment, with the IEEE 802.11 MAC, the total time expended by a MH in transmitting a l-bytes datagram will be

$$T^{'}_{I,overall}(l,j) = T_{tx}(l,m_j) + T_{ov} + T^{'}_{CW} \tag{2}$$

where $T_{tx}(l,m_j)$ denotes the data transmission time for a node in R_j using modulation scheme m_j, T_{ov} represents the constant overhead, $T_{DIFS} + 3 \cdot T_{SIFS} + T_{RTS} + T_{CTS} + T_{ACK} + 4 \cdot T_{PLCP}$, and $T^{'}_{CW}$ denotes the contention window time, $\sum_{j=1}^{K} \left[(1 - P_{coll}) \cdot P_{coll}^{j-1} \cdot \frac{CW(j)}{2}\right] + P_{coll}^{K} \cdot \frac{CW(K)}{2}$. In this window time, $CW(j)$ is $(2^{j-1} \cdot (aCWmin+1) - 1) \cdot aSlotTime$ when $1 \leq j \leq 6$ and becomes $aCWmax \cdot aSlotTime$ when $j \geq 6$[1], K denotes the maximum number of retransmission, and P_{coll} presents the collision probability in the network, and is now obtained with simulations of GloMoSim.

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[1] $aCWnin$ is the minimum contention window size, $aCWmax$ is the maximum contention window size, and aSlotime is the slot time.

With these, we can analyze a node's throughput by considering that the channel utilization of a node in R_j is the ratio between the time to send one packet and the time during which all other mobile hosts transmit once with possible collisions. Because the channel access probability of CSMA/CA is equal for all mobile hosts, the channel utilization factor of a node in R_j can be calculated as

$$U_I^j(l) = \frac{T'_{I,overall}(l,j)}{\sum_{i=1}^{M} N_i \cdot T'_{I,overall}(l,i)} \tag{3}$$

where N_i denotes the number of nodes in R_j. Given that and l-bytes UDP data payload, the node throughput in R_j can be obtained with

$$\begin{aligned} \psi_I^j(l) &= U_I^j(l) \cdot \frac{l}{TR_j \cdot T'_{I,overall}(l,j)} \cdot TR_j \\ &= \frac{l \cdot T'_{I,overall}(l,j)}{\left(\sum_{i=1}^{M} N_i \cdot T'_{I,overall}(l,i)\right) \cdot T'_{I,overall}(l,j)} \\ &= \frac{l}{\sum_{i=1}^{M} N_i \cdot T'_{I,overall}(l,i)} \end{aligned} \tag{4}$$

It can be readily seen in the above that no particular terms with regard to the R_j are involved in the final formula, which implies that a node located in an inner region and using a higher rate to transmit l-bytes data obtains the same throughput as a node located in an outer region and using a lower rate for the same data. Contrary to all expectations of the multiple-rate PHY, this result exhibits the fact that a higher data rate does not bring the throughput higher than the others if it competes with a lower rate. This can be regarded as a performance anomaly problem, and its reason is clearly shown in Eqs. (3) and (4): when only one packet can be transmitted with whatever rate, the equal long term channel access probability leads to the same throughput for all nodes.

Solving The Performance Anomaly Problem of IEEE 802.11 MAC with Degraded RAAR

The basic approach to solving the performance anomaly problem in IEEE 802.11 MAC is to use the same base data rate to send multiple back-to-back data packets whenever the channel is held. This is the so called base-rate time share given in Eq. (1) at the very beginning, and it is indeed the core concept of OAR [2] and AAR [3]. However, the focus of these methods is on the opportunistic performance gain when the channel quality is good for transmission, not on the solution of the anomaly problem.

In our work, D-RAAR aims at both getting the opportunistic performance gain and solving the anomaly problem together when RAAR's relay scheme can not work at that time. That is, when no relay nodes can be found or when a given relay node is missed due to mobility or channel condition change, a sender locating in R_j will use the modulation m_j to transmit multiple back-to-back packets directly to AP, if the channel condition is allowed (referring to Fig. 5). In this case, a MH can transmit the number of $G_D^{(j)}(l)$ back-to-back packets, i.e., the number of $\lfloor \frac{T_{tx}(l,1)}{T'_{tx}(l,m_j)} \rfloor$ or $\lceil \frac{T_{tx}(l,1)}{T'_{tx}(l,m_j)} \rceil$ packets to AP. In above, $T_{tx}(l,1)$ denotes the transmission time of l-bytes UDP data payload using the basic rate with the slowest modulation scheme, 1, and $T'_{tx}(l,m_j)$ denotes the transmission time for the same payload in D-RAAR, which can be obtained as $T'_{tx}(l,m_j) = T_{tx}(l,m_j) + T_{ACK} + 2 \cdot T_{SIFS}$ (referring to Fig. 5).

We now estimate the D-RRAR's throughput by analysis. Consider that a mobile host locating in R_j is ready to use the modulation scheme m_j to transmit l-bytes UDP data payload to AP directly when no relay nodes can be found at that time. Based on the base rate adopted in the MMI-WLAN, the overall transmission time can be calculated as

$$T'_{D,overall}(l,j) = G_D^{(j)}(l) \cdot T'_{tx}(l,m_j) + T_{ov} + T'_{CW} \tag{5}$$

Under the same consideration that the long term channel access probability is equal for all nodes, in D-RAAR, the channel utilization factor of a node in R_j can be

$$U_D^j(l) = \frac{T'_{D,overall}(l,j)}{\sum_{i=1}^{M} N_i \cdot T'_{D,overall}(l,i)} \tag{6}$$

Replacing $U_I^j(l)$ in Eq. (4) with $U_D^j(l)$ in above and considering the overall transmission time of D-RAAR, the resulted equation leads to the fact that in spite of the utilization factor, if multiple packets can be transmitted in a basic slot-time, the node throughput of D-RAAR can increase by several times when compared with IEEE 802.11 MAC. That is,

$$\begin{aligned} \psi_D^j(l) &= U_D^j(l) \cdot \frac{G_D^{(j)}(l) \cdot l}{TR_j \cdot T'_{D,overall}(l,j)} \cdot TR_j \\ &= \frac{T'_{D,overall}(l,j) \cdot G_D^{(j)}(l) \cdot l}{\left(\sum_{i=1}^{M} N_i \cdot T'_{D,overall}(l,i)\right) \cdot T'_{D,overall}(l,j)} \\ &= \frac{G_D^{(j)}(l) \cdot l}{\sum_{i=1}^{M} N_i \cdot T'_{D,overall}(l,i)}. \end{aligned} \tag{7}$$

Note that if the value of the denominator is similar to that of IEEE 802.11 MAC, $G_D^{(j)}(l)$ in the numerator in fact represents the gain factor that D-RAAR can increase on the throughput.

Throughput Analysis of RAAR

As shown above, if the performance-gain factor of D-RAAR, $G_D^{(j)}(l)$, can be larger than 1, the MMI-WLAN's throughput can benefit from only D-RAAR. However, with the degraded method, nodes in the outer regions may not enjoy such performance gain much since the rates that can be obtained there are only marginally larger than the base rate in usual cases. Accordingly, RAAR provides suitable intermediate nodes for relaying data to *AP*, and further increases the throughput of these nodes, as analyzed below.

At first, the overall transmission time in the multiple node environment can be obtained with

$$T'_{R,overall}(l,m,m') = G_R^{(j)}(l) \cdot T_{tx}(l,m,m') + T_{ov} + T'_{CW} \qquad (8)$$

where $G_R^{(j)}(l)$ represents the number of multiple back-to-back packets that can be obtained with RAAR, given by $\lfloor \frac{T_{tx}(l,1)}{T_{tx}(l,m,m')} \rfloor$ or $\lceil \frac{T_{tx}(l,1)}{T_{tx}(l,m,m')} \rceil$, and $T_{tx}(l,m,m')$ denotes the data transmission time when the relay node is involved. Referring to Fig. 4, this time can be obtained with $T_{tx}(l,m,m') = 3 \cdot T_{SIFS} + 3 \cdot T_{PCLP} + T_{tx}(l,m) + T_{tx}(l,m') + T_{ACK}$, where $T_{tx}(l,m)$ and $T_{tx}(l,m')$ denote the transmission time of this packet from the sender to the relay node and that from the relay node to the AP, respectively.

Given this time, in RAAR, the channel utilization factor of a node in R_j can be obtained with

$$U_R^j(l) = \frac{T'_{R,overall}(l,m,m')}{\sum_{i=1}^{M} N_i \cdot T'_{overall}(l,m,m')} \qquad (9)$$

Accordingly, when considering $G_R^{(j)}(l)$ packets delivered in the basic slot-time, $T_{tx}(l,1)$, the node throughput of RAAR in R_j can be estimated by

$$\begin{aligned}
\psi_R^j(l) &= U_R^j(l) \cdot \frac{G_R^{(j)}(l) \cdot l}{TR_j \cdot T'_{R,overall}(l,m,m')} \cdot TR_j \\
&= \frac{T'_{R,overall}(l,m,m') \cdot G_R^{(j)}(l) \cdot l}{\left(\sum_{i=1}^{M} N_i \cdot T'_{R,overall}(l,m,m')\right) \cdot T'_{R,overall}(l,m,m')} \\
&= \frac{G_R^{(j)}(l) \cdot l}{\sum_{i=1}^{M} N_i \cdot T'_{R,overall}(l,m,m')} \qquad (10)
\end{aligned}$$

Throughput Comparison of IEEE 802.11 MAC, D-RAAR, and RAAR

In this subsection, the analysis indicated in the previous section is verified and its results are further confirmed with simulations of GloMoSim. With both analysis and simulation, we exhibit the possible performance benefit of D-RAAR and that of RAAR.

The environment under consideration is shown in Fig. 6, wherein five nodes are located in each region, and in total eight regions are taken into account in the MMI-WLAN according to the IEEE 802.11a measure data shown in Fig. 1. For simplicity, no nodes change their regions in the run time and a suitable relay node can be found when a sender want to delivery its data to AP. With this scenario, the methods under consideration are analyzed and simulated, and their results are given in Fig. 7.

Fig. 7(a) shows the node throughputs in R_8 with RAAR, and those in R_1 to R_7 with IEEE 802.11 MAC, for different sizes of UDP data payload. It can be seen from both analysis and simulation that IEEE 802.11 MAC results in the same throughput in spite of a node's location, which is the so-called 802.11 performance anomaly problem indicated previously, while RAAR significantly improves the node throughput in the outermost region, as expected. Fig. (7)b shows the node throughput obtained with D-RAAR for different sizes of UDP data payload. Obviously, D-RAAR gives nodes in inner regions higher throughput than nodes in outer regions, fully utilizing the capability of multi-rate IEEE 802.11a PHY. Finally, Fig. (7)c shows the node throughput obtained with RAAR in the outermost region, R_8. For comparison, the theoretical results of all regions and simulation results of R_8 with D-RAAR are also given. It is readily observable that the node throughput of R_8 is significantly improved by RAAR. This confirms our argument that, even though D-RAAR can transmit multiple back-to-back packets when nodes near AP, in the outermost region, R_8, such a degraded method can provide at most one packet with the lowest data rate, 6 Mbps. In such situation, RAAR shows its capability most remarkably.

Given the results in Fig. (7)c, the question arises that, in addition to the outermost region, how many other regions can benefit from RAAR. To answer this question, we extend the experiment in Fig. (7)c to collect not only D-RAAR's results, but those of RAAR for each region and each UDP payload size. These experimental results are now shown in Fig. 8. As shown in Fig. (8)a, the performance-gain-factor ratio, $G_R^{(j)}(l)/G_D^{(j)}(l)$, is larger than or equal to one in R_8 to R_5 for most data payload sizes, which implies the possible throughput benefits existing in these regions. This is confirmed in Fig. (8)b, which shows the corresponding ratios between the RAAR's throughputs and the D-RAAR's throughputs. For example, the value of 3 for payload size of 2000 bytes indicates that the RAAR's throughput can be $3\times$ that of D-RAAR, in the outermost region. Apart from this most remarkable example, other values larger than 1 can be also seen from R_8 to R_5 for most payload sizes.

These results suggest that the node throughput can benefit from RAAR when nodes are located in an outer region of the MMI-WLAN. In particular, the outermost four regions are preferred when using the measure data given in [1]. With this evaluation scheme, we estimate which regions can benefit from RAAR, and except for IEEE 802.11a, the same evaluation scheme is also considered to be applicable to other multi-rate 802.11 PHY. This would be an interesting possibility for future research.

4. Conclusion

In this paper, we introduce the Relay-Based Adaptive Auto Rate protocol, which can find a suitable relay node for data transmission between transmitter and receiver. RAAR can dynamically adjust a node's modulation scheme to achieve its maximal throughput regarding the transmission distance and the channel condition. When mobility and channel condition changes cause the relay node's information to be out of date, RAAR reverts back to a degraded version of this method, namely D-RAAR, to transmit multiple back-to-back packets directly from the sender to AP without the aid of a relay node. Experiment results indicate that with this scheme, significant improvement on throughput can be achieved for nodes located at the fringe of the AP's transmission.

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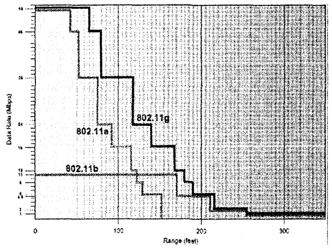


Fig. 1. Expected 802.11a, 802.11b, and 802.11g Data Rates at Varying Distance from Access Point

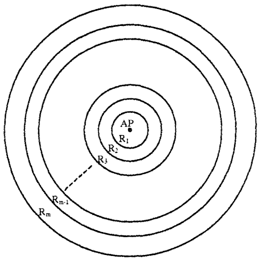


Fig. 2. Network architecture of the MMI-IWLAN

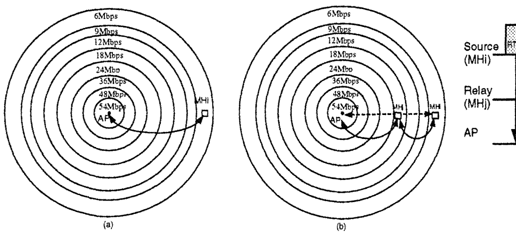


Fig. 3. Environment for the single node's throughput comparison
(a) direct transmission
(b) transmission with relay node

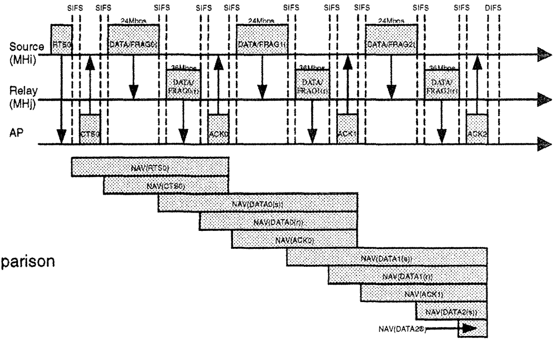


Fig. 4. The control message flow of RAAR

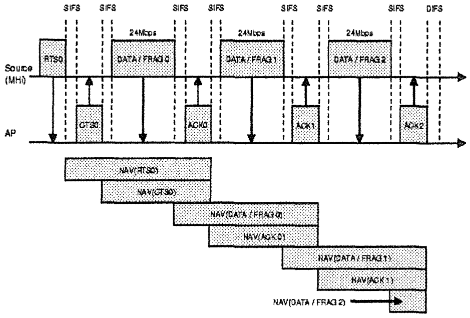


Fig. 5. The control message flow of D-RAAR

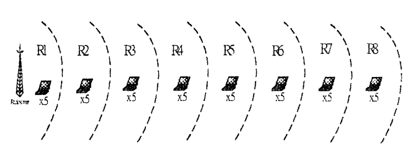
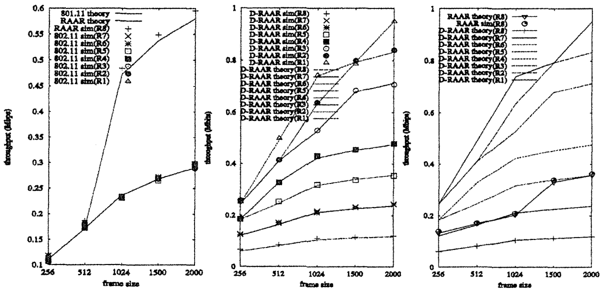


Fig. 6. The environment with multiple nodes deployed in the MMI-WLAN



(a) (b) (c)

Fig. 7. Throughput comparison results : (a) $\psi_I^j(l)$, $j = 1,\dots,7$ and $\psi_R^j(l)$, $j = 8$ (b) $\psi_D^j(l)$, $j = 1,\dots,8$ and (c) $\psi_D^j(l)$, $j = 1,\dots,8$ and $\psi_R^j(l)$, $j = 8$

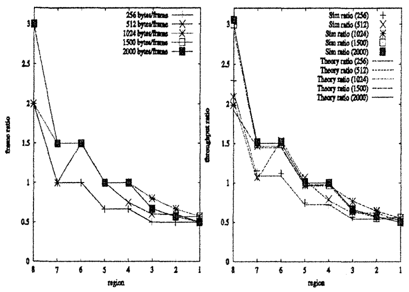


Fig. 8. Performance ratio : (a) performance - gain factor ratio, $G_R^j(l)/G_D^j(l)$, and (b) throughput ratio, $\psi_R^j(l)/\psi_D^j(l)$