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# An Enhanced Minstrel Link Adaption Scheme for IEEE 802.11 WLANs

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***Abstract***

*Link adaption varies channel parameters to match dynamic changes in wireless link in order to achieve an optimal throughput performance. It is a very important research issue in Wireless LANs(WLANs), but there is few description about that in 802.11 specifications. In this paper, we propose an Enhanced Minstrel Link Adaption (EMLA) scheme, which is partly based on Minstrel and includes three parts of SNR Calibration, MCS Protection and Guard interval(Gi) Adaption. SNR Calibration is a mechanism to estimate the downlink SNR from transmitter side via probing. The more accurate of the SNR estimation brings the more rational of the MCS selection, thus the transmitting error ratio decreases.MCS Protection provides a MCS range according to the SNR estimation and only MCS in the range is permitted to select on transmitter, which prevent the MCS from misadjusting, then PHY_rate of transmitting is protected. Another improvement comes from the Gi adaption. By choosing the Gi mode dynamically, the transmitter can adapt to the channel state and extend effective transmission time. The experiment and simulation shows, in contrast to Minstrel, EMLA can cope with the worsening of the throughput caused by collision, interference and time varying effectively, therefore network performance enhanced.*

***Keywords***: *Link adaption, Minstrel, MCS, Gi mode, WLAN*

## 1. Introduction

As the most prevailing wireless access technology, the WLANs has been developed rapidly in recent years, especially in physical layer (PHY). 802.11b, the first amendment to the IEEE 802.11 specification, uses Direct Sequence Spread Spectrum (DSSS) in PHY, and supports four Modulation and Coding Sets (MCSs) at the rates of 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps [1]. Then, 802.11a/g raises the PHY throughput to 54 Mbps by introducing Orthogonal Frequency Division Multiplexing (OFDM), and the MCS level is also extend to 12 [2], which is still compatible with 802.11b in MCSs less than four. 802.11n, being proposed in 2004, is the mainstream of WLANs currently. Based on original OFDM, and by increasing sub carriers(from 48 to 52), enhancing coding efficiency(from 3/4 to 5/6), broadening bandwidth (from 20MHz to 40MHz) and introducing Multi-Input and Multi-Output(MIMO), which supports 4 spatial streams simultaneous, 802.11n can reach 600 Mbps in PHY, and has more MCSs[3]. The newest amendment, 802.11ac is the upgrading version of 802.11n. It broadens single user’s bandwidth to 80MHz and supports 256QAM and MU-MIMO, so WLANs peak rate can reach up to 1 Gbps and more MCS levels appears[4]. In spite that WLANs’ peak throughput upgrades gradually, the actual network throughput cannot reach theoretical value, due to wireless channel’s interference, fading and multi-users conflict. Furthermore, although in 802.11 different MCSs are defined in details on modulation and coding schemes, it has not described on how to choose MCS and other link parameters according to real channel condition. Therefore, it is necessary to research on WLANs’ link adaption

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technology, to ensure that each link parameter selection could adapt wireless channel changes and ensure the best performance of WLANs in real deployment.

In 802.11, MCS adaption is the core of link adaption. There are two fundamental issues: the first is what's kind of Channel State Information (CSI) does adaptive adjust depend on? The second is how to adjust according to the CSI? According to CSI, link adaption can fall into three categories: the first one is acknowledgment feedback (ACK) based on MAC layer. Bell labs propose an Automatic Rate Fallback (ARF) scheme [5] in 1990s, which is based on keeping track of a timing-function and missed ACKs. When successful ACKs number exceeds a certain threshold, MCS is upgraded; while when failed ACK appears, MCS would be degraded. The ARF enjoys the advantage of the simplification in implementation, easy acquisition of ACK and high compatibility in Station (STA), but ACK's success or failure has randomness and misadjustment would appear sometimes if directly adjust according to the latest ACK result. In addition, ACK cannot reflect real-time channel changes as feedback delay. So there is an improvement on ARF to adapt channel condition by dynamically adjusting MCS threshold of rising or falling [6].

The second one is based on measured CSI on PHY layer, such as RSSI, SNR. Then link adaption based on RSSI is proposed, which speculates on the best MCS for current channel according to measured RSSI value by establishing the mapping relation between MCS and RSSI [7]. However, as measured RSSI value comes from transmitter side and cannot accurately reflect channel state on receiver side, and MCS is not totally corresponding to channel quality in spite of their relevance. And the interference widely exists in WLANs would also influence the accuracy of MCS adjustment based on RSSI. In addition, neither ACK feedback nor measured CSI has taken collision into consideration. As MAC layer of WLANs adopts Distributed coordination Function (DCF) scheduling mode which is lack of unified management, the collision exists among multi-users and multi-APs extensively, and the best rate cannot be obtained with serious collision even with the best wireless channel quality. Collision is the main reason for transmission failure in multi-users and high density scenario. If only adjust based on ACK, MCS level would decline radically and user throughput would be seriously worsen. So link adaption algorithm considering collision is proposed , which takes advantage of Clear Channel Assessment(CCA) mechanism and by means of RTS Probing to avoids collision before data transmission and achieve better performance[8, 16]. However, RTS/CTS is not universally deployed in real infrastructures, and RTS/CTS would also consume wireless resource, and RTS/CTS itself cannot prevent collision [12]. Therefore, this kind of algorithm still has its limitation yet.

The third is link adaption based on long-term statistics. A probability table is established for each STA to predict the maximum throughput or minimum error ratio by means of periodical training, which is regarded as the reference of MCS selection in next transmission. The typical algorithm is Minstrel, which is the most prevalent algorithm in currently commercial WLANs, and applied in WLAN AP based on MadWiFi, Ath5x and Ath9x [9-11]. Minstrel algorithm supposed that the interference, fading and collision in channel has been taken into consideration in historical statistics. So real-time measurement is not necessary and only persistent looking around of MCS and refreshing the statistics in rate table is enough. Minstrel has been proved to enjoy favorable effect in most slow-varying and low-density indoor channel condition. But when channel varies quickly or in high-density condition, in which random and unexpected collision is frequent, this algorithm has its limitation too, and even inferior to constant-rate algorithm [13, 14]. And with the evolution of WLAN and increasing of MCS levels, periodical training itself would have influence on performance.

Link adaption is designed for network throughput improvement, and throughput is usually determined by three elements of PHY rate, packet error rate (PER) and effective transmission time. So, most of the link adaption schemes concentrate on enhancing PHY rate, reducing PER or extending effective transmission time. ARF would improve throughput by reducing PER, from which MCS selection would be conservative. Link adaption based on channel measurement would select the higher MCS to improve throughput, but meanwhile, the higher MCS stands for higher PER. Based on training statistics, Minstrel can get balanced between lower PER and higher MCS to some extent. As for extending effective transmission time, CCA technology is a way by reducing collision rate and ShortGi technology in 802.11n is another way by shortening guard interval between symbols.

Considering on the three elements in link adaption, an enhanced scheme named EMLA is proposed in this paper. This scheme is partly based on Minstrel, but by means of SNR calibration mechanism, transmitter can acquire relatively accurate estimation of signal strength on receiver side. And a MCS protection mechanism is introduced, which establishes a MCS protection range corresponding to a certain SNR grade, and permit transmitter to select MCS within protection range to communicate with receiver. In this way, the MCS selection can quickly and accurately match channel varying condition to reduce transmission error, and avoid MCS mis-degrading due to possible collision. Furthermore, ShortGi is introduced in 802.11n to extend effective transmission time. While Gi mode exists as semi-static parameter and cannot be adjusted dynamically, so the enhanced scheme brings Gi mode into adaptive adjustment, and carries on improving WLANs' performance by selecting Gi Mode according to channel quality and relevancy.

The WLANs discussed in this paper is based on IEEE802.11n, and only the Distributed Coordination Function (DCF) is considered. The remainder of this paper is organized as follows: Section II would give a simple introduction on MCS in 802.11n and Minstrel technology; Section III would propose the EMLA scheme and elaborate on its key technology; Section VI would carry out customized experiments and simulations, to demonstrate on the gains of the enhanced scheme; then it comes to the conclusion in Section V.

## 2. Preliminaries

Minstrel is the most widely used link adaption in commercial WLANs. But few documents elaborate on its implementation and performance. So this paper would give a brief introduction on Minstrel firstly. Typical Minstrel consists of three parts: MCS Finding, MCS Table Updating and MCS Probing.

### 2.1 MCS Finding

In WLANs, AP and STA would negotiate on initial configuration, which cannot determine the MCS when AP and STA begin to communicate but can determine the channel parameters for communication between them, such as a/b/g/n modes, single, double or multi-spatial stream, and bandwidth of 20MHz or 40MHz. According to the channel configuration, Minstrel can acquire a MCS range. The highest MCS in the range is the $MCS_h$ corresponding to max PHY rate in current channel. By means of calculating the predicted throughput (Throughput) of each MCS in [1, $MCS_h$], and using the formula as 1), MCS Finding choose the MCS with the highest throughput as the MCS up-threshold, that is $MCS_0$.

$$Throughput_p = f_{rate}(MCS) \times (1 - PER) \quad 1)$$

In1), $f_{rate}(.)$ refers to the mapping table from MCS to PHY rate.

After selection of $MCS_0$, $MCS_{1\sim3}$ could also be chosen sequentially downwards to be an alternative MCS sets for the next transmission. In the sets, $MCS_0$ is the rate with the best throughput, $MCS_1$ is the rate with the second best throughput, $MCS_2$ is the rate with the highest probability of success, and $MCS_3$ is the lowest available rate, as shown in

 

Table 1. A packet is first transmitted at rate $MCS_0$ for retry0 attempts. If not successful, the packet is then transmitted at $MCS_1$ for retry 1 attempts, and so on. The transmission will go on until the sum of retry0, retry1, retry2 and retry3 attempts have been made from $MCS_0$ to $MCS_3$, or the packet has been successfully transmitted. Once the packet is successfully transmitted, any remainder of the retry is ignored. In Ath9K, retry0~3 respectively is 2, 2, 2, 4, and this is also a typical value of Minstrel [11].

**Table 1. Minstrel Retry Chain**

| **Try** | **Look around mode** | | **Normal mode** |
|---|---|---|---|
| | **Radom<Best** | **Radom>Best** | |
| $MCS_0$ | Best Rate | Radom Rate | Best Rate |
| $MCS_1$ | Radom Rate | Best Rate | 2nd Best Rate |
| $MCS_2$ | Best Prob | Best Prob | Best Prob |
| $MCS_3$ | Base Rate | Base Rate | Base Rate |

### 2.2 MCS Table Updating

MCS table refers to historical PER information corresponding to each level of MCS. Only continuously refreshing MCS table can acquire relatively accurate throughput rate estimation. In fact, it is a kind of training, and the longer training time is, the more valuable MCS table is and the more accurate MCS Finding is.

Define max retry attempts as N for one packet sending. N=retry0+retry1+retry2+retry3. n is the index of the successful MCS:

$$\mathrm{PER}_{mcs} = \begin{cases} HisPER_{mcs} \times \alpha + 100 \times (1-\alpha) .............mcs \neq mcs_n \\ HisPER_{mcs} \times \alpha + PER(n) \times (1-\alpha) .......mcs = mcs_n \end{cases}$$

$$\mathrm{PER(n)}=\sum_{i=1}^{n} retries_n / (\sum_{i=1}^{n} retries_n + 1) \qquad 2)$$

In 2), $PER_{mcs}$ refers to historical PER of this MCS level, and. The selection of α is the key of the Minstrel algorithm, called Exponential Weighted Moving Average (EWMA). Using EWMA allows us to shift more importance on recent results, than older results. Consequently, we can cope with environmental changes, as old results from a potentially different environment are ignored.

### 2.3 MCS Probing

MCS Table Updating could update MCS0~3 according to data packet sending and retry, but cannot update all the MCSs in MCS Table. Once channel changes due to interference or fading, MCS cannot be adjusted timely. Therefore, Minstrel has designed MCS Probing.

MCS Probing contains two modes. One is normal mode: when current data packet transmission succeeds at $MCS_0$, PER corresponding to $MCS_0$ is less than a threshold (12% for example), and the time apart from last MCS upgrades exceeds a threshold (50ms for example). MCS Probing would start to level up MCS to $MCS_h$+1, and refresh the PER information in MCS table according to the transmission result of $MCS_h$+1.

Minstrel transmits 90% of the data frames using normal mode, and the remaining 10% using look round mode, in which another random rate is selected for MCS Table Updating. During look round transmission, two random MCS is selected, among which the higher one is set to replace $MCS_0$, and the lower one is set as $MCS_1$. Additionally, as normal mode, $MCS_2$ is still the rate with the highest chance of success and $MCS_3$ is the lowest available base rate.

As showed in Table 1, by means of Minstrel Retry Chain and after a period of training, MCS Probing of all grades could be done and MCS table is acquired. MCS table stands for the success probability of every MCS transmission, and is statistics based on long-term, which can reflect the trend of channel changes and guide system to make better choice of MCS. What should be noticed is that Minstrel is still link adaption according to PER statistics, so when PER cannot fully represent the channel quality changes or PER has not updated timely, the algorithm still has its limitation to some extent.

## 3. The Proposed Enhanced Minstrel Link Adaption Scheme

In this section, we would present the details of EMLA scheme. By introducing SNR calibration, MCS Protection, Gi adaption mechanism into typical Minstrel, this scheme can solve the problems of Minstrel which simply depends on PER, cannot timely adapt to channel changes and selects MCS over-conservatively in high-density coverage and collision scenario. In this way, WLANs performance would be improved.

### 3.1 SNR Calibration via Probing

The main scenario of WLANs is indoor coverage, which is a typical slow-fading channel.

$$MCS_{optim} = f_{snr2mcs}(SNR_{dl}) \qquad 3)$$

In 3), $f_{snr2mcs}(.)$ is the mapping function from SNR to MCS. Mapping relation is the theoretical demodulation threshold of MCS in a certain channel condition. Table 2 gives the example of demodulation threshold of MCS0~6 in channel D [17] when PER<10%:

**Table 2. MCS Mapping to SNR**

| **MCS** | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| **SNR(dB)** | 5.0 | 7.8 | 12.3 | 14.0 | 19.0 | 21.7 | 24.0 |

Selection of an optimal MCS in transmitter comes from accurate estimation of the $SNR_{dl}$. However WLANs is lack of power control mechanism, so transmitter cannot directly acquire receiver's SNR measurement. Usually, $SNR_{dl}$ is calibrated by $SNR_{ul}$ using $SNR_{dl}=SNR_{ul}+\Delta$. As a constant, $\Delta$ is used to represent dissymmetry of uplink and downlink. WLANs is a typical system of dissymmetry: AP transmitting power is higher than STA, and transmit powers of several STA are also distinctive, such as lap-top, data card and smart-phone. Besides, influenced by channel changes, such as STA moving or shadow effect, $\Delta$ itself would change. So a more accurate estimation of $\Delta$ must be obtained from $SNR_{dl}$ calibration. This paper proposes a SNR calibration via probing.

Standard probing is a periodical event, and $T_c$ stands for the probing period, and $N_c$ represent repetition times of probing. Considered that $\Delta$ is a slow-varying parameter, $T_c$ can be set in seconds. Within every $T_c$, probing data packet send from the highest MCS to the lowest one according to the negotiating MCS sets between AP and STAs. And in order to shorten the probing period and avoid the interference between multi-streams, only single spatial stream is selected from MCS=7 to MCS=0, as shown in Figure 1:

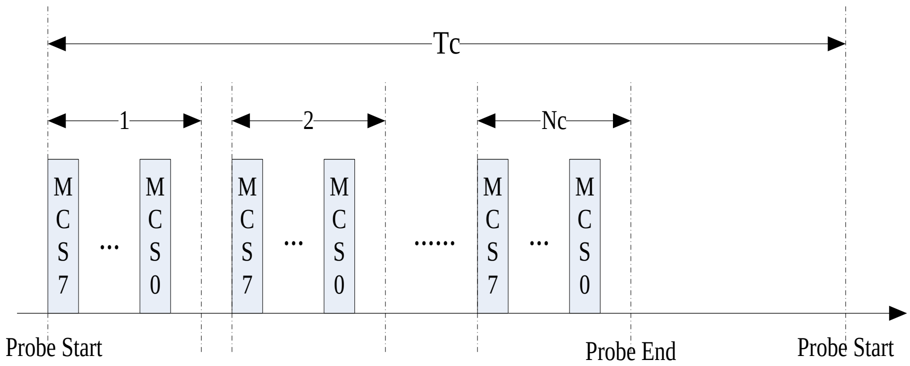


**Figure 1. Probing Procedure of SNR Calibration**

After probing, PER of all MCS is counted on during probing respectively:

$$PER_i = \frac{\sum_{j=1}^{N} PacketLoss_{MCS_{i,j}}}{\sum_{j=1}^{N} PacketAck_{MCS_{i,j}} + \sum_{j=1}^{N} PacketLoss_{MCS_{i,j}}} \quad 4)$$

Then, the predicted throughput of each MCS is calculated according to PER and theoretical PHY_rate, and the maximum prediction is corresponding to the optimal MCS:

$$MCS_{optim} = \arg\max_i(\mathrm{PHY\_}Rate_i \times (1 - PER_i)) \quad 5)$$

During probing, there are several $SNR_{ul}$ measurements, on which we can get mean value of $SNR_{ul}$:

$$\overline{SNR_{ul}} = 10\lg(\frac{1}{N}\sum_{n=1}^{N} 10^{\frac{SNR_{ul}(n)}{10}}) \quad 6)$$

In 6), $SNR_{ul}(n)$ is the $n^{th}$ $SNR_{ul}$ measurement value during probing. After acquiring $SNR_{ul}$ average value, use $\overline{SNR_{ul}}$ and $MCS_{optim}$ to calibration:

$$\Delta = f_{mcs2snr}(MCS_{optim}) - \overline{SNR_{ul}} \quad 7)$$

In 7), $f_{mcs2snr}(.)$ is the mapping function from MCS to SNR, which can be got by making use of MCS's demodulation threshold, referring to Table 2. In order to reduce calibration error, every Δ from calibration could be filtered and $SNR_{dl}$ after calibration is:

$$SNR_{dl}(k) = \overline{SNR_{ul}(k)} + \Delta(k) \quad 8)$$

The acquiring of $SNR_{dl}$ calibration can improve rationality of MCS selection, which is the base of the whole enhanced scheme.

### 3.2 MCS Protection

The core idea of MCS protection is: in channel with high SNR, link adaption scheme should not degrade the MCS level. Minstrel would adjust MCS fully depending on transmission PER, so this algorithm's performance would be greatly influenced, in condition of high SNR and high PER, such as serious hidden node collision or multi-user collision. Either MCS selection progresses radically to cause over-high PER, or MCS selection is conservative to cause channel resource waste and performance loss. Therefore a MCS protection mechanism is necessary.

Firstly, we establish a semi-static mapping table in which several SNR ranges are set up. As $SNR_{dl}$ has been calibrated, a mapping table can be established between SNR range and proposed MCS according to channel simulation [15]. Then according to the statistics of every MCS, a mapping relation is established between MCS levels and "MCS selection experience". "MCS selection experience" represents utilized information of MCS in history, which can be selected times or PER accumulation. SNR range is set as the gap of two MCS demodulation thresholds. If the gap is over large, which means too many MCS levels within a SNR range, then MCS protection precision would be insufficient. On the contrary, if the gap is over small, then even a tiny SNR error would affect on the selection of MCS protection. As the example of Table 4, 5dB is selected.

Uplink SNR information can be acquired in ACK frame after decoding. By means of calibration, SNR ranges corresponding can be selected. And "MCS selection experience" can be updated according to the MCS selected in the latest transmission.

$$P_{ij}(n) = (1-\beta) \times P_{ij}(n-1) + \beta \times \delta_{ij}(n) \qquad 9)$$

In 9), $P_{ij}(n)$ refers to MCS selection experience corresponding to the $n^{th}$ updating in the $i^{th}$ SNR range, β refers to filter factor, and $\delta_{ij}$ is described as follow:

$$\delta_{ij}(n) = \begin{cases} 1 - PER_{mcsj} .....j \neq MCS_j \\ P_{ij}(n-1)........j = MCS_j \end{cases} \qquad 10)$$

Physical meaning of $P_{ij}$ is: the accumulated transmission probability of all MCS in all SNR ranges. This probability is used to calculate predicted throughput corresponding to each MCS:

$$MCS_{protection} = \arg\max_{i}(PHY\_rate_j \times P_{ij}) \qquad 11)$$

In 11), i refers to $i^{th}$ SNR range, j refers to $j^{th}$ MCS. $PHY\_rate_j$ refers to PHY_rate corresponding to $j^{th}$ MCS, and select MCS with maximum $throughput_{predicted}$ as $MCS_{protection}$.

In MCS finding of Minstrel, if PER of current MCS increased, $MCS_0$ would be degraded without protection to find expected MCS of better throughput. Taking single spatial stream for example, $MCS_0$ would be degraded to MSC=0; in a similar way, when channel condition is recovered, MCS probing would still stay at low level for a while and $MCS_{optim}$ cannot be immediately recovered. So we can improve on the Minstrel by the mechanism of MCS protection, which means in a certain channel state, $MCS_0$ should not be degraded to be lower than $MCS_{protection}$.

There are two MCS protection trigger conditions: one is that $MCS_0$ is degraded to be lower than $MCS_{protection}$; the other is that $MCS_{protection}$ updates with channel changes periodically. The period is $T_p$. Algorithm procedure is described as Figure 2. In Figure 2, the part outside of the black rectangle is typical Minstrel algorithm procedure, and the part inside is improved scheme based on MCS protection and SNR calibration. This improvement can effectively prevent PER from rising caused by collision and performance loss caused by MCS degrading; MCSoptim and throughput can recover quickly after real channel interference is removed; the over-conservative problem of Minstrel selection is solved preferably.

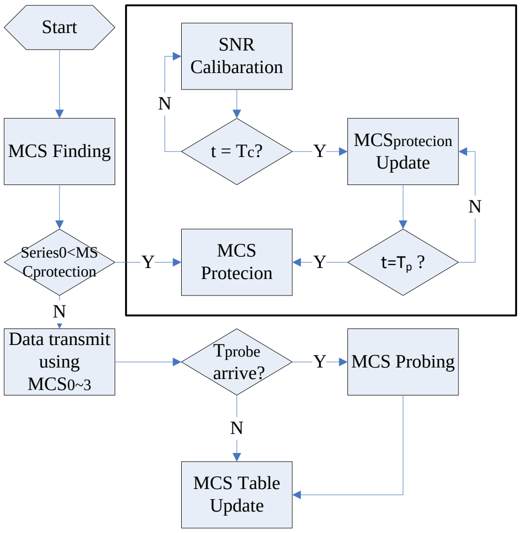


**Figure 2. Flow Chart for MCS Protection and SNR Calibration**

### 3.3 Gi Adaption via Probing

Gi mode itself is a semi-static parameter, and is determined when AP and STA initially negotiate. In 802.11a/g, Gi only has LongGi mode of 800ns; in 802.11n, ShortGi of 400ns is introduced. Theoretically, as guard interval of OFDM symbols is shorter, ShortGi has 11% higher throughput improvement in PHY than LongGi. The selection of ShortGi or LongGi depends on channel relevancy. In the channel with less relevancy and interference, selecting ShortGi would bring performance gain; on the contrary, false selecting ShortGi would worsen performance. The relevancy change in real-time, but Gi mode is semi-static parameter which cannot reflect channel condition. Gi adaption would be started through considering about detection on ShortGi and LongGi, which enables WLAN to adapt to channel changes and extend user's effective transmission time.

As the time delaying parameter of channel which determines on Gi mode is slow-varying parameter, periodically probing procedure can be adopted to find the suitable Gi mode in a certain period. On the other hand, in order to reduce probing expense, event trigger probing can be taken into consideration.

 

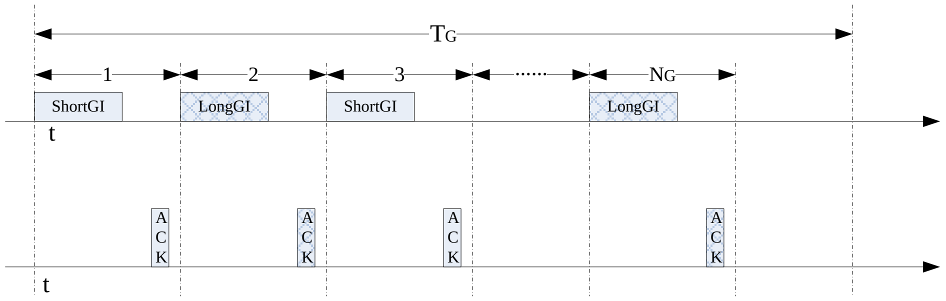


**Figure 3. Probing Procedure of Gi Adaption**

Periodical detection mode means that every user regards $T_G$ as trigger detection period. Considering about the influence of channel fading and collision on probing accuracy, ShortGi and LongGi is alternatively adopted to detect channel and $N_G$ detection packets are sent. $N_G$ should be large enough to prevent influence of channel time selective fading and collision packet loss on probing accuracy. Probing procedure is described in Figure 3. All the probing frame should use the lowest MCS with single stream, which reduces the PER causing by multi-stream interference.

Periodical detection mode could acquire the performance condition in different Gi mode of user. But within the period, improper Gi mode selection would cause unnecessary performance loss. Event trigger mode can effectively solve this problem. Define event trigger detection as: 1) if current Gi mode is ShortGi, PER<10% within detection period, so channel condition is good with less interference, and probing won't be started in next period; 2) if current mode is LongGi, and N times results are LongGi continuously, then probing won't be started in next period.

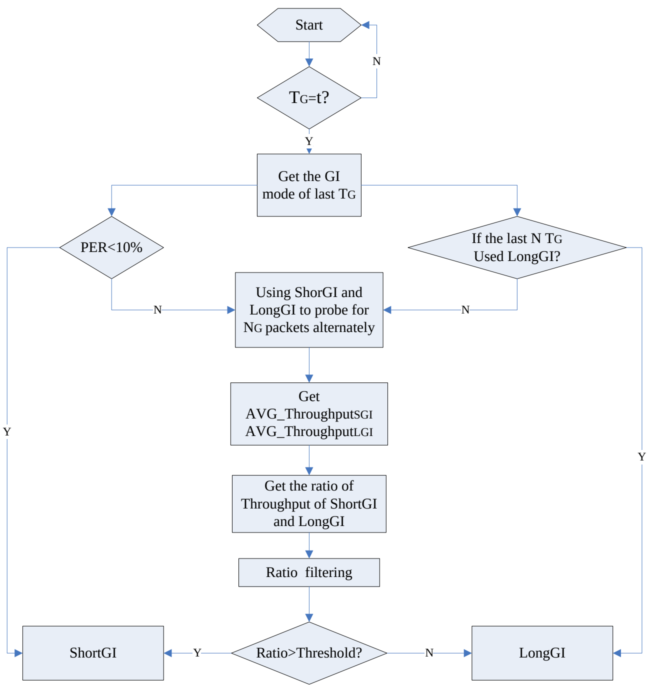


**Figure 4. Flow Chart of Gi Adaption**

After completing $N_G$ times probing, Gi mode selection can be done according to PER within the period. Respectively count on throughput rate of ShortGi and LongGi, and estimate on their throughput. The method is to count on instant throughput rate after every probing transmission:

$$Throughput_{SGi}^{(m)}(n) = 1 / \sum_{i=1}^{retries^{(m)}(n)} [\frac{1}{PHY\_rate_{SGi}^{(m)}(i,n)}] \quad 12)$$

$$AVG\_Throughput_{SGi}^{(m)} = \frac{1}{N_{Gi\_Probe}} \sum_{n=1}^{N_{Gi\_Probe}} Throughput_{SGi}^{(m)}(n) \quad 13)$$

In 12), $retries^{(m)}(n)$ refers to total retries times of $n^{th}$ ShortGi probing within $m^{th}$ probing period, for example, if retries times is (2,1,0,0) corresponding to each series, then total retries is 3 times, so $retries^{(m)}(n)=3$. $PHY\_rate_{SGi}^{(m)}(i, n)$ means that MCS rate of $n^{th}$ ShortGi probing in $m^{th}$ Probing period. Count on average throughput in probing period based on instant throughput rate. In a similar way, throughput of LongGi can be estimated. To reduce the influence of probing throughput rate random fluctuation, above-mentioned estimated throughput rate needs division and filtering. Define $T_{ins}^{(m)}$ as the average throughput ratio of ShortGi and LongGi at the end of $m^{th}$ probing:

$$T_{ins}^{(m)} = \frac{AVG\_Throughput_{SGi}^{(m)}}{AVG\_Throughput_{LGi}^{(m)}} \quad 14)$$

If $T_{ins}^{(m)} \geq \Omega_0$, then ShortGi is adopted, otherwise LongGi is adopted. $\Omega_0$is judgment threshold. The algorithm flow is shown as Figure 4.

Section III gives detailed description on EMLA, and three mechanisms of SNR Calibration, MCS Protection and Gi Adaption are proposed to improve PHY rate, reduce transmission error rate and extend effective communication time, thus performance improvement is achieved. The next section would have experiment and simulation analysis on the enhanced scheme and three mechanisms respectively.

## 4. Experiment and Simulation

As EMLA can protect MCS in channel with high SNR even if PER worsens due to collision or other events, and recovers soon after collision is relieved. Therefore, we have designed two typical collision scenarios for verification: hidden node collision and multi-user collision. Then we simulate three typical Channel Modes B, D and E in 802.11n[13] to assess on Gi Adaption and verify its gain compared with fixed ShortGi and LongGi mode. Finally a experiment of real deployment is done to evaluate the composite enhancement of the total solution. In order to achieve fully assessment, we have divided the enhanced scheme into 5 sub-schemes, as described in Table 3:

**Table 3. Minstrel and 5 Sub-Schemes of EMLA**

| | |
|---|---|
| **Scheme1** | Typical Minstrel, ShortGi |
| **Scheme2** | Minstrel with MCS protection but without SNR calibration, ShortGi |
| **Scheme3** | Minstrel with MCS protection and SNR calibration: $T_c$=200s;$N_c$= 3, ShortGi |
| **Scheme4** | Minstrel with MCS protection and SNR calibration: $T_c$=400s;$N_c$= 5, ShortGi |

 

| | |
|---|---|
| **Scheme5** | Minstrel with MCS protection and SNR calibration: $T_c$=600s;$N_c$= 7, ShortGi |
| **Scheme6** | Minstrel with MCS protection and SNR calibration: $T_c$=400s;$N_c$= 5,Adaptive Gi |

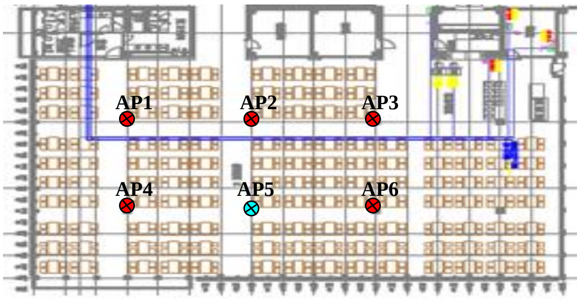


**Figure 5. Test Bed for Real Deployment**

The test bed is an employees' dining room with 60 meters in length, 30 meters in width and 3 meters in height. Six test APs are mounted behind pillars respectively, so AP1 and AP3 are invisible for each other, and can be seen as hidden node scenario; AP5 is used for multi-user collision scenario.

### 4.1 Scenario I: Hidden Node Collision

Hidden node problem is the main cause of collision in WLANs. Ideally, hidden node problem can be prevented by means of RTS/CTS mechanism, but in some special conditions, RTS/CTS still cannot be heard by hide node. For example, the CTS cannot be heard by hidden node when the node is sending or receiving signal at the same time or with fierce influence. As shown in Figure 6:

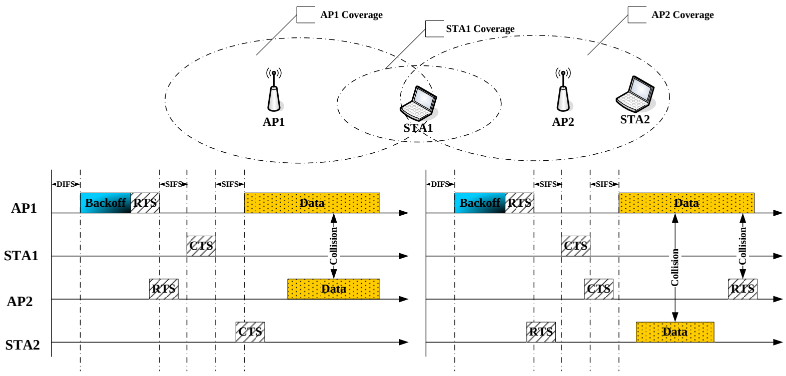


**Figure 6. Hidden Node Problem When RTS/CTS Works**

For simplification, both AP1 and AP2 adopt single stream transmission with the MCS<7. UDP transmission is done between AP1 and STA1, and data link between AP2 and STA2 works as hidden node collision, and the throughput and PER is recorded in Table 4:

**Table 4. Throughput and PER Of AP1 and AP2**

| Performance index | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 5 |
|---|---|---|---|---|---|
| Throughput of AP1(Mbps) | 30.1 | 32 | 33 | 36 | 31.7 |
| Throughput of AP2(Mbps) | 45.2 | 45.1 | 45.3 | 44.5 | 45.2 |
| PER of AP1 | 32% | 47% | 58% | 51% | 55% |

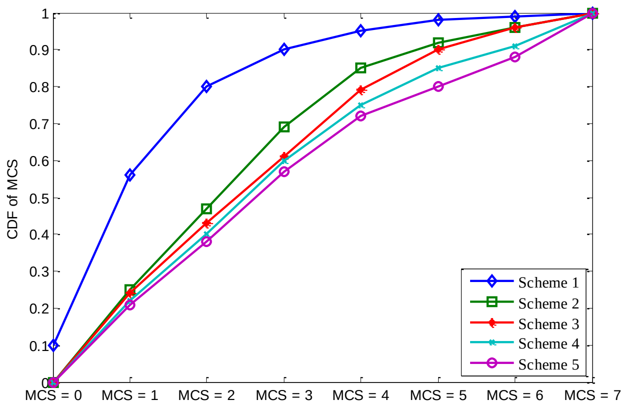


**Figure 7. Cumulative Distribution Function (CDF) Of MCS**

From test result we can see that Scheme2~5 can improve Minstrel in varying degrees, among which scheme4 is the best with 19.6% improvement; from CDF of MCS we can see that the enhanced MCS scheme is more positive owe to MCS protection introduction: in a certain channel SNR condition, MCS won't be degraded quickly as a result of PER from collision. Besides, as for scheme5, when Tc is extended to 600s, the throughput would be declined compared with scheme4, because the SNR feedback is not timely enough, and there is extra expense of SNR probing.

### 4.2 Scenario II: Multi-User Collision

Multi-user collision is another typical scenario. In order to establish scenario in which all STAs can hear from each other, set AP5 and STAs at near point (10m) equidistance, and set AP5 as center circled by STAs. As AP and STAs can hear from each other, so RTS/CTS are default to off. In this scenario, AP adopts dual-stream transmission, and the highest MCS is 15. Seven test cases have been selected with user number increased from 1 to 60. The throughput and PER result are as recorded in Figure 8:

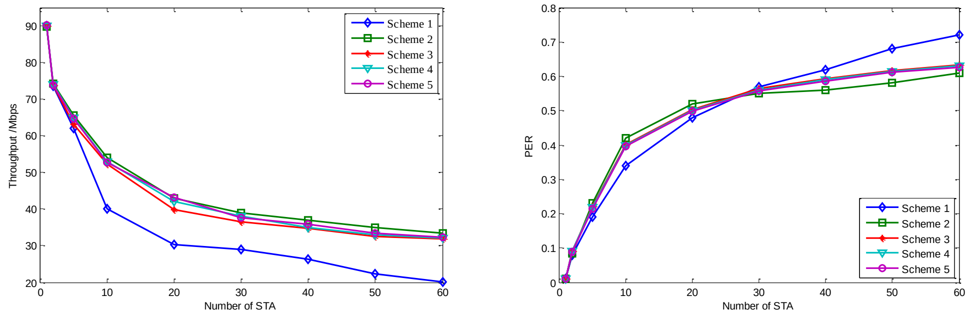


**Figure 8. Throughput and PER Of Multi-User Test from Scheme1 to 5**

From test it can be seen that SNR has no changes as STAs are all equidistance. So system gain comes largely from MCS protection because MCS would not drop to bottom resulting from PER increasing in multi-user collision, and it would recover quickly once transmission chance comes back; SNR calibration would cause some loss of throughput and PER slightly.

In addition, it is interesting that when there are few concurrent users, PER of enhanced scheme is slightly higher than Minstrel. But when concurrent user increases, PER of enhanced schemes is relatively low. This means that by MCS Protection, enhanced scheme tends to select higher MCS which on one side stands for higher transmission error rate, and on the other side stands for less channel occupation and higher channel utilization and lower collision rate in the same data transmission. So when the user increases, the PER of enhanced schemes increases slower compared with typical Minstrel. Thus better performance is obtained.

### 4.3 Scenario III: Simulation on Channel Mode B, D And E

In 802.11n, Channel Mode B has an RMS delay spread of 15 ns, where there is no performance degradation up to a time offset of 100 ns, and it is considered as a channel suitable for ShortGi; Channel Mode D has an RMS delay spread of 50 ns, where there is a slight performance degradation; Channel Mode E has an RMS delay spread of 100 ns, and due to time offset exceeds 100ns, performance degraded fiercely.

In three channel modes, a test on ShortGi, LongGi and AdaptiveGi in five SNR levels is done; the highest MCS is MCS15, the time offset between AP and STA is fixed as 100ns; AdaptiveGi adopts probing period $T_G$=1000, $N_G$=20, which means 10 times of ShortGi and LongGi probing per second respectively. The result in Table 5 is acquired:

**Table 5. Throughput Comparison of Longgi, Shortgi and Adaptivegi**

| Channel Mode B | | | | |
|---|---|---|---|---|
| **SNR** | **$\text{Throughput}_{LongGi}$ (Mbps)** | **$\text{Throughput}_{ShortGi}$ (Mbps)** | **$\text{Throughput}_{AdaptiveGi}$ (Mbps)** | **ShortGi recognition probability** |
| 10dB | 11.5 | 12.6 | 12.3 | 95.2% |
| 20 dB | 31.1 | 34.5 | 33.2 | 98.1% |
| 30 dB | 51 | 57.2 | 56.9 | 98.9% |

 

| | | | | |
|---|---|---|---|---|
| 40 dB | 61.8 | 68.7 | 68.5 | 99.5% |
| 50 dB | 63.7 | 70.7 | 70.5 | 100% |
| **Channel Mode D** | | | | |
| 10 dB | 11.5 | 12.3 | 12.1 | 44.1% |
| 20 dB | 31.5 | 30.6 | 31.3 | 47.2% |
| 30 dB | 52.1 | 53 | 52.3 | 52.3% |
| 40 dB | 61.5 | 64.5 | 64.3 | 51.5% |
| 50 dB | 64.1 | 67 | 66.8 | 52.1% |
| **Channel Mode E** | | | | |
| 10 dB | 12 | 8.1 | 11.9 | 6.3% |
| 20 dB | 31 | 19.5 | 30.9 | 4.8% |
| 30 dB | 52 | 40.2 | 51.5 | 2.5% |
| 40 dB | 61.7 | 51 | 61.2 | 0.3% |
| 50 dB | 64.3 | 53.6 | 64.1 | 0% |

From PHY performance we can see that in Channel Mode B, adaptive Gi would gain 9%~10% compared with LongGi and 0~1.5% compared with ShortGi; in Channel Mode E, AdaptiveGi would gain -3%~0.8% compared with LongGi and above 30% compared with ShortGi; in Channel Mode D AdaptiveGi is equal to LongGi or ShortGi. From recognition probability, in Channel Mode B, the probability of adaptive Gi selects ShortGi is above 90%; in Channel Mode E, the LongGi selection probability is above 85%; in Channel Mode D, ShortGi would bring PER increasing, and the probability of AdaptiveGi selects ShortGi or LongGi is the same. It means that AdaptiveGi can accurately recognize channel condition from which it selects Gi mode, to acquire performance gain.

### 4.4 Real Deployment Experiment

As the result of the formal test, we can find that scheme4 has the best performance, compared to schemes with the other SNR calibration parameters. So in the real deployment, we choose Scheme1, 2 and 4 to stand for the scheme of typical Minstrel, Minstrel with MCS Protection and Minstrel with both MCS Protection and SNR Calibration. In addition, scheme 6 is introduced to assemble the Gi Adaption in the scheme4.

The experiment is done in the test bed in Figure 5, and all the APs in the dinning-room turns on to provide internet service for the employees. The rush hour everyday is 11:00

 

am to 13:00 pm, and peak user number exceeds 140.We gather the total network throughput and the user numbers every 3 minutes to get the dynamic trend of the four schemes.

5th January, 2015: experiment of real deployment using scheme1.

6th January, 2015: experiment of real deployment using scheme2.

7th January, 2015: experiment of real deployment using scheme4.

8th January, 2015: experiment of real deployment using scheme6, and the following result is acquired:

As shown in Figure 9, with the increasing of the user number, the dynamic throughput of Scheme1 decreased rapidly due to the fierce collision of multi-users. However, owing to the MCS Protection, scheme2 has obvious improvement in the same circumstance, and has 32 percent increasing in average throughput per-user in contrast to Scheme1. As to the Schem4, the introduction of the SNR Calibration makes the MCS selection more rational and brings 4 percent promotion. Another slight enhancement comes from the mechanism of Gi Adaption, because of this kind of high density indoor scenario is a typical channel mode E, which is not suitable to the ShortGi, and scheme 6 will choose LongGi mode to match the state of the channel. So scheme6 can be look on as the recommended scheme of EMLA in real deployment.

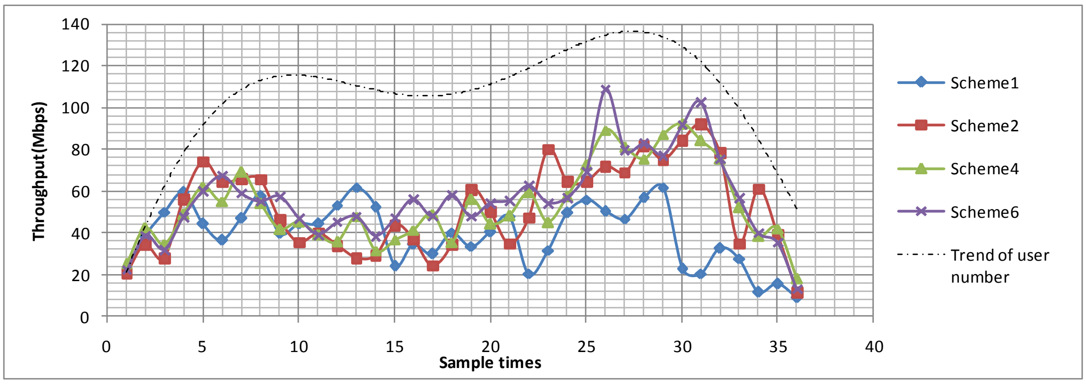


**Figure 9. Dynamic Throughput Comparison of Scheme1, 2, 4, 6 In Real Deployment**

In summary, by means of experiments and simulations, the effectiveness of three enhanced mechanisms based on Minstrel proposed by this paper has been verified. Among them, two typical collision scenarios have focused on MCS Protection scheme gain testing—MCS protection could effectively solve the problem of MCS degradation resulting from collision; in the simulation of Channel Mode B/D/E, Gi Adaption can adapt to Gi mode in time-delay to enable user perform always at the best Gi mode. As for the real deployment experiment, the composite enhancement of EMLA appears, and each part has its contribution.

## 5. Conclusion

In this paper, we describe an enhanced link adaption scheme for 802.11n WLANs, basing on the Minstrel, called EMLA in details. Scheme enhancement comes from SNR Calibration, MCS Protection and Gi Adaption. By means of SNR Calibration, transmitter can select MCS more rational to reduce PER; by means of MCS Protection, MCS would not be mis-degraded or even declined to zero in circumstances of random events like collision or fading in wireless environment, and once the random event is relieved, MCS could recover immediately; by means of Gi Adaption, Gi mode changes from semi-static parameter to dynamic parameter, and transmitter would select Gi mode according to channel state, which is in fact a kind of improvement by extending valid transmission time. The experiments and simulation shows that compared with Minstrel, the EMLA performs better in hidden node collision and multi-user collision; the throughput of EMLA could quickly recover after SNR recovers; besides, in the three typical time-varying channels in 802.11n, the enhanced scheme has better adaptive ability. Currently, the EMLA has been gradually applied to commercial infrastructure in WLANs, and the dedicated experiment of real deployment at last, proves the composite enhancement of the scheme.

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