

Rate Adaptive Channel MAC

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Abstract. A novel ‘Rate adaptive Channel MAC paradigm’ has been proposed considering perfect channel prediction and optimal rate adaptation. Simulation results reveal a significant performance gap between the theoretical rate adaptive Channel MAC and existing rate adaptive protocols- such as ‘Opportunistic Auto Rate’ (OAR).

1 Introduction

Rate adaptive transmission schemes use bandwidth efficient coded modulation techniques to increase throughput over the channels with variable Signal-to-Interference and Noise (SINR) ratio due to fading and interference from other transmissions [1]. At each SINR point, the coded modulation scheme which gives the highest throughput with minimal bit error rate (i.e. below a certain bit error rate threshold) is selected. Following this principal, standards such as IEEE 802.11 medium access protocols have introduced the physical layer multi-rate capability. As the multi-rate schemes exists in the physical layer, adaptive MAC mechanisms are required to exploit this capability. Sender based rate adaptation schemes (e.g. [2]) and receiver based adaptation schemes (e.g. [3], [4]) enables multi-rate features into MAC. Generally receiver based rate adaptive MAC performs better than the sender-based rate adaptive MACs [3]. In receiver-based rate adaptive MACs, the channel quality measurement is done at the receiver during the RTS/CTS exchange. Hence, the channel estimates in these MACs are close to the channel condition during the actual data transmission time opposed to the sender-based approaches. Receiver Based Auto Rate (RBAR) [3] and Opportunistic Auto Rate (OAR) [4] are two prominent examples of receiver-based MACs. In RBAR, every RTS-CTS-DATA-ACK handshaking mechanism (we define it as a cycle) is rate adaptive. In other words, all data packets within a cycle is transmitted with the optimal data rate selected by the receiver based on the received RTS power within that cycle. In OAR, on the other hand, a number of packets is transmitted within a cycle (i.e. after a single RTS-CTS exchange) based on the channel coherence interval and the feasible data rate selected in the same way of RBAR protocol. However, it is possible that the channel condition will significantly change during the multi-packet transmission sequences of OAR. If the transmission at the original rate is maintained (selected by RTS-CTS exchange), error rates may become large if the channel quality worsens leading to

packet losses. Conversely, the rate selection becomes sub-optimal if the channel quality is further improved during the multiple data transmissions.

In OAR, throughput improvement is possible (i.e. decrease the packet loss or improve the sub-optimal to optimal rate selection) if the sender and receiver adapt the data rate during a cycle. Moreover, considering perfect channel prediction and time-share fairness constraint, each transmitter-receiver pair can fully utilise its non-fade duration using a rate-adaptive transmission, if a common probability of good channel¹ persists in the network. The scope of this paper is thus to combine both (a) scheduling and (b) rate adaptive transmission based on the channel state information at the receiver, to design a rate adaptive opportunistic MAC. The channel utilisation of single-rate ‘Channel MAC’ described in [5] only considers the scheduling policy. The channel of a user, which goes up the threshold first, is given access to the medium provided that no one else is transmitting. The single-rate ‘Channel MAC’ (which calculates the channel utilisation only) is extended in this paper including the rate adaptation features similar to [1]. We assume a perfect data rate adaptation based on the channel condition during multiple data packet transmissions during the non-fade duration. The aim is to identify the theoretical maximum throughput limit of the Channel MAC paradigm considering data rate adaptation. We name this technique “Rate adaptive Channel MAC”.

2 System Model

Let us define a neighborhood of $2n$ nodes, where $N_T \in (1, 2, \dots, n)$ are the transmitters and $N_R \in (1, 2, \dots, n)$ are the receivers. For symmetry let us assume that each transmitter $i \in N_T$ is communicating with receiver $i \in N_R$. We assume a constant transmission power for the system. Each transmitter is sending DATA packets to its receiver without any intermittent delay. No control frame is used.

2.1 Channel Model

We consider a two-state channel model. It has either a non-fade state “ON” state with gain $g[t] > 0$ or a fade state “OFF” with $g[t] = 0$. We assume that the non-fade duration, termed Average Non-Fade Duration (ANFD), l , is constant, after which the channel goes into a fade with an arbitrary distributed fade duration with the mean Θ . Hence probability of good channel, p , is calculated as follows:

$$p = \frac{l}{l + \Theta} \quad (1)$$

We assume each ANFD consists of a number of block. The block-length depends on the the data-rate given a fixed length packet. Suppose data-rate is selected based on the instantaneous channel states. Then the packet transmission time, l_i , for a constant \bar{P} sized packet at data-rate R_i is $l_i = \bar{P}/R_i$. We assume $g[t]$ is constant over the block-length l_i where the channel is optimally suitable to support the data-rate R_i .

¹ Which is equivalent to a common average non-fade duration in all channels.

3 Rate Adaptive Channel MAC Throughput

3.1 Rate Selection Probability in Rayleigh Fading Channel

Number of threshold-based techniques for rate selection have been used in literature [1],[3],[4]. In a threshold based scheme, the rate is chosen by comparing the received SNR against an array of thresholds representing performance limits of the available modulation techniques. The modulation technique with the highest data rate and the bit error rate less than a constraint value for the estimated SNR is chosen. The selected modulation technique results in the feasible data rate to be used in subsequent transmissions. Let $r_1, r_2, r_3, \dots, r_{m-1}$ are power threshold for different suitable rate limits. For example, r_1 dB indicates that if the received power level is below r_1 dB, rate R_1 is feasible. In case the received power level is above r_1 but below r_2 , rate R_2 is feasible and so on. A region surrounded by two subsequent power threshold, which is suitable for a particular rate is called a "rate-region". For example, R_2 rate-region is surrounded by r_1 and r_2 power thresholds.

Case 1. $l_k \rightarrow 0$ (l_k is the packet transmission time of \bar{P} sized packet with the data-rate R_k): First, we identify the rate region where the cutoff threshold, P_c is located. Assume P_c is located in R_k rate-region ($k < m$). That is $P_c \in R_k$. According to [6], the probability that DATA packet is transmitted with R_k feasible rate is $(R_k) = p - e^{-r_k/P_{av}}$. Here p is the probability of good channel condition beyond the selected threshold P_c . The second part denotes the probability of received power is above the cutoff r_k . P_{av} is the average received power. Similarly

$$P(R_z) = e^{-r_{z-1}/P_{av}} - e^{-r_z/P_{av}} \text{ (when } k < z < m) \quad (2)$$

$$P(R_m) = e^{-r_{m-1}/P_{av}} \quad (3)$$

Hence, the mean data rate for such a transmission is:

$$\bar{R} = \frac{1}{\sum_{i=k}^m P(R_i)} \sum_{i=k}^m [P(R_i) \times R_i] \quad (4)$$

As the packets are assumed to be infinitesimally small in this case, the channel conditions should remain the same during each packet transmission. Hence this case corresponds to the optimum rate achieved with the proposed scheme.

Case 2. $l_k > 0$: We identify total number of l_i ($k \leq i \leq m$) fitted within an ANFD duration with corresponding feasible data rates. The total transmission time at R_i data rate within an ANFD is

$$T_{R_i} = l \frac{P(R_i)}{\sum_i P(R_i)} \quad (5)$$

Hence the number of transmitted packet x_i at R_i data rate is $x_i = \lfloor T_{R_i}/l_i \rfloor$. Therefore mean data rate is

$$\bar{T} = \frac{\sum_{i=k}^m x_i l_i}{l} \frac{1}{\sum_{i=k}^m P(R_i)} \sum_{i=k}^m [P(R_i) \times R_i] \quad (6)$$

3.2 Channel Utilisation in Channel MAC Considering Collision

We define Normalised propagation delay w.r.t ANFD as $\bar{a} = \frac{a}{l}$. Total arrival rate by n node pairs is $O = nr$ where r is the level crossing arte by a single channel.

Following [7], we derive

$$U = \frac{\frac{1}{O} e^{-\bar{a}O}}{O(1 + 2\bar{a}) + e^{-\bar{a}O}} \quad (7)$$

3.3 Rate Adaptive Channel MAC

We define the throughput of Channel MAC as the product of utilisation and the average rate during a transmission period.

(i) $l_k \rightarrow 0$: Combining Equation 7 and 4, we get the throughput for rate adaptive Channel MAC as follows:

$$S_{rate-adaptive1} = \bar{R} \times U \quad (8)$$

(ii) $l_k > 0$: Combining Equation 7 and 6, we get the throughput for rate adaptive Channel MAC as follows:

$$S_{rate-adaptive2} = \bar{T} \times U \quad (9)$$

4 Simulation Study

The simulation in this paper is conducted using MATLAB. However, the OAR simulation is done using NS2. The available rates for both protocols are assumed to be 2, 5.5 and 11 Mbps.

We consider Rayleigh fading as a small scale fading incorporated with the channel. The packet level simulator described in [8] is used to model the time-scale fading with parameters 10 kmph node velocity and 2 GHz carrier frequency.

4.1 Single-hop Environment

We consider a single-hop scenario. Transmit power, P_t is set to 0.2818W. The transmission range is set to 250 m. Thus receiver sensitivity at 250m is -71.4dBm. Rate threshold for 5.5Mbps and 11Mbps are selected as -67.4 and -55.41 dBm as in [4]. The maximum Doppler frequency is set to 20 Hz².

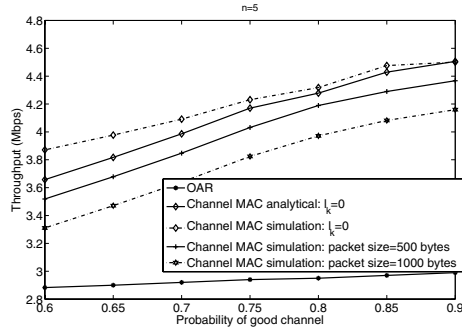


Fig. 1. Throughput performance of rate adaptive Channel MAC and OAR

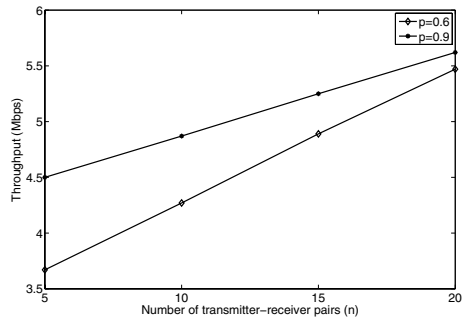


Fig. 2. Throughput performance of analytical Channel MAC ($l_k = 0$) at different n and p values

Figure 1 shows throughput performance of rate adaptive Channel MAC for $l_k = 0$ and $l_k > 0$ (packet size= 500 and 1000 bytes) for $n = 5$. Corresponding OAR throughput results (packet size=1000 bytes) are also included in this figure for comparison. The discrepancy between the analytical and simulation results for the rate adaptive Channel MAC is due to the assumption that arrivals are poisson distributed in the analytical calculations, while the simulation uses actual rayleigh channel fading models, as explained in [9]. Figure 1 shows that throughput decreases with the increasing packet sizes. This is due to the fact with increasing packet sizes, the probability of changes in fading conditions during a packet transmission increases, leading to sub-optimum rate selections or packet losses. Both of these conditions leads to overall throughput degradation. However, at $p = 0.9$, the rate adaptive Channel MAC throughput is 40% higher than the OAR throughput considering 1000 byte packet size. In rate adaptive Channel MAC, the good channel conditions are fully utilised, resulting in relatively linear throughput increases with p , which is in contrast to the under-utilisation of the channel in OAR.

² If carrier frequency, f_c is 2000 MHz and velocity of node is 10 Kmph, the maximum Doppler frequency, $f_m = f_d = \frac{v}{c}f_c \cos(0)$, results in 18.5 Hz.

In figure 2, the throughput results of the analytical Channel MAC ($l_k = 0$) at different p and n values are given. It can be observed that rate adaptive Channel MAC achieves higher throughput at lower p values with increasing n , improving the potential operating range. Due to the multiuser diversity effect in the Channel MAC, the probability of finding at least one good channel at a given time increases with higher number of nodes, which improves the transmission opportunities.

5 Conclusion

In this paper we propose a mechanism to provide rate adaptation to the Channel MAC protocol. The objective of the rate adaptation scheme is to find the transmission rates for each transmission interval to maximise the throughput. We analytically evaluate the rate adaptive MAC based on perfect channel state information. We then demonstrate the effectiveness of the protocol using the analytical equations and a separate simulation study. The simulation results reveal up to 75% throughput improvement can be achieved with Channel MAC as compared to OAR in a single hop network.

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