Adaptive rate controller for mobile ad hoc networks

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Abstract: Mobile devices in the IEEE 802.11 wireless local area network (WLAN) have the ability to transmit data frames at one of four transmission rates 1Mb/s, 2Mb/s, 5.5Mb/s and 11Mb/s. This is because the commercial WLAN transceivers are equipped with several modulation schemes. According to the characteristics of the modulation scheme, a higher transmission rate will result in a smaller transmission range and longer time consumption on data frame transmission. If the channel environment is relatively clear and the transmission distance is short, one should choose a higher transmission rate for data transmission to maximise channel utilisation. On the contrary, a lower transmission rate should be selected to minimise the frame loss and frame error probabilities if the bit error rate is high. Therefore, the problem of choosing a proper transmission rate to accommodate a varying environment is a new and valuable problem in the wireless LANs. To our knowledge, it is very difficult and impractical to formalise an indoor environment since the channel status is quite unstable and unpredictable. Instead, we propose an adaptive rate controller (ARC), which employs the powerful fuzzy set function, for intelligently selecting the transmission rate for frame transmissions. This fuzzy control function refers the received signal strength indicator (RSSI), the frame error rate (FER) and the medium access control (MAC) delay to make a correct decision. Simulation results demonstrate that the proposed fuzzy controller indeed enhances the network throughput and the access delay.

Keywords: ad hoc; fuzzy; MAC; multi-rate; WLAN.

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1 Introduction

Wireless communication is a rapidly emerging technology providing users with network connectivity without being tethered to a wired network. An ad hoc wireless local area network (WLAN) is a collection of mobile hosts (MHs), which forms a temporary network without the aid of any pre-established infrastructure or centralised administration. For example, the ad hoc WLAN is able to conveniently and rapidly set up communication links for information exchange between members in a working group, in an emergent rescue team or in a battle field, and so on.

The IEEE 802.11 WLAN standard was approved in June 1997 and the first edition of new IEEE 802.11 standard was published in 1999 [1] with data rates of 1Mb/s and 2Mb/s. In order to provide high bandwidth to users, several drafts are proposed to provide high-rate extension of the physical (PHY) layer [2]. The high-rate PHY extension for the direct sequence spread spectrum (DSSS) system is specified in the 2.4GHz band for ISM (industrial, science, and medical) applications [3].

Recently, adaptive transmission techniques have been extensively investigated for the improvement of transmission performance in wireless communications and these techniques vary the transmission power [4], transmission frame length [5-7] coding rate/scheme [8], and modulation technology [9-13] under the time-varying channel. For instances, papers [9] and [12] varied the constellation size according to different kinds of channel conditions to get a better transmission performance. In paper [11], authors studied the theoretical performance limitation of adaptive modulation with and without power control. In papers [10] and [13], different adaptive modulations were investigated with the dynamic channel allocation (DCA) technology. Besides, the variable-rate quadrature amplitude modulation (QAM) schemes have also been proposed in several third-generation wireless communication systems [14]. All of them are trying to improve the effective data rate under the specified bit error rate (BER). Williams et al. [13] proposed the concept that throughput could be increased by permitting MH, which nears the centre of the cell, to use the high-level modulation scheme. In contrast, MH nears the fringes of the cell and has to use low-level (e.g., binary) modulation to cope with the lower signal-to-noise ratio (SNR). The same concept has also been proposed in [15-17]. Similarly, the Harris and Lucent companies have proposed a high data-rate modulation scheme ‘Complementary Code Keying’ (CCK) [18-20], which was referred from the ‘Complementary Code’ [21-23]. The IEEE working group (WG) had finally adopted the CCK to support data rate up to 11Mb/s.

To provide the inter-operability with existing networks, the IEEE 802.11 baseband processor [19] has the ability to provide four different modulation schemes: DBPSK, DQPSK, CCK, and MBOK. Based on these schemes, four different data rates (1Mb, 2Mb/s, 5.5Mb/s, 11Mb/s) are supported in WLANs. By using the concept of adaptive modulation [24,25], mobile hosts in a multi-rate WLAN select the modulation scheme and transmission rate according to the detected SNR and the required transmission quality. In [25], the transmission rate of each frame is dynamically selected according to the detected SNR of the previous transmission/reception but not on a predetermined rate. The previous version of this paper was presented in [26], which first introduced the concept of multi-rate control by using a modulation scheme with fuzzy rules. Differing from using the SNR in [25], we use three different metrics: the received signal strength indication (RSSI), medium access control (MAC) delay, and frame error rate (FER), to adjust the rate for data transmission.

The remainder of this paper is organised as follows. Section 2 briefly describes the basic operations of the DCF in the IEEE 802.11 standard. In Section 3, we describe three metrics used in proposed adaptive rate controller (ARC). Section 4 describes the corresponding membership functions of the fuzzy control. The simulation model is demonstrated in Section 5. Finally, simulation results and conclusions are presented in Sections 6 and 7 respectively.

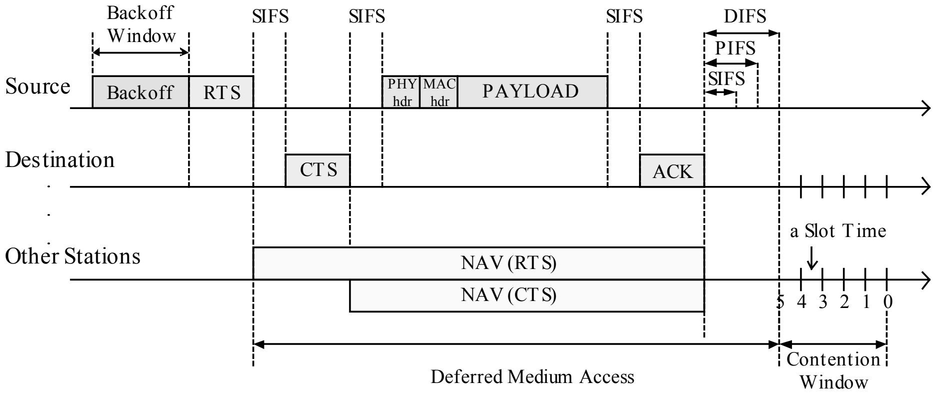
2 Description of the IEEE 802.11 protocol

This standard includes a basic distributed coordination function (DCF) and an optional point coordination function (PCF). The DCF uses carrier sense multiple access with collision avoidance (CSMA/CA) as the basic channel access protocol to transmit asynchronous data in the contention period. When a MH wants to transmit frames, it needs to monitor the channel activity before its transmission. If the MH perceives that the channel is idle for a time period equal to a distributed inter-frame space (DIFS), it will trigger a random backoff delay before transmission (this is the ‘collision avoidance’ feature of the CSMA/CA protocol). Otherwise, the MH persists in monitoring the channel until it detects channel idle for the DIFS duration. The backoff time is measured in slot time, denoted as ح in abbreviation, which is defined as the time needed for a node to detect a frame, to accummulate the time needs for the propagation delay, the time needed to switch from the receiving state to the transmitting state, and the time to signal to the MAC layer the state of the channel.

The random backoff procedure can efficiently minimise the collision probability. In addition, to avoid channel capture, a MH must wait a random backoff time between two consecutive frame transmissions even if the medium is sensed idle for the DIFS period after precedent transmission. As an exception to this rule, the protocol provides a fragmentation mechanism, which allows a MH to transmit a number of MAC protocol data units (MPDUs) successively without performing the backoff delay. The only constraint is that these fragmented MPDUs belong to a same PDU in the upper protocol layer. These fragments are then transmitted in sequence, with only a short inter-frame space (SIFS) between them, so that only the first fragment must contend for the channel access. Obviously, the SIFS should be shorter than DIFS.

For each frame transmission, the DCF defines an optionally four-way handshaking scheme as shown in Figure 1. This scheme uses request to send/clear to send (RTS/CTS) control frames to solve the well-known *hidden terminal problem* [27] and to provide virtual carrier sense for saving battery power [28]. The duration field in the MAC header of a control/data frame is used to carry the information of time period requested for a complete transmission. Any listening MH receiving this information will update its network allocation vector (NAV), which contains the information of the interval that the channel will remain busy. In this paper, we assume that each data transmission should first issue the RTS frame and CTS frame, and follow with an acknowledgment (ACK) frame. To prevent the handshaking process from disturbing by other transmissions, the SIFS is also used to guarantee that the control frames have a higher priority than data frames.

Figure 1 An illustration of RTS/CTS and backoff mechanism of DCF



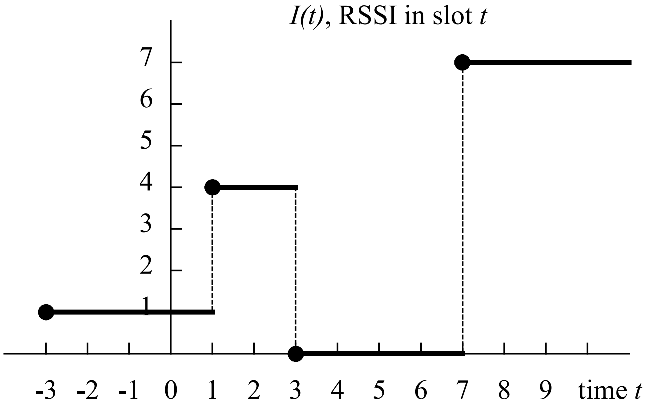
3 Three environment parameters in ARC

Because the data rate is inversely proportional with the transmission distance, if we are able to derive the exact distance between a pair of transceivers, the proper transmission rate may be determined in a more simply way. Unfortunately, there is no information that can help us to obtain the distance information. Besides, to only have the distance information is not sufficient for one to make the right decision because of the channel noise, fading and shadowing. Obviously, such rate control algorithm is a classical and tough control problem, which should be solved by powerful fuzzy set theory. In the following subsections, we will introduce three metrics used in the proposed fuzzy controller.

3.1 Received signal strength indication (RSSI)

The simple way to roughly estimate the transmission distance is to measure the received signal strength indication (RSSI), which can be provided from the physical layer (PHY) when a transceiver receives a data, management or acknowledgement frame. Figure 2 illustrates a sequence example of the received signals strength $I(t)$ where $I(t)$ is the normalised RSSI value at time t. Let $I(t) = [0\ , S_{max}]$, where S_{max} is the maximum value of RSSI presented in the PHY layer. (We note that the S_{max} of a WLAN card may different from the others.) In order to obtain a more precise RSSI value, we use the average RSSI, denoted as $I_{avg}(t)$, as the referred environment parameter to reflect the changing channel status. To do this, the average RSSI is derived from averaging a number of n consecutive RSSI values of received frames. That is, we have $I_{avg}(t) = \sum_{i=0}^{n-1} I(t-i)/n$. In this paper, we simply set $S_{max} = 63$ [29] and n=7.

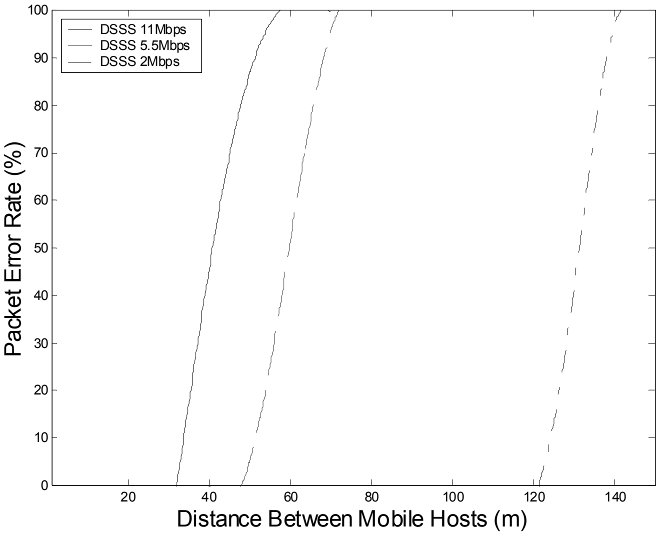
Figure 2 Example of detected RSSI sequence



3.2 Frame error rate (FER)

The frame error rate (FER), denote as E, is another important measurement for the proposed fuzzy controller. A system with a higher FER means that the channel interference is high and the transmission rate should be downgraded (i.e. employing a higher level modulation scheme) against interferences. Otherwise, a higher transmission rate could be used to enhance network throughput as previously mentioned. Hence, an aggressive ARC would attempt to use the highest transmission rate to obtain the throughput gain when the FER is small. As soon as the FER climbs high, the ARC must automatically and smoothly decrease the transmission rate to accommodate the channel condition and the transmission distance. Figure 3 shows our measured FER under different transmission distances and different transmission rates in a relatively clear outdoor environment. The considered frame length is 1058 Bytes (= 1024 bytes payload plus 34 bytes MAC header/trailer overhead). We can see that the longest transmission distances for 2Mb/s, 5.5Mb/s and 11Mb/s are about 120, 50, and 30 meters, respectively. Similar with RSSI parameter, the average FER is also measured and used in our proposed ARC.

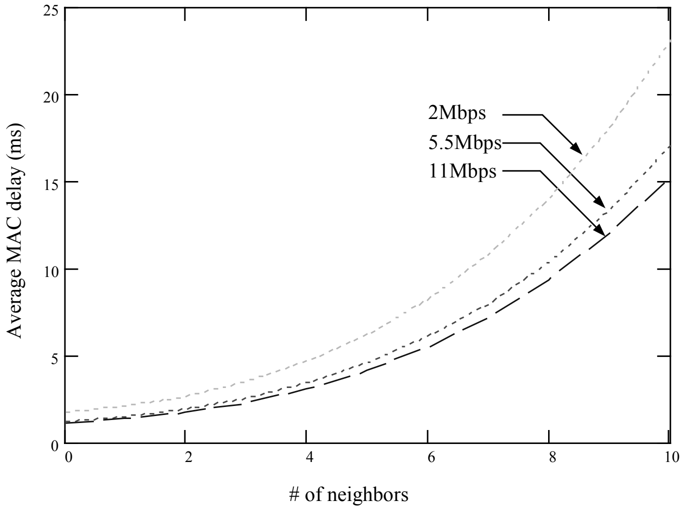
Figure 3 The measured FER by IEEE 802.11 WLAN cards under different transmission distances and different transmission rates



3.3 MAC delay

The MAC delay is defined as the time interval, which starts from when a MH enters the transmission state to send a frame and ends when the transmission is complete. The MAC delay *D* is an implicit indicator of the degree of channel congestion. A longer MAC delay implies more MHs are contending on the channel. From our previous work [30], the estimated MAC delays under different date rates and different numbers of neighbours in a random ad hoc WLAN are illustrated in Figure 4. We can see that the MAC delay is increasing with the increasing number of neighbours. Moreover, using a higher data rate for data transmission will obtain a smaller MAC delay since the channel occupancy period is shorter than that of a lower data rate. However, the lowest MAC delay may not be obtained all the time since the transmission distance is limited by the highest transmission rate.

Figure 4 The estimated average MAC delay of a mobile host under different numbers of neighbours and different transmission rates when the packet arrival rate is 0:001 and the mean packet length is 200 octets

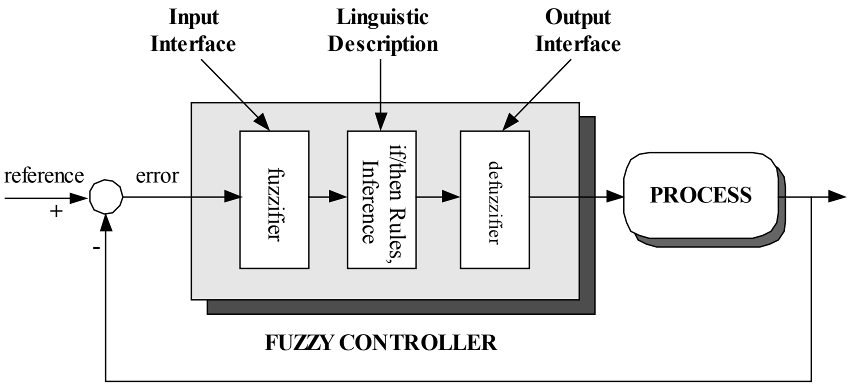


4 Adaptive rate controller (ARC)

4.1 Fuzzy logic controller

The core of a fuzzy controller is a linguistic description prescribing appropriate action for a given state. In fuzzy controllers the aim is to incorporate expert human knowledge in the control algorithm. In this sense, a fuzzy controller may be viewed as a real-time expert system, i.e. a model of the thinking processes an expert might go through in the course of manipulating the process. The basic structure of a fuzzy controller is outlined in Figure 5.

Figure 5 Block diagram of fuzzy process control system



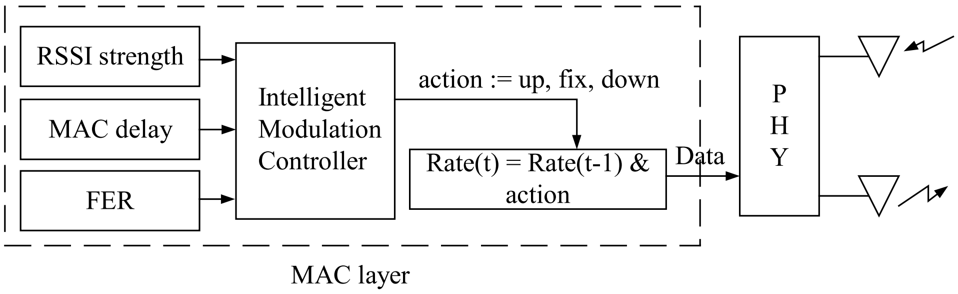
4.2 Fuzzy estimators

A typical fuzzy logic system consists of four fundamental blocks: a fuzzifier, a fuzzy rule base, an inference engine, and a defuzzifier. In the fuzzifier, crisp inputs are fuzzified into linguistic values to be associated to the input linguistic variables. The fuzzy rule base is a knowledge-base control characterised by a set of linguistic statements in the form of "if-then" rules that describe a fuzzy logic relationship. After fuzzification, the inference engine refers to the fuzzy rule base containing fuzzy IF-THEN rules to derive the linguistic values for the intermediate and output linguistic variables. Once the output linguistic values are available, the defuzzifier produces the final crisp values from the output linguistic values. The details can be referred to [30].

4.3 ARC fuzzy controller

Figure 6 shows the architecture of the AMC with fuzzy function, in which the intelligent modulation fuzzy controller adjusts the transmission rate according to the average RSSI, average FER and average MAC delay, which are measured from previous *n* transmissions or receptions between two mobile hosts.

Figure 6 A block diagram of the intelligent modulation controller



Fuzzifier: recall that these three input linguistic variables for the fuzzy controller are denoted as *I*, *E*, and *D*, respectively. The term sets of them are *T*(*I*) = {Weak, Fair, Strong} = {We, Fa, St}, *T*(*E*) = {Low, Medium, High} = {Lo, Me, Hi}, and *T*(*D*) = {Small, Medium, Large} = {Sm, Me, La}. The membership functions for *T*(*I*), *T*(*E*) and *T*(*D*) are respectively shown in Figures 7, 8 and 9. By using these membership functions, we convert the input system performance parameters into suitable linguistic values, which are needed in the inference engine.

Figure 7 The membership functions of the RSSI (I)

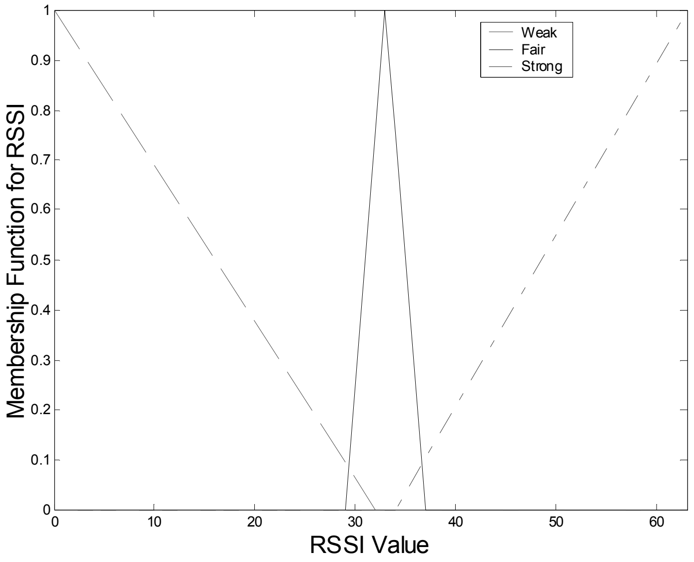


Figure 8 The membership functions of the FER (E)

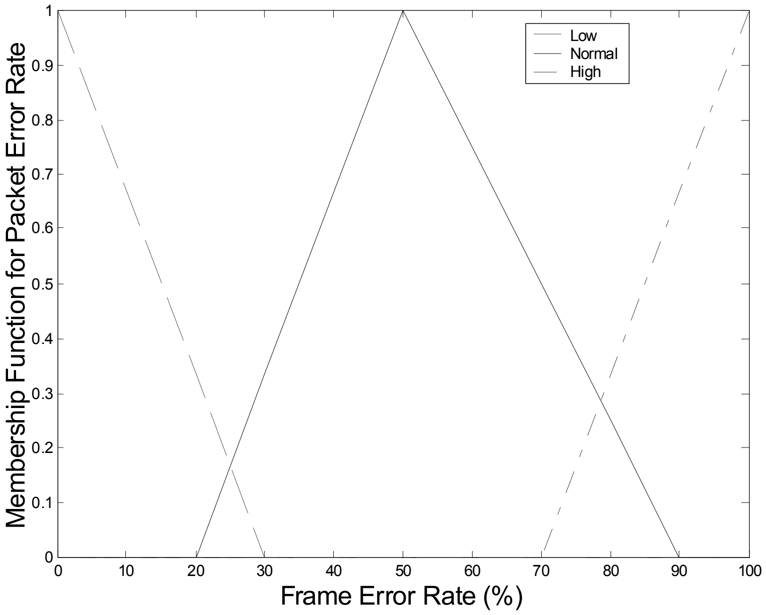
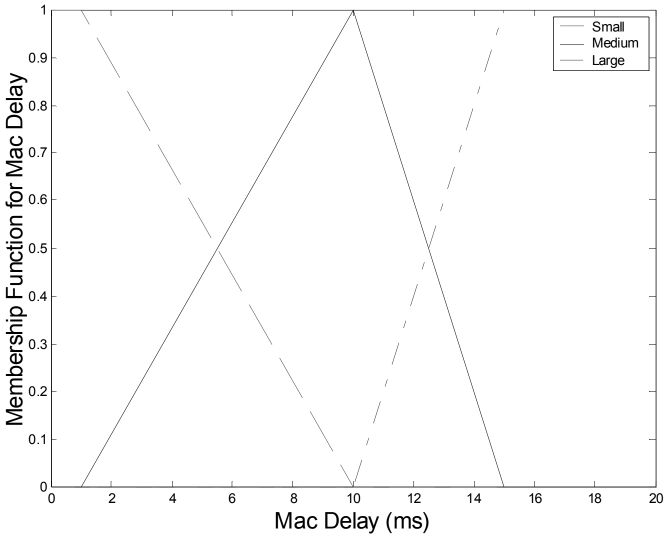


Figure 9 The membership functions of the MAC delay (D)



Fuzzy rule base: The fuzzy rule base contains a set of fuzzy control rules, defined in a linguistic way, to describe the control policy. The rules base is shown in Table 1.

Table 1 Fuzzy control rules

Rule	*Ir(t)*	*Er(t)*	*Dr(t)*	*ACT*	*Rule*	*Ir(t)*	*Er(t)*	*Dr(t)*	*ACT*
1	St	Hi	La	⇓	15	Fa	Me	Sm	⇓
2	St	Hi	Me	⇓	16	Fa	Lo	La	⇑
3	St	Hi	Sm	⇓	17	Fa	Lo	Me	⇔
4	St	Me	La	⇑	18	Fa	Lo	Sm	⇓
5	St	Me	Me	⇑	19	We	Hi	La	⇓
6	St	Me	Sm	⇔	20	We	Hi	Me	⇓
7	St	Lo	La	⇑	21	We	Hi	Sm	⇓
8	St	Lo	Me	⇔	22	We	Me	La	⇔
9	St	Lo	Sm	⇔	23	We	Me	Me	⇔
10	Fa	Hi	La	⇓	24	We	Me	Sm	⇔
11	Fa	Hi	Me	⇓	25	We	Lo	La	⇔
12	Fa	Hi	Sm	⇓	26	We	Lo	Me	⇔
13	Fa	Me	La	⇑	27	We	Lo	Sm	⇑
14	Fa	Me	Me	⇔					

Inference engine: the inference engine infers the fuzzy control action under the fuzzy control rules and the related input linguistic parameters. To derive the fuzzification result, the Max-Min inference method is adopted [31]. We can obtain the linguistic values from Fuzzifier, denoted by $\mu_{St}I(t)$, $\mu_{Fa}I(t)$, $\mu_{We}I(t)$, $\mu_{Hi}E(t)$, $\mu_{Me}E(t)$, $\mu_{Lo}E(t)$, $\mu_{La}D(t)$, $\mu_{Me}D(t)$, $\mu_{Sm}D(t)$; where $\mu x(y)$ represents the corresponding membership value of input value y in term x. By applying the min operator, we have

$$\text{Weight} = \min(I(t)\,,\, E(t)\,,\, D(t)).$$

For example, we can get $w1 = \min(\mu_{St}I(t), \mu_{Hi}E(t), \mu_{La}D(t))$, $w2 = \min(\mu_{St}I(t), \mu_{Hi}E(t), \mu_{Me}D(t))$ and so on. After deriving the overall weight values of w1~w27, we apply the max operator to yield the weighted value of ACT, denoted by w_{act}. That is:

$$w_{act} = \max(w1,w2,w3,w4,w5,w6,w7,w8,w9,w10,w11,w12,w13,w14,w15,$$
$$w16,w17,w18,w19,w20,w21,w22,w23,w24,w25,w26,w27).$$

Defuzzifier: the defuzzifier converts the inferred fuzzy control action into a nonfuzzy control action under a defuzzification strategy. The output linguistic variable is *ACT* and its term set is defined as *T*(*ACT*)={ Up, Fix, Down }={⇑ ⇔ ⇓}. The symbols ⇑ (⇓) denote that the MH would switch the current transmission rate to a higher (lower) transmission rate if possible. After finishing inference, we set the ACT depend on w_{act}. For example, w_{act} = w1, from Table 1, output linguistic variable ACT has decided to be ⇓ .That is meant to switch the current transmission rate to lower transmission rate, 11Mbps->5.5Mbps, 5.5Mbps->2Mbps, 2Mbps->2Mbps (if 2Mbps is the lowest transmission rate).

5 Simulation model

In order to evaluate the efficiency of the proposed fuzzy function, we built a detailed simulation model based on the distributed coordination function (DCF) of IEEE 802.11 WLAN. The simulator is modelled as a shared-media radio with three different nominal bit rates of 2Mb/s, 5.5Mb/s, and 11Mb/s correspond to three nominal radio ranges of 120m, 50m, and 30m, respectively. Each packet is transmitted directly, without considering the routing in network layer.

In simulations, we considered the realistic system parameters (i.e. the direct sequence spread spectrum (DSSS) physical specification) in IEEE 802.11 MAC protocol, which are shown in Table 2. The unslotted carrier sense multiple access (CSMA) technique with collision avoidance (CSMA/CA) is used to transmit these packets. The RTS/CTS exchange precedes data frame transmission and implements a form of virtual carrier sensing and channel reservation to reduce the impact of the hidden terminal problem [27]. Data frame transmission is followed by an ACK. The radio model uses characteristics similar to a commercial radio interface, Lucent's WaveLAN [32]. The PLCP preamble/header and RTS/CTS control frames are sent in transmission rate 1Mb/s and 2Mb/s respectively. For a more complete and detailed presentation, please refer to the 802.11 standard [1,3].

Table 2 System parameters in simulations

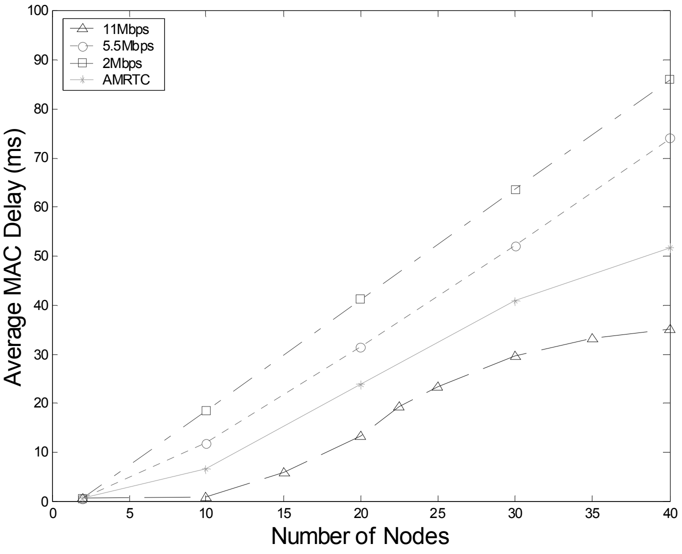
Parameter	*Normal Value*
Transmission rate	2,5.5,11Mb/s
Transmission range (2Mb/s)	120m
Transmission range (5.5Mb/s)	50m
Transmission range (11Mb/s)	30m
RTS frame length	160 bits
CTS frame length	112 bits
ACK frame length	112 bits
A slot time	20 μs
Air propagation delay	1 μs
SIFS	10 μs
DIFS	50 μs
PLCP preamble + PLCP header	192 μs
MAC header	34 octets
CW min	31 slots
CW max	1023 slots
Average frame length	200 octets

Stations are randomly distributed in a 100m×100m square. The diagonal line of this square is about 141m and is slightly higher than the maximum transmission distance of the lowest transmission rate (see Figure 3). This will cause failure transmissions in most cases of using a higher data rate, e.g. 5.5Mb/s or 11Mb/s. Each MH will generate data frame following an arrival process characterised by the Poisson process. That is, the inter-arrival time of data frames is exponentially distributed with average message arrival rate λ¸ and the size of data frame (measured in slot times) is assumed to be a positive random variable, denoted by L, which is generally distributed. In this paper, we consider two simulation models. The first one assumes all MHs are static and the second one allows MHs to move according to the *random waypoint* model in the square field. In the second simulation model, each MH starts its journey from a random location to a random destination with a randomly chosen speed that is uniformly distributed between 0-20 m/s. Once the destination is reached, another random point is targeted after a short pause.

6 Simulation results

Figure 10 illustrates the derived average MAC delays by approaches with fixed transmission rates 2Mb/s, 5.5Mb/s, and 11Mb/s and our ARC under different numbers of MHs. When the number of nodes becomes larger, the network load will become higher and all approaches will suffer a longer MAC delay as expected. The approach with 11Mb/s transmission rate always performs the lowest average MAC delay than the other data rates. The reason is that the using the highest transmission rate will reduce the frame duration as well as the number of competitors in transmission range. On the other hand, the approach with fixed 2Mb/s transmission rate always gets the highest average MAC delay. We also note that the proposed ARC provides a moderate average MAC delay among them under all kinds of network loads. Since the MAC delay derived by approach with 11Mb/s is the lower bound in network, we can say that the ARC derives the second best result. This is because that the dynamic rate adjustment will try to use a higher data rate, meanwhile, it will also keep the number of contending MHs as small as possible.

Figure 10 Comparisons of average MAC delays derived by approaches with fixed transmission rates 2/5Mb/s, 5/11Mb/s and proposed ARC under different number of nodes when packet arrival rate λ= 0.001 and mean packet length L = 200 octets



We emphasise that although the approach with 11Mb/s outperforms our adaptive approach in the MAC delay metric it does not imply it will get a higher network throughput. Thus, another important performance metrics ‘goodput’ *G* is defined and measured as follows: $G = Sp/Sc$, where *Sp* is the amount of successfully transmitted data and *Sc* is the amount of transmitted data including control frames (RTS/CTS and ACK) and MAC/PHY headers. Figure 11 shows that the ARC can provide a higher goodput than the other approaches. The reason is the ARC dynamically adjusts the transmission rate according to the three environment parameters: RSSI, MAC delay, and FER. The goodput of the 11Mb/s approach significantly decreases as the number of MHs increases since the 11Mb/s approach is limited by the shortest transmission range and may suffer a much serious frame loss. Therefore, we conclude that a properly selected transmission rate will incur a lower number of MHs to **content the medium** and use less time to transmit a frame successfully. This also means that the ARC makes data transmissions robust in any time-varying environment and especially in the ISM band.

Author, the meaning of highlighted phrase ‘content the medium’ might not be clear to the reader; is it possible to re-word this phrase to give more clarity?

Figure 11 The comparison of goodput by using different transmission rates 2/5Mbs, 5/11Mb/s and proposed ARC under different number of nodes when packet arrival rate λ= 0:001 and mean packet length L = 200 octets

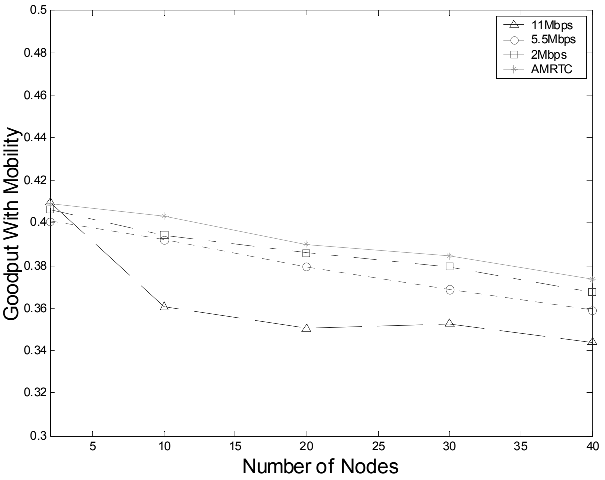
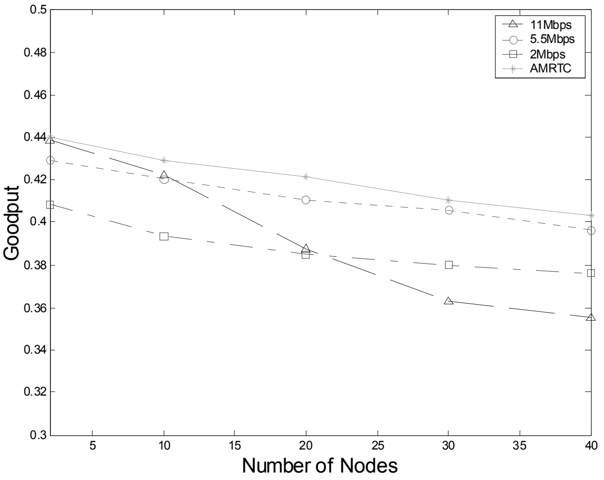


Figure 12 shows the mobility influence in ad hoc networks. The goodput of each approach will be decreased by mobility since MH may move out a transmission range during the transmission period. The ARC derives the highest goodput among all approaches since the ARC has the ability to select the proper transmission rate to minimise the packet loss ratio and to maximise the channel utilisation. Compared with Figure 9, the 2Mb/s approach in the mobility model gets a higher goodput than approaches with 5.5Mb/s and 11Mb/s since the 2Mb/s approach has the largest coverage area which can eliminate the impact of MHs move out of transmission range.

Figure 12 The comparison of goodput with mobility by using different transmission rates 2/5.5/11 Mb/s and proposed ARC under different number of nodes when packet arrival rate λ= 0.001 and mean packet length *L* = 200 octets



7 Conclusions

In this paper, we had proposed an adaptive rate controller (ARC), which employs the fuzzy set function, for intelligently selecting the transmission rate in a WLAN. This fuzzy control function refers the received signal strength indicator (RSSI), frame error rate (FER) and medium access control (MAC) delay from previous received/transmitted frames to make a right decision. Simulation results demonstrated that the proposed fuzzy controller has the capability to obtain the maximum network throughput as compared with approaches with a fixed data rate.

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