Media Access Control Schemes for Mobile Ad Hoc Networks

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Abstract. Multi-rate capabilities are supported by the physical layers of most 802.11 devices. To enhance the network throughput of MANETs, transfer rate adaptation at MAC layer should employ the multi-rate capability at physical and the information of previous transmissions provided by MAC and physical layers. In this paper, we propose a transfer rate adaptation scheme plus back-to-back frame transmissions, and fragmentation at MAC layer, named TRAF. TRAF adopts a bi-direction-based approach with an extended option to select an appropriate rate for frame transmission under fast changing channel conditions. Consecutive back-to-back frame transmissions to fully utilize good channel quality during a coherent time interval and fragmentation algorithm to maintain high throughput under worse channel conditions are recommended in TRAF. Extensive simulation is experimented to evaluate the performance of TRAF. Regarding simulation results, frame delivery ratio, and network throughput of TRAF are significantly improved by comparing to that of other protocols.

1 Introduction

Wireless local area networks (WLANs) are becoming increasingly popular [10]. New requirements of high speed transmissions for broadband wireless multimedia applications are emerging. Scientists and engineers are developing and designing efficient modulation techniques and media access control schemes to accomplish the requirements. Nowadays, the IEEE 802.11 [1, 2, 3] MAC protocols can provide physical-layers with multi-rate capabilities. In original 802.11, a frame is sent at a single base rate. With the multi-rate capability, a number of rates can be chosen to transmit frames according to channel conditions.

In mobile wireless networks, path loss, fading, and interference cause variations in the received signal-to-noise ratio (SNR) and the bit error rate (BER). Because of the lower the SNR, the more difficult it is for the modulation to decode the received signal. Since high rate transfer typically applies denser modulation encodings, a trade off generally emerges between data rate and BER. When SNR is sufficiently high to switch to a higher speed, such that BER of the modulation still be preserved under an acceptable level for correctly encoding the received data, the higher speed modulation can be selected to transmit frames at a higher rate.

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Some control protocols for rate adaptation are proposed. ARF [14] is a sender-based approach. RBAR [11] recommends that a sending rate is selected by a receiver instead of by a sender. OAR [18] indicates that the channel quality is stable in a channel coherent interval. A sender can exploit the interval to send more frames. In this paper, we propose TRAF protocol. TRAF provides an extended option, a two-way rate adaptation scheme and per-frame-based back-to-back transmissions, and frame fragmentation algorithm. To evaluate the performance of TRAF, a simulator is developed to measure frame delivery ratio and network throughput of TRAF. Simulation results are compared to that of other rate adaptation protocols. The results show that TRAF outperforms other approaches.

The remainder of this paper is organized as follows. In Section 2, we describe some background material concerning 802.11. Related researches, e.g. ARF, RBAR, and OAR are briefly presented in Section 3. In section 4, we firstly point out our observations about the issues in previously proposed approaches. Then, we propose our solutions to the issues. Performance simulation and discussion are presented in Section 5. Finally, Section 6 concludes this paper.

2 IEEE 802.11 Overview

A brief introduction of the IEEE 802.11b based on frequency hopping spread spectrum (FHSS) physical layer is described in this section. The description includes DCF, NAV update mechanism, multi-rate capability, and fragmentation scheme. Since the paper focuses on MANET (also known as independent basic service set, IBSS), thus only fields concerning IBSS are presented. The concept is possible to apply to other high speed 802.11 MAC.

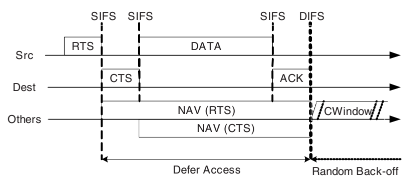

Fig. 1. DCF frame sequence

Distributed Coordination Function (DCF). In 802.11 [1, 6, 7, 9, 15], DCF is a basic medium access protocol. All traffic uses immediate positive ACK frame. The virtual carrier sense mechanism is achieved by distributing reservation information. The exchange of RTS/CTS frames prior to the actual data frame is to distribute this medium reservation information. The RTS/CTS frames contain a duration field for reserving the medium. All nodes within the reception range of either the source or the destination shall learn of the medium reservation. For example the transmissions shown in Figure 1, when Src has a frame to send, it calculates the time needed to transmit CTS, data and ACK frames (assume SIFS time is included in each frame) at current data rate, which forms the reservation duration in RTS frame. Then, Src sends the RTS frame to Dest at base rate. Others in the reception range of Src postpone their transmission attempts for the duration declared in the RTS frame. If Dest can receive the RTS frame, it immediately replies a CTS frame with the duration field copied from RTS. Others in the reception range of Dest defer their access for the duration declared in the CTS frame. DATA and ACK frames also carry a duration fields for a period to the end of ACK frame, respectively, to information hidden/exposed nodes [19].

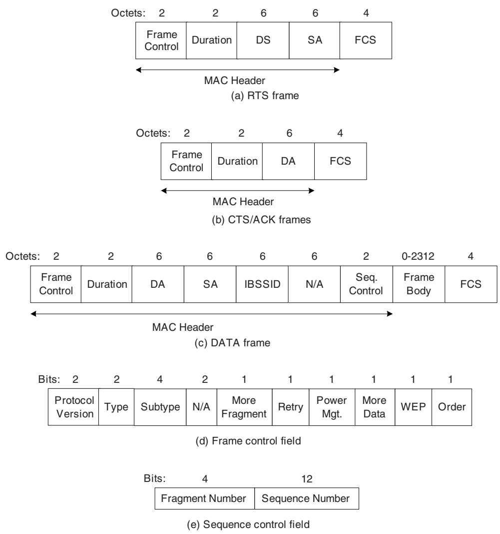

Fig. 2. Frame formats

MAC Frame Formats. There are 3 types of frame, including management frame, control frame, and data frame. In each type of frame, there are several subtypes. For example, RTS/CTS frames are subtypes of control type. The frame formats of RTC, CTS, DATA, and ACK frames are depicted in Figure 2, where SA and DA denote Src and Dest MAC addresses, respectively. More fragment bit is used for frame fragmentation and presents that there is a fragment next to current fragment transmission. Retry bit is set if the frame is a retransmitted one. Power management bit indicates a sender is working in power saving mode. More data bit represents that there is an impending frame to transmit. WEP bit means wire equivalent privacy. Frame ordering is controlled by Order bit. Fragment number and sequence number are 2 sub-fields in sequence control filed. Readers can refer to 802.11 [1] for detailed application of these fields.

Network Allocation Vector (NAV). A virtual carrier sense mechanism is referred to as the NAV. NAV maintains a predication of future traffic on the medium based on duration information that is announced in RTS/CTS frames. NAV can be thought of as a counter, which counts down to zero at a uniform speed. When the counter is zero, the virtual carrier sense indication is that the medium is idle. Nodes receiving a valid frame shall update their NAV with the information received in the duration field, but only when the new NAV value is greater than the current NAV value and the frame is not addressed to the receiving node.

Fragmentation. MAC layer may fragment and reassemble a frame. The length of a fragment shall have same octets except the last. When a frame is transmitted with fragmentation, MAC layer shall set more fragment bit, reset fragment number for the first fragment. Then, MAC layer keeps the values of more fragment and sequence number unchanged, and increases fragment number by one for each following fragment. MAC shall reset more fragment bit for the last fragment to inform the recipient to reassemble all the received fragments. Retransmission is allowed for the fragmentation and de-fragmentation mechanisms.

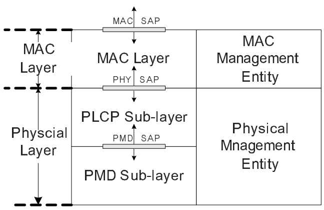

Fig. 3. Layer model

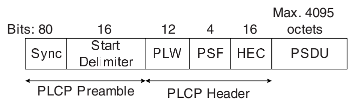

Fig. 4. PLCP frame format

Multi-rate Capability. Nowadays, physical layers in most of wireless interfaces have multiple data transfer rate capabilities that allow MAC management entity to perform dynamic rate switching with the objective of improving the performance. All control frames and frames for broadcast or multicast shall be transmitted at base rate, which is one of rates in the IBSS basic rate set and is determined on the network started, so they will be understood by all nodes. Data and/or management frames with unicast address shall be transmitted on any supported data rate selected by rate switching mechanism.

A physical layer is divided into physical layer control protocol (PLCP) and physical medium dependent (PMD) sub-layers. Figure 3 shows the 802.11 layer model. A MAC frame, also named MAC protocol data unit (MPDU), with rate information is passed a parameter of physical service access point (PHY_SAP) to the PLCP sub-layer. In PLCP sub-layer, a PLCP preamble is added in the front of PLCP header followed by a payload, which is the MPDU passed from the MAC layer. The rate parameter in PHY_SAP call is formatted into the payload rate information in the PLCP header. The format of PLCP frame is shown in Figure 4. The PLCP preamble and PLCP header shall be transmitted at the base rate chosen from the IBSS basic rate set. The PLW specifies the number of octets contained in the PSDU. The PLCY payload will be transmitted at the rate specified in the PLCP signaling field (PSF) as shown in Figure 4. Therefore, all receivers can synchronize to the PLCP preamble and the recipients can receive the PLCP frame at the same rate used by the sender.

3 Related Work

In wireless communications, the signal at the recipient is a superposition of different reflections of the same signal, noises of background and interferences from nearby channels. The received signal power strength is heavily dependent on the spatial locations of sender and recipient. Any motion of sender or recipient causes the signal strength to vary with time. SNR is used by the physical layer to capture the channel [17]. The larger SNR, the better the chance of any frame is received with lower BER. In addition, some modulation schemes are more efficient than others at transmitting information with a given SNR and bandwidth [8]. Currently, almost all physical interfaces for WALN provide multiple transfer rates that support dynamic rate switching for improving the throughput of WLAN. There are two steps to rate selection: Channel quality estimation and rate adaptation. Channel quality estimation involves measuring the time-varying metrics (e.g. SNR, BER) of wireless channel which would be used as a short-term or long-term predictor. Rate adaptation schemes employ the predictor to select an appropriate rate. A threshold-based scheme in [5, 13] is a common technique for rate determination.

Some rate adaptation protocols [4, 11, 12, 14, 16, 18] have been developed for MANET. In [14], the authors propose the auto rate fallback (ARF) protocol for 802.11 used in Lucent's WaveLAN II devices. In ARF, the sender selects the best rate based on information from previous data frame transmissions. It incrementally increases or decreases the rate after a number of consecutive successes or losses, respectively. In this way, ARF doesn't need to modify 802.11 MAC frame formats. But the previous information can't represent current channel condition at present.

In [11], the authors present the receiver-based auto-rate (RBAR) protocol. The key idea of RBAR is to allow a receiver to estimate channel quality and to select an appropriate rate during RTS/CTS frame exchange for the next data frame. Since the rate selection is done by a receiver during latest RTS/CTS exchange, the channel quality estimation is nearer to actual transmission time of data frame than the sender-based approaches, like ARF. However, the rate chosen by the receiver must be carried back to the sender by CTS frame. Modification to 802.11 MAC frame formats to carry the rate related information is then unavoidable. RBAR redefines both MAC layer and physical layer frame formats. At MAC layer, RBAR redefines the 16-bits duration fields of RTS/CTS frames into two sub-fields: 4-bits data rate and 12-bits data frame length. The purpose of the modification is a tentative reservation to inform all overhearing nodes to calculate and to set their NAV by the rate and the length information. A new reservation sub-header (RSH) is also redefined into the data frame header as a final confirmation to previous tentative reservation. At physical layer (PLCP), the signal field of PLCP header is redefined to be 4-bits RSH rate and 4-bits data rate. RBAR applies different rates to send RSH and data frame.

Sadeghi et al. [18] propose another receiver-based approach, the opportunistic auto rate (OAR) MAC protocol. The key observation is that channel coherent times are typically at least multiple frame transmission times. Consequently, when a mobile sender is granted channel access while encountering a high quality channel, OAR grants the sender a channel access time that allows multiple frame transmissions in proportion to the ratio of the achievable data rate over the base rate. Consequently, OAR transmits more frames under high quality channel than under low quality channel. OAR basically appears similar features and drawbacks of RBAR, such as timely receiver-based rate selection and frame format redefinition. In addition, OAR provides new back-to-back frame transmissions by using fragmentation technique to fully utilize the high quality channel for sending more frames. During back-to-back transmissions, a sender sets the more fragments flag in frame control field of MAC header for each intermediate fragment (a frame is treated as a fragment) until the last fragment is transmitted. The sender must also set the fragment number in sequence control field of MAC header to 0. This prevents the receiver from treating the data fragment as a part of an actual fragmented frame. Since OAR redefines application meaning of fragmentation, it causes certain side-effect. We explain this in detail in the observation 6 of next section.

4 The Proposed Protocol

4.1 Observations

With 802.11 [1, 2, 3], most of wireless interfaces nowadays support multiple data transfer rate capabilities. As described in section 3, lots of rate switching protocols had been proposed to exploit the multiple rate capability to improve the performance of MANET. The enhancement shown in [11] was significant in comparison with that of merely using a single fixed rate.

Observation 1*: Adequate rate adaptation would result in positive effect on the throughput of a MANET with the interfaces of multi-rate transfer capability.*

With simpler ARF, the sender heuristically selects a data transfer rate. ARF works well when the channel condition is relative smooth. Frames are easily got loss as channel variation is drastic, and the throughput of ARF clearly degrades as moving speed increased. [11] shows that ARF can not rapidly react to the fast channel variation. In contrast to ARF, RBAR decides a transfer rate by a recipient. A recipient gets the receiving condition from its radio [1]. Thus, the recipient is the most suitable one to choose a transfer rate for the following frame transmissions. The results of performance evaluation in [11] showed that BRAR outperforms ARF in considering channel variation and various moving speed.

Observation 2: *A recipient can provide more accurate information of channel variation than a sender***.**

OAR [18] adopted the concept of the receiver-based approach to quickly react a data transfer rate to a channel variation. In addition, they leverage the back-to-back fragmentation scheme to further enhance the throughput of MANET. The enhancement is mainly attributed to diminish back-off times and contention chances between several consecutive data fragment transmissions in the residual time saved with a faster transfer rate relative to the original slower one. The throughput advance of OAR against RBAR can be clearly seen in [18].

Observation 3: *Using the residual time saved from faster transfer rate to send more frames with back-to-back frame transmissions can further enhance the throughput of MANET.*

OAR transmits all consecutive fragments with a fixed transfer rate decided by the recipient. However, to adapt the receiver-based transfer rate by per fragment basis can closely react to the latest channel condition. Thus, better channel adaptation quality than that of OAR can be obtained. This enhancement can be seen from the result of simulations in section 5.

Observation 4: *The rate adaptation to channel variation by per fragment basis is timely than a single fixed rate for all consecutive fragments.*

In RBAR, the MAC header and the PLCP header are redefined to carry the data transfer rate and to declare the data frame length. The recipient basically follows the rate specified by the sender for most of cases. However, in the case of channel condition changes violently, the receiver must refer the receiving signal level indicated by the physical layer. With the receiver-based rating concept, although the throughput is really improved by RBAR protocol, there are some drawbacks occurred. Firstly, the modifications at the duration field of the MAC header in the RTS/CTS frames. The overhearing nodes which obey only the standard definition would not interpret the rate and the length of a RBAR frame in a right way. Furthermore, the redefinition at the signal field of the PLCP header would results that the receiver can not differentiate the PLCP header of RBAR from that of standard 802.11. Therefore, RBAR can not be understood by the nodes implemented according to 802.11. OAR adopts similar redefinitions as RBAR. Thus, the drawbacks also accompany OAR.

Observation 5: *To modify the definition of MAC header and PLCP header should be very careful to insure the compatibility to 802.11 and to guaranty the interoperability to huge existing installation bases.*

OAR utilizes fragmentation to implement back-to-back fragment transmissions. Although, this is a good idea, to consider the conformation to 802.11, the back-to-back fragment transmissions may result in some side effects. Regarding 802.11, a MPDS at the sender side is possible to be fragmented in order to be sent via a wireless channel, at the receiving side all the fragments will be reassembled according to their fragment number with the same frame sequence number. In the case of two or more separated MPDSs are sent as consecutive fragments with same frame sequence, then they would be reassembled into a single MPDS at the receiver. This may cause frame disorganization, e.g. two frames belonged to two flows respectively could be combined into one frame for one flow. Another case is that the consecutive fragments (frames) have different frame sequence numbers, of course at the receiver end they can be kept for reassembling in different buffer lists. However, there is only one last fragment with more fragment bit set to zero to inform the completion for reassembling. Other frames in fragment form still wait to be reassembled until time-out occurred.

Observation 6: *The concept of back-to-back frame transmissions is nice. Yet to implement the idea with fragmentation may mislead into incompatibility and cause severe resource wastage.*

4.2 Our Methods

To get rid of the problems originated from the related research proposals as described in the observation section, we try to propose a new wireless medium access control protocol to provide not only a dynamic multi-rate adaptation capability, but also with an active fragmentation to preserve a high data transfer rate under a short-term BER rising over a intermittently interfered wireless channel. In general, all the recommendations obtained from previous observations would be infused into the new design. However, the purpose of the utilization of fragmentation is entirely different between our method and OAR. We will explain it in detail at the back-to-back transmissions subsection later.

Option for Bi-directional Rate Adaptation. To provide a better dynamic multi-rate data transfer over an unreliable wireless channel, the receiver-based rate-decision strategy is adopted in our design. Both of RBAR and OAR approach the strategy by redefining the duration of MAC header to carry the data transfer rate. The drawback is that the newer protocols would be incompatible to huge existing 802.11 adapters. Inspecting 802.11 as Figure 2, there is no reserved field in RTS/CTS frames to carry rate information.

Instead of redefinition, we append an option field to the standard RTS/CTS/Data/ACK (abbreviated as RTS-R/CTS-R/Data-R/ACK-R) frames as depicted in Figure 5 to piggyback extension information. The option field is consisted of code and data fields. Code specifies the option type. Data is 2-byte field and its meaning is dependent on the code field. For a RTS-R, the code is 1 and the data consists of a 1-byte transfer rate, which will be used for the next transmission, and a 1-byte receiving rate at which its transceiver affords to receive.

AT the beginning of a communication, a sender formats these two rates into an option field plus a checksum, and appends the option to the tail of RTS frame. Since the RTS is sending at base rate, the overhearing nodes can understand the frame and would pick out the duration to update its NAV, and they simply ignore the tail option field. A receiver with the option capability verifies the correctness of RTS-R option by comparing the checksum at the tail and interprets the tail option back into the correct rates. A best-fit acceptable rate from an operational rate set is chosen by the recipient with referring to the rate requested by the sender and the signal level indicated from its physical layer. The best-fit acceptable rate can be chosen by a threshold-based technique as studied in [5, 13]. Let θ_i, i=1, 2, …, N, represents a SNR threshold at which the corresponding BER is equal to an adequate working level, e.g. 10^{-5}. Also let α_i represents a data transfer rate approximately matching to the threshold. Thus, a transfer rate α_i can be chosen by the following algorithms, i=0, 1, …, N, where α_0 is the minimum speed at which a transceiver can support and α_N is the maximum speed.

If (SNR <θ_1) then choose α_0
If (θ_i < SNR <θ_{i+1}) then choose α_i
If (θ_N < SNR) then choose α_N

The recipient then replies a CTS-R frame with code being 1 at base rate back to the sender. The nodes covered by the receiver will update their NAV with the duration field of CTS-R frame as it received a normal CTS frame. As our designation, the sender can get the confirmed rate from option field and will use it for the next transmission. With RTS-R/CTS-R exchange, all the nodes of conforming either to 802.11 or the option-extended one can interoperate to each others.

An alternate suggestion to add the option extension is to allocate reserved subtypes in the frame control field of MAC header of a control-type frame as shown in Figure 2(d), for defining new RTS-R/CTS-R/ACK-R control frames. In this way, the option

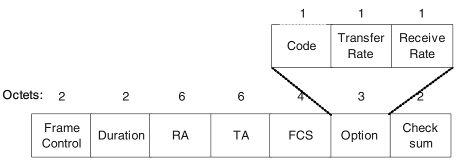

Fig. 5 (a). RTS-R format

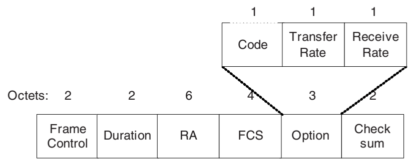

Fig. 5 (b). CTS-R and ACK-R format

filed can be put between the MAC address fields and the FCS field, and checksum field can be omitted. The sender and the recipient must support the new defined control frames to correctly interpret the option. As for the overhearing nodes, they treat the new control frames as normal control frames and extract the duration field from the MAC header to update their NAV as usual.

In summary, the observations 1, 2, and 5 in the former section are deliberately considered and designed into our proposal. Therefore, the compatibility and interoperability can be maintained in addition to support the bi-directional multi-rate frame transfer over an unreliable wireless channel by per frame basis.

Back-to-Back Transmission. The benefit of back-to-back transmissions was already explained in the observation 3 in the former section. However, the observation 6 also presented a caution of incompatibility if the back-to-back transmissions were implemented with fragmentation manner as the approach proposed in OAR. Thus, we design back-to-back transmissions with per frame basis. Consider that the time period to transmit a frame with base rate, selected from one of the basic rate set [1], is t_{FB}. Assume that the multi-rate capabilities are supported by both of a sender and a recipient. As the example with back-to-back frame transmissions shown in Figure 6, the data frame 1 which original would be sent by base rate (here we assume the base rate is 1 Mbps), now will be sent by 5 Mbps. If the sender still has other frames waiting to be sent, and the residual time, denoted as t_{FBR}, is at least long enough to transmit more than one frame (plus the length of an ACK time). The sender can transmit the next frame after SIFS when ACK-R is received. With this similar way, all the pending frames can be sent until t_{FBR} is too short to transmit the next one frame. On the other hand, suppose that there is no more frame pending at the sender and t_{FBR} is longer than a threshold (2SIFS + RTS time + CTS time + C, C is a constant), CF_End control frame is sent to inform all overhearing nodes to reset their NAV for better channel utilization. If t_{FBR} is less than the threshold, the sender will do nothing and just let the residual time pass by.

The 3-tuple specified in each frame in Figure 6 denotes current transfer rate, expected transfer rate, and acceptable receiving rate, respectively. The first rate can be specified at the PLCP signal field as shown in Figure 4. The second and the third rates are indicated on the data part of RTS-R/CTS-R/ACK-R option filed as shown in Figure 5. For instance, SRC sends RTS-R with (1, 11, 1) 3-tuple, the first number means that RTS-R is to be transferred at base rate, the second rate describes that the next frame is expected to be transferred at 11 Mbps, and the last rate represents an acceptable receiving rate at 1 Mbps which SRC can afford to receive. Next, DEST replies CTS-R with (1, 11, 5), which means CTS-R is to be transferred at 1 Mbps as

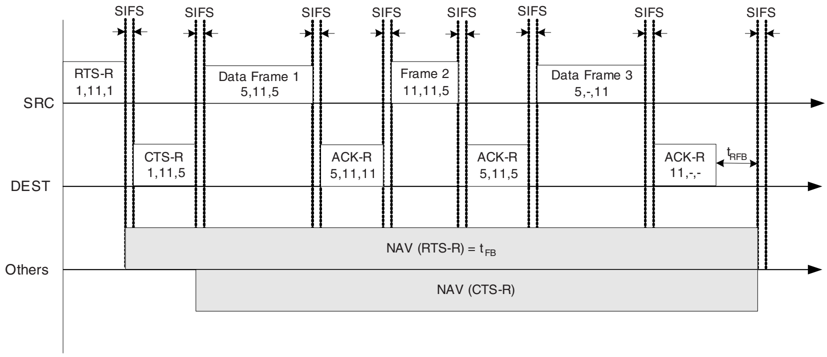

Fig. 6. Back-to-back transmission

requested by the third rate of RTS-R, and it also expects to transfer the next frame at 11 Mbps and it may receive a frame at a speed of 5 Mbps. After that, SRC transmits its first Data-R frame at 5 Mbps as the rate specified on the third rate of 3-tuple in CTS-R, expects its next transfer rate to be 11 Mbps, and expresses its affordable receiving rate to be 5 Mbps. Next, DEST knows to send its ACK-R at 5 Mbps, requests to send its next frame at 11 Mbps, and describes its affordable receiving rate at 11 Mbps. Then, SRC can transmit it's the second Data-R frame at a higher rate of 11 Mbps, informs its next transmission speed to be 11 Mbps, and tells its affordable receiving rate at 11 Mbps. With the similar manner, consecutive data frames and control frames can be transmitted with bidirectional rate adaptation which best fit to the signal level on the bidirectional link.

Fragmentation Algorithm. In mobile wireless networks, interference, fading, and path loss result in the variation of SNR at recipients. Such variation further causes a variation in the BER. Higher data rate α_i usually causes higher BER for a given SNR. Note that, for a given SNR, a decrease in the data rate results in a decrease in BER as shown in Figure 7. Therefore, there is a tradeoff between data rate and BER. In data rate selection, as chosen by RBAR and OAR, the data rate is decreased while SNR decreased beneath a threshold θ, while the corresponding BER is higher than an adequate value for demodulation, e.g. 10^{-5}. Denotes δ as the short-term variation in SNR, and the increased BER corresponding to θ-δ is too high for a normal frame transmission, e.g. BER is equal to 10^{-4}, but it is still low enough for a shorter frame to be transferred. For instance in 802.11b FHSS [1], the maximal length of a MPDU as a payload of PLCP frame transmission is specified as 4095 octets, which equals 32888 bits (128 bits PCLP header plus 8×4095 bits payload), and it is in a magnitude of 10^5 bits. Undoubtedly, a frame with a length of 10^5 would suffer a high broken probability when it is transferred over a wireless channel with 10^{-4} BER. Instead of simply choosing a lower data rate, a frame fragmentation scheme is applied to divide a normal frame become several short fragments. The length of the fragments is shortened to a magnitude of less than 10^{-4}, if the MPDU is partitioned into 10 or more fragments. Ideally, these fragments would have higher probability to pass through the wireless channel affected by the impact of δ variation in SNR. Thus, there is no need to switch down transfer rate and the throughput will be kept at the same level of the original SNR as without the impact. Therefore, the data rate selection algorithms are refined by considering the δ variation and fragmentation.

If (SNR <$\theta_{1-\delta}$) then choose α_0
If (θ_i-δ< SNR <θ) then choose α_i plus fragmentation
If (θ_i < SNR <θ_{i+1}-δ) then choose α_i
If (θ_N < SNR) then choose α_N

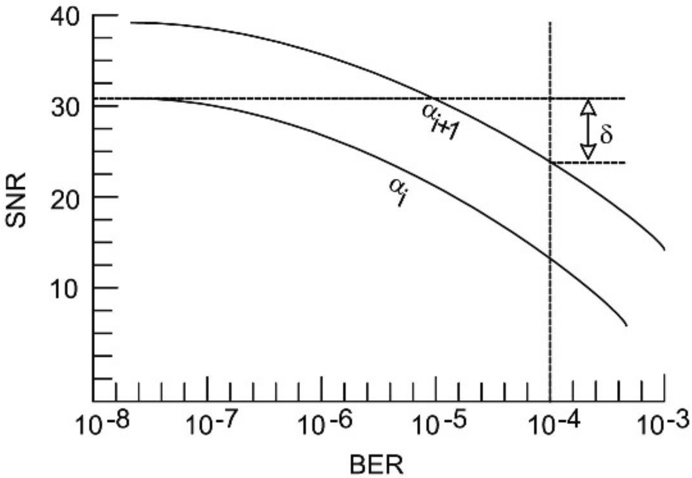

Fig. 7. SNR vs BER

Assume a bit error occurred in a normal frame transmission. The broken frame would be discarded by a recipient. The sender will try to retransmit it after a time-out timer and a DIFS period plus random back-off slots. It is still possible for a fragment being discarded by a recipient due to a bit error happened during a fragment transmission. In this case, the dropped fragment can be retransmitted with similar way. Even so, the cost of a transmitting failure for a long frame is still much higher than that of a short fragment. Let *F(i)* and *f(i,j)* denote frame *i* with length *L* and fragment *j* with length *l* in frame *i*, respectively. Also let *P(i)* and *p(i,j)* denote the transmitting failure probabilities of *F(i)* and *f(i,j)*, respectively. Thus, $P(i)=1-(1-BER)^L$ and $p(i,j)=1-(1-BER)^l$. where $P(i) > p(i,j)$ and $L>l$. The failure cost to transmit *F(i)* with a frame way or with fragments way would be $P(i) \times L$ and $\Sigma ip(i,j) \times l$, respectively. With fragmentation, the cost of $P(i) \times L-\Sigma_i p(i,j) \times l$ would be saved for a frame transmission. For instance, given $L=10^5$ bits, $l=10^4$ bits, and $BER=10^{-4}$, thus $P=0.6321$, $p=0.0952$. Therefore, with fragmentation, successful probability of a fragment is much higher than that of a frame. When one failure occurs, the saved cost is 5369 bits per frame transmission. This is also equal to throughput enhancement. Although, overhead from fragmentation is not considered here, it is relative small to compare to data fragment itself. In this example, total overhead is *9×(ACK time+SIFS).*

5 Simulation Experiments

5.1 Simulation Model

To simulate all protocols, we develop a simulator with sophisticated functions which implement detailed control schemes of each rate-adaptation protocol, including fix rate at 1, 2, 5.5, and 11 Mbps, ARF, RBAR, OAR, and TRAF. We are currently interested in the performance of proposed protocol at MAC layer viewpoint. Thus, we assume all nodes are in the transmission range of each others. In the simulator, we assume all communicating pairs are modeled as flows with constant bit rate (CBR) and send the frames with fixed frame length. Each flow is interfered with fast changing channel noise. Thus, its receiving strength is modeled as dynamically changing SNR. The SNR is randomly generated during the simulation period with a mean value of 17 dB and a deviation value of 12 dB. It is generated at a timing of exponential distribution with a mean interval of 10 ms. Moreover, mobility affects both line-of-sight interference and channel coherence time. It is modeled as a drifting effect to the SNR of each flow. When the end nodes of a flow move closer, its SNR would be increased a certain amount. On the contrary, the SNR would be decreased. We model 4 relationships corresponding to 4 data rats into the simulation model. Acceptable SNR ranges of 1, 2, 5.5, 11 Mbps transfer rates are given by [5...9], [11...15], [17...21], [23...27], respectively. BER range corresponding to SNR range at each transfer rate is given by [10^{-4}...10^{-8}]. For instance, at a certain time, if a flow transmits a frame with SNR equal to 19, according to the given SNR range and the given BER range, the data rate is 5.5 Mbps and the BER is 10^{-6}. As for the hidden terminal problem [19], it can be deemed as a noise impact with an abruptly changing SNR, it is implicitly included in the dynamically generated SNR values. When we simulate TRAF with fragmentation, δ variation in the fragmentation algorithm as described in Section 4 is set to 1 dB to observe throughput improvement.

5.2 Frame Delivery Ratio

The frame delivery ratio is denoted as the aggregate number of successfully sent frames divided by the aggregate number of generated frames. In this simulation, we set the CBR of each flow to 384 Kbps, the frame length is fixed to 2048 bits, and add one flow at a time to observe the frame delivery ratio. As shown in Figure 8, when there is only one flow, most of protocols deliver frames with high successful rates, except fix transfer rate protocols like 2, 5.5, and 11 Mbps. The reason is fix transfer rate protocols can't adapt to the fast changing channel conditions, which is represented with the dynamically generated SNR. When a frame is sending with fast transfer rate over the channel with a low SNR, it would fail to demodulate the receiving frame at the recipient. As for the lowest fix transfer rate at 1 Mbps, most of channel conditions are better than the lowest SNR requirement of the rate. Thus, the frame delivery ratio would be high for the lowest fix rate transmission. Next, when flows are added into the network, more frames are generated for transmission in the same period, the broken frames caused by BER and collisions due to frame congestion gradually depress the frame delivery ratio. Generally speaking, the rate-adaptable protocols outperform the fix rate protocols. Especially, the proposed TRAF performs the best.

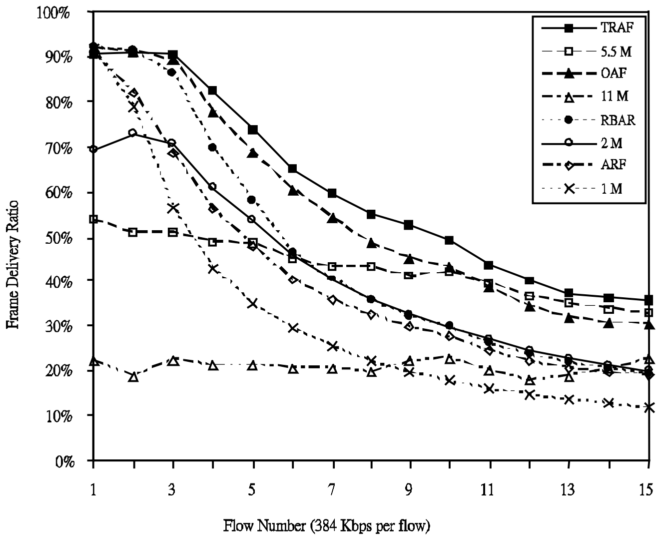

Fig. 8. Frame delivery ration vs. flows

5.3 Network Throughput

In this simulation, we would observe the network throughput of each protocol versus the network load modeled by multiple CBR flows. Here, the definition of network throughput is equivalent to that of channel utilization which is denoted as the total sent bits divided by total bandwidth at base rate. All flows keep same CBR and same frame size as previous simulation.

At the beginning with one flow as shown in Figure 9, all protocols demonstrate low network throughputs, this is due to low frame generation rate so that there is few frames ready to send. After more flows are added into the network one by one, the network throughputs are gradually increased accordingly. Where 1, 2 Mbps, ARF, and RBAR reach the saturate throughput earlier than others at about 3 to 5 flows. Other protocols keep increasing as the number of flows continuously increases. Clearly, TRAF outperform other protocols for whole simulation period. It is interesting to notice that 5.5 Mbps even has better network throughput than OAR. The reason is that OAR sends RTS/CTS control frames at base rate, and then it sends data frames with appropriate rate. Thus, RTS/CTS become essential overheads to OAR. On the contrary, 5.5 Mbps fix rate send all control frames and data frames with same high rate. Thus, the RTS/CTS overheads are shortened by higher transfer rate.

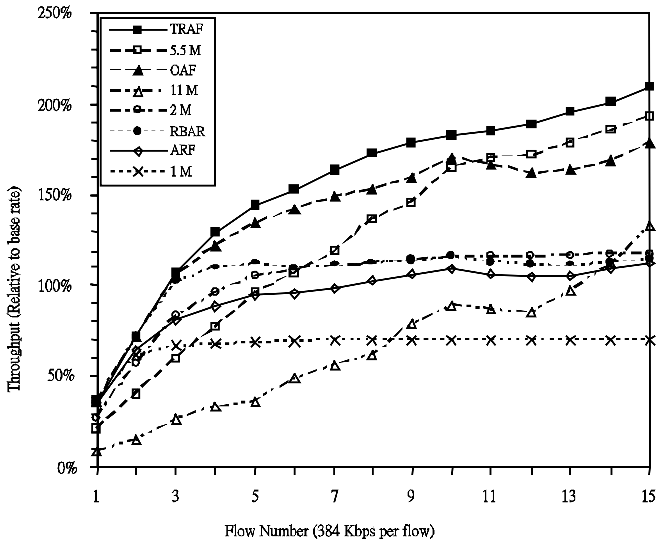

Fig. 9. Throughput vs. flows

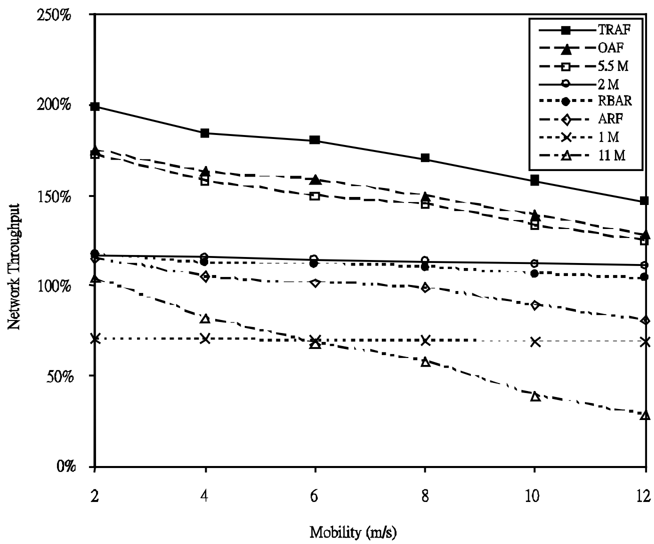

Fig. 10. Throughput vs. Mobility

In addition, as the mean value of SNR chosen for the simulation is 17, which exactly falls on the modulation scheme with transfer rate of 5.5 Mbps, this also favors the 5.5 Mbps transfer rate. Note that 1 Mbps has the lowest network throughput. Since most of time the SNR is higher than the lowest SNR requirement of 1 Mbps, and a fix rate protocol never tries to increase its transfer rate to fully utilize good channel conditions to transfer more frames.

5.4 Mobility

Mobility affects the communicating flows in two ways. When both end nodes move closer to each other, the SNR of the flow is getting better. On the contrary, when end nodes move farther, the SNR of the flow is getting worse. We model the influences as a two-states machine, the state is stayed for a time interval generated by an exponential distribution with a mean value. Simulation was started with 10 flows with same CBR and same frame size. Simulation results are shown in Figure 10. As mobility increases, the network throughputs of most of protocols are going down accordingly, especially 11 Mbps. On the other hand, RBAR and low fix rate protocols such as 1 and 2 Mbps are insensitive to the SNR variation caused from mobility.

6 Conclusion

In this paper, we introduced TRAF rate adaptation protocol for MANET. With TRAF, a node at high channel quality can transmit multiple frames in a way of back-to-back transmissions at a rate as fast as possible. During back-to-back transmission interval, bi-directional rate exchanges are executed through the proposed option extension. With the bi-directional rate adaptation in per frame basis, TRAF enhances channel utilization with timely fast rate adaptation. Even while the recipient suffers from worse channel quality, TRAF still can adopt frame fragmentation mechanism to increase successful delivery rate and to maintain high channel throughput. Moreover, TRAF follows the 802.11 standard without any redefinition or modification. Consequently, backward compatibility can be promised as much as possible. Extensive simulation experiments are performed to compare the frame delivery ratio, network throughput, and mobility impact of TRAF to that of other protocols. The results show that significant improvements are achieved as our expectation.

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