Received: Added at production | Revised: Added at production | Accepted: Added at production

DOI: xxx/xxxx

RESEARCH ARTICLE

Evaluating the Impact of Aggregation and RTS/CTS schemes on IEEE 802.11 Based Linear Wireless Ad-Hoc Networks

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Abstract

The Linear Wireless Ad-Hoc Network (Linear WANET), as a branch of the Ad-Hoc network, refers to a self-organizing multi-hop wireless network in which nodes are arranged linearly. Frame aggregation and RTS/CTS schemes are introduced in IEEE 802.11 aims to improve network transmission performance. However, the traditional mechanisms may not have good adaptability in linear multi-hop networks. Thus, we defined a Linear WANET simulation model based on the IEEE 802.11 protocol. We established this model on the NS-3 network simulator to perform A-MSDU, A-MPDU, and two-level frame aggregation simulation and analyzed the aggregation performance under different channel environments. Meanwhile, the RTS/CTS and TXOP mechanisms were also simulated in this paper. We analyzed the performance of each mechanism in a Linear WANET under saturated and unsaturated environments.

We found that in a Linear WANET, the A-MSDU mechanism can improve system performance to a limited extent, but at the same time, it will increase the packet loss rate and delay. Although the A-MPDU mechanism can reduce the retransmission overhead, the higher A-MPDU Limit cannot further improve the throughput of the Linear WANET. Meanwhile, in the case of single A-MPDU aggregation, there has a lowest data delivery interval that the Linear WANET system can withstand. Besides, we also found that the native TXOP mechanism cannot effectively improve the system efficiency of Linear WANET. And the RTS/CTS mechanism can improve the performance of Linear WANETs, especially in a saturated throughput environment.

KEYWORDS:

Ad Hoc; WANET; Aggregation; TXOP; RTS/CTS; IEEE 802.11

1 | INTRODUCTION

With the rapid development of science and technology in the 21st century and the continuous advancement of the Internet and network technologies, people have begun to pursue convenient, fast, practical, and efficient new communication methods. This constant demand has stimulated the vigorous development of wireless network technology. In the field of emergency communications, we often need to transmit a large number of medical images and real-time video streams from the disaster-stricken area to the outside world. For news reporters who need to report on the spot, they need emergency wireless communication systems to transmit the videos and news they shot to broadcast stations in unaffected areas. However, the interruption of power facilities and communication infrastructures caused by environmental factors will make traditional mobile networks and terrestrial wired networks unusable. Furthermore, as the satellite communication channel conditions are greatly affected by the weather, and the personal satellite equipment is too expensive, the satellite communication is difficult to promote in the civilian field.

The establishment of temporary wireless networks to support particular data transmission in the disaster-stricken areas or indoor venues is one of the urgent tasks in news reporting missions. The emergence of wireless ad hoc network (WANET) technology is of great significance to study the temporary wireless data transmission in the above situations. The WANET is a non-fixed autonomous system which generally composed of many interconnected network nodes. Compared with WANET topology, Linear WANET is a self-organizing network with linearly arranged nodes. It has many different characteristics that are of value in both theoretical research and actual practice.

The current academic research on the optimization of ad hoc networks mainly focuses on the mesh networks and centralized networks, while linear multi-hop wireless networks are rarely involved. The Linear WANET studied in this paper is a temporary network. According to its application scenarios, its nodes will not move on a large scale. This paper mainly studies the impact of multi-hop characteristic on linear network and the impact of external factors on various MAC mechanisms. Meanwhile, since the IEEE 802.11 protocol was initially developed for centralized networks, some performance enhancement mechanisms for the IEEE 802.11 protocol, such as frame aggregation mechanism and TXOP mechanism, may not adapt or even cause performance degradation in Linear WANETs. Therefore, we need to explore the characteristics of various mechanisms under Linear WANET through a large number of experiments and simulations. The exploration will help us to summarize a set of practical adaptive network optimization algorithms that adapt to Linear WANETs.

The structure of the Linear WANET system in this paper is based on the IEEE 802.11ac protocol. The nodes in the IEEE 802.11 networks are often configured in AP (Access Point) mode or STA (Station) mode, as well as mixed AP-STA mode. We consider a linear multi-hop wireless network with multiple AP-STA node pairs. A user node will deliver messages to the source node through relaying nodes between them. The transmission of data is bidirectional, and there can be many terminals access to this link. The relay nodes can be placed randomly, but for achieving better performance, the nodes in the linear wireless network should be placed equidistantly[1].

We consider three types of nodes in this system: Source node, Relay node and User node. The only source node is configured as AP mode; other nodes are configured as AP+STA mode, which allows nodes to access other nodes while being accessed[2].

Our major contributions in this paper are listed as follows:

- We use NS-3 as the primary simulator to model and simulate the Linear WANET system. In detail, we utilize the discrete event simulation feature of NS-3 to design performance verification for the A-MSDU aggregation, the A-MPDU aggregation, and the two-level frame aggregation schemes. The code used in the simulation has been uploaded to github[3].
- We analyzed the simulation results and put forward suggestions for improving the performance of the frame aggregation mechanism in Linear WANETs.
- Similarly, we designed simulation performance verification for the TXOP mechanism and RTS/CTS mechanism. By comparing the delay and packet loss rate under saturated and unsaturated throughput conditions, we analyzed the effect of the TXOP mechanism and RTS/CTS mechanism on Linear WANETs, and put forward suggestions for improving the performance of the RTS/CTS mechanism in Linear WANETs.

The remainder of this paper is organized as follows. Section 2 briefly discusses the previous efforts on the aggregation scheme and RTS/CTS scheme for wireless networks. In Section 3, we present the network model and analyze the transmission characteristics of Linear WANETs. We discussed the aggregation performance on Linear WANETs in Section 4. The discussion of the TXOP mechanism and RTS/CTS mechanism performance on Linear WANETs is shown in Section 5. Finally, this paper concludes with Section 6.

2 | PREVIOUS EFFORTS

In recent years, with the continuous advancement of communication technology, wireless multi-hop Ad Hoc networks have been widely studied[4,5,6,7]. The wireless multi-hop Ad Hoc network is particularly suitable for non-fixed networks such as the construction of temporary network communication services. Under normal circumstances, the wireless signals could be extremely fragile due to the possibly severe signal attenuation from path loss and shadow fading[8]. So the relay techniques are commonly applied for accomplishing the transmission in wireless network. Relay technology has been widely used in multi-hop Ad Hoc networks. The relay technology focuses on solving the optimal position of the relay node, thereby effectively improving network performance and reducing power consumption[9,10,11].

However, Martin and Daniele[12] analyzed the advantages of long hop in Ad Hoc network. Compared with short-hop networks, long-hop Ad Hoc networks have great advantages in terms of total network power consumption, path efficiency, and routing overhead. Moreover, long hops do not necessarily increase crosstalk and reduce end-to-end reliability. Once the required bandwidth normalized ratio (spectral efficiency) is greater than the path loss, the single-hop routing is better than two-hop routing. Nevertheless, traditional commercial wireless devices generally use omnidirectional antennas with a wide coverage range but a short coverage distance. Simultaneously, under the power limit of the FCC (Federal Communications Commission) on RF (Radio Frequency) devices, it is difficult for a single-hop route to achieve a wide transmission coverage. So Dai[13] discussed the promotion of directional antennas on the performance of wireless multi-hop sensor networks. Directional antenna technology can further reduce the number of hops in long-distance Linear WANETs, thereby bringing better network performance with limited transmission power.

Multi-hop characteristics are one of the most important characteristics of WANET. How to solve the hidden node problem has always been a major difficulty in WANET research[14,15]. In the traditional IEEE 802.11 protocol, the CSMA/CA mechanism has been adopted to avoid signal conflicts caused by hidden node problem. Since this mechanism was originally designed for traditional star topology networks, and in subsequent evolutionary protocols such as IEEE 802.11n/ac, the CSMA/CA mechanism has not been modified. This results in the frame aggregation mechanism, TXOP mechanism, and RTS/CTS mechanism that all fail to adapt to multi-hop characteristics. Therefore, the effect of running the traditional IEEE 802.11 protocol in Linear WANET is often unsatisfactory.

The frame aggregation mechanism is one of the key technologies which first proposed in IEEE 802.11n protocol. This technology can reduce the frame overhead and significantly improve data transmission efficiency[16,17]. IEEE 802.11n specified two forms of frame aggregation: A-MSDU (Aggregate MAC Service Data Unit) and A-MPDU (Aggregate MAC Protocol Data Unit). The two-level aggregation can perform A-MPDU aggregation by using A-MSDU as a single MPDU to improve the MAC layer frame transmission efficiency further and reduce frame aggregation overhead. However, in an environment with poor channel conditions, two-level aggregation may cause frequent retransmissions and serious retransmission overhead[18,19]. Besides, in the single A-MPDU aggregation, the signal-to-noise ratio (SNR) and frame error rate (FER) will also have a more significant impact on the frame aggregation efficiency[20]. Jan and Sebastian[21] discussed the optimal MPDU size in different channels under the latest IEEE 802.11ax protocol. The results show that increasing the MPDU size can effectively improve the efficiency of the MAC layer. However, the use of larger MPDUs often brings higher FER (Frame Error Rate) and system delay. In a channel with a high error rate, only a smaller MPDU can achieve higher throughput.

Boris and Alex[22] analyzed the throughput performance of UDP and TCP under the traditional wireless access model of IEEE 802.11n, and the results showed that the channel utilization would increase with the increase of maximum frame aggregation length. However, we found that, when the maximum aggregation length exceeds a specific value, the increase in channel utilization will no longer be significant. This phenomenon is incredibly apparent in the state of unsaturated throughput.

The RTS/CTS mechanism can effectively avoid the hidden node problem. If the data frame is too long, the RTS/CTS mechanism can productively reduce frame errors and retransmission losses caused by collisions. In a WANET, the limitation of transmission performance mainly comes from the channel occupation caused by multi-hop, which will lead to the extension of the transmission interval at the PHY layer[23]. However, the transmission rate between adjacent nodes is much higher than the overall transmission rate of the multi-hop system, that is, the data transmission time at the sender is much shorter than the waiting and backoff time. Although the use of the RTS/CTS mechanism will increase the information exchange frequency between nodes, the overhead it brings belongs to the sending overhead, and the sending overhead always accounts for a relatively small amount in the total overhead of the Linear WANET system. Moreover, the RTS/CTS mechanism can reduce transmission collision probability. Therefore, in a Linear WANET system, the RTS/CTS mechanism should be enabled.

In this paper, we simulated the frame aggregation mechanism, RTS/CTS mechanism and TXOP mechanism under Linear WANETs. We focused on analyzing the impact of external factors such as the UDP packet size, data rate, channel status, and saturated/unsaturated throughput status on the performance of Linear WANET system. Meanwhile, based on the transmission characteristics of Linear WANET, this paper analyzes the problem of buffer overflow caused by excessive data rate, the limitation performance of A-MPDU mechanism, the reduction of TXOP efficiency, and the effect of RTS/CTS mechanism on the improvement of system performance.

3 | LINEAR WANET MODEL AND TRANSMISSION CHARACTERISTICS

We divide the nodes in the Linear WANET into three categories: Source node, Relay node, and User node. As shown in Fig. 1, the N-hop connection is carried out from the User node (U) to the destination Source node (S) via multiple Relays (R_i, i = 1, 2,..., N-1), which are placed equidistant between the user and source nodes in a linear form. The relay nodes can be randomly located, but in order to facilitate analysis and achieve better performance, the nodes in a linear wireless network should be set equidistant[24]. The distance between S and U is L, the distance between two adjacent nodes is thus $d = L/N$. It is assumed that the source node is backlogged, i.e., the source node always has data to transmit. Each node is equipped with an limit-capacity buffer, where received packets are stored in a first-in–first-out fashion. This case models a scenario where a large amount of information rests at the source, e.g., a large file in an UDP-type application.

The nodes can be self-organized and connected by the On-Demand Cross-Layer Connection Strategy (ODCLCS) based on WLAN. The ODCLCS is designed for Wireless Self-organized Link (WSOL) system. WSOL system aims to build a stable and humanity communication link by using ODCLCS and other necessary programs[2]. Some abbreviations are listed in Table 1 for readers' reference.

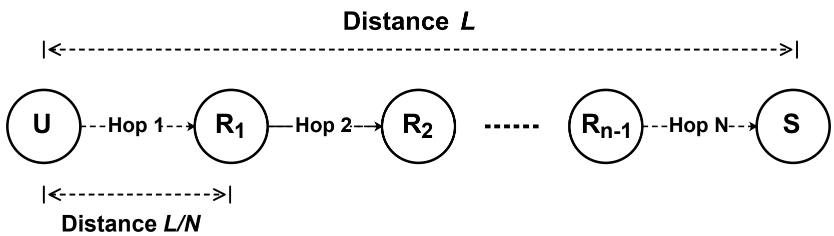

FIGURE 1 Linear WANET Model (N-hop)

TABLE 1 Terminologies

Symbol	Description	Symbol	Description
N	The number of hops	UDP_S	UDP Payload Size
S	Source node in Linear WANET	Inv	Packet Sending Interval of Application Layer
R_i	Relay nodes in Linear WANET	AC	Access Categories
U	User node in Linear WANET	LPR	Lost Packets Rate
L	Distance between Source node and User node	BER	Bit Error Rate
d	Distance between two adjacent nodes	FER	Frame Error Rate
MSDU	MAC Service Data Unit	SIFS	Short Inter-Frame Space
MPDU	MAC Protocol Data Unit	AIFS	Arbitration Inter-Frame Space
PSDU	PHY Service Data Unit	TXOP	Transmission Opportunity
PPDU	PHY Protocol Data Unit	NAV	Network Allocation Vector
LLC	Logical Link Control Layer	BA	Block Acknowledgment
AP_L	A-MPDU Limit	NS-3	A discrete-event network simulator
AS_L	A-MSDU Limit	WANET	Wireless Ad-Hoc Network
AP	Access Point mode	STA	Station mode
ODCLCS	On-Demand Cross-Layer Connection Strategy	WSOL	Wireless Self-organized Link
RTS/CTS	Request To Send / Clear To Send	TXOP	Transmission Opportunity

All nodes use IEEE 802.11ac protocol as the MAC layer protocol. We assume that each node uses static IP, and the transport layer protocol mainly uses UDP. Static IP here does not mean that we use static IP assignments for all nodes when they are established. Instead, we use an on-demand automatic IP assignment method, which was described in our previous paper[2]. Since this paper focuses on the performance of frame aggregation and RTS/CTS mechanisms in Linear WANETs, it does not involve IP routing at the network layer. Therefore, it is assumed that all nodes are configured using static routes as a way to control the variables.

Meanwhile, most network devices use a single wireless transceiver chipset, each node of Linear WANET uses the same frequency for communication. In order to ensure the accuracy of the simulation results, the distance and channel state between each node should be kept uniform.

The problem of hidden nodes is very prominent in Linear WANETs. As shown in Fig. 2, the hidden node problem can cause data congestion. When R2 is transmitting data, nodes in its collision domain will be disturbed and cannot receive data. The node U has to wait for the transmission of R2 to complete before transmitting messages. In a linear single-frequency multi-hop wireless network, due to collisions and the hidden-node problem, the throughput will decrease exponentially as the number of hops increases. But this downward trend is no longer evident after the number of hops is more than four[25].

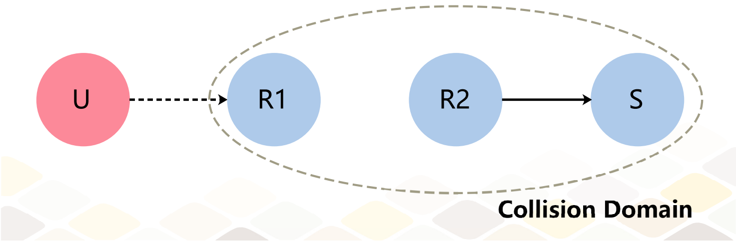

FIGURE 2 The hidden-node problem in Linear WANET

The transmission characteristics of the linear single-frequency multi-hop wireless networks will also affect the Block Acknowledgment (BA) mechanism. BA technology comes from the IEEE 802.11e standard and is now widely used in 802.11n and subsequent IEEE standards. In a multi-hop network, the receiver will perform FCS verification after receiving the A-MPDU aggregated frame, and return a BA frame according to the error condition. If there is an error in the received frame, the receiver rearrangement buffer will mark the incorrect MPDU, and only forwards the correct MPDUs to the Logical Link Control (LLC) layer in order. The rearrangement buffer will stop after encountering the error MPDU and wait for the next reception. The detailed process is shown in Fig. 3. The sender first sends an A-MPDU which composed of 5 MPDUs to the receiver, where MPDU3 is an error unit caused by interference during the transmission. After receiving data, the receiving buffer rearranges the MPDUs and reports it to LLC. Due to the error of MPDU3, both MPDU4 and MPDU5 will be reserved in the rearrangement buffer. Meanwhile, the receiver returns a marked BA frame, instructing the sender to retransmit MPDU3. Both MPDU4 and MPDU5 will be uploaded to LLC after receiving the correct MPDU3 in the next reception.

When the sender performs the second transmission, the new sending queue will be MPDU 3, 6, 7, 8, 9. After the CRC (Cyclic Redundancy Check) check, no transmission error occurred this time. The receiver received all data ultimately, rearranged and sent all MPDUs 3, 4, 5, 6, 7, 8, and 9 to the LLC.

In the Linear WANET, after receiving an error A-MPDU for the first time and returning the BA frame, the receiver will not wait for the sender to retransmit next frame. Instead, the receiver will send the correct MPDUs directly to the next hop. Therefore, error frame retransmission will be forced to shelve due to the transmission characteristics of Linear WANET. If the A-MPDU error occurs in the front position of the entire frame, the data sent to the next hop will be significantly slashed. Meanwhile, the retransmitted data will also occupy the available data space in the next transmission.

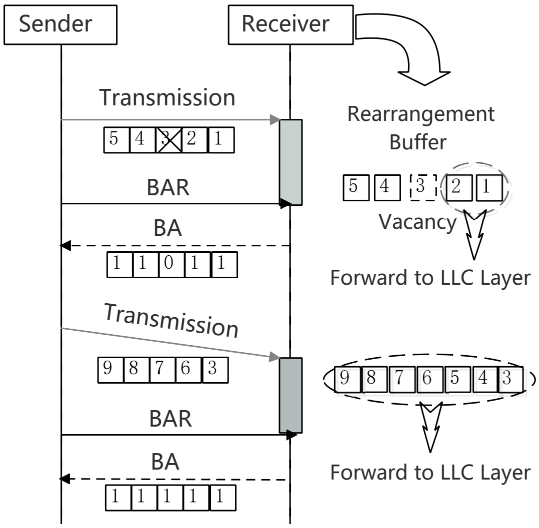

FIGURE 3 The interactive process of BA frame

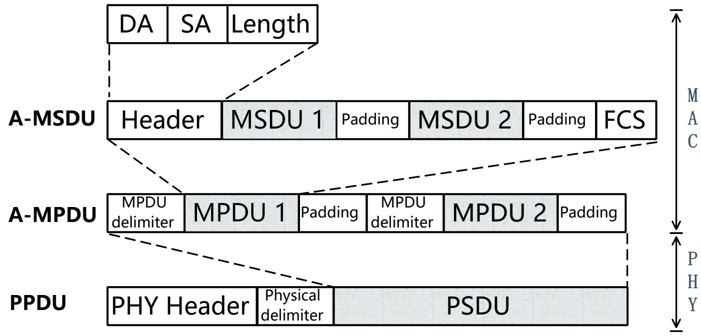

FIGURE 4 The two-level aggregation structure

4 | AGGREGATION PERFORMANCE ON LINEAR WANET

4.1 | Frame Aggregation Mechanism

As one of the critical technologies introduced in IEEE 802.11n, the frame aggregation mechanism can effectively reduce the overhead of the PHY and MAC layer by combining multiple frames and effectively improve the network throughput. IEEE 802.11n specifies two forms of frame aggregation: A-MSDU and A-MPDU. The two aggregation methods can be matched with each other to form a two-level aggregation. The two-level aggregation can perform A-MPDU aggregation by using A-MSDU as a single MPDU to improve the MAC layer frame transmission efficiency further and reduce frame aggregation overhead.

The A-MSDU mechanism accumulates MSDU frames from the LLC layer with the same receiving address and Traffic Identifier (TID) and encapsulates them in one MPDU. During the A-MSDU aggregation process, when the sum of the MSDUs in the aggregation buffer exceeds the maximum A-MSDU length or the maximum duration limit, the A-MSDU will stop the aggregation and be sent immediately. The maximum length of the A-MSDU specified by the IEEE 802.11n and 802.11ac protocols is 7935 bytes and 11454 bytes, respectively.

The A-MSDU mechanism can effectively reduce channel access overhead and frame header overhead. Especially when the MSDU is small, the A-MSDU mechanism can effectively improve MAC efficiency. However, since the A-MSDU subframe does not contain a Frame Check Sequence (FCS), if an MSDU error occurs during data transmission, the entire A-MSDU must be retransmitted. When the channel status is not good, the efficiency of the MAC layer that uses A-MSDU aggregation will be significantly reduced.

The A-MPDU mechanism aggregates multiple MPDUs in one PHY Protocol Data Unit (PPDU), and each MPDU contains only one MSDU or A-MSDU. The IEEE 802.11n and 802.11ac protocols respectively stipulate that the maximum length of A-MPDU is 65535 bytes and 1048575 bytes, and each A-MPDU can aggregate up to 64 MPDUs.

Unlike MSDU, each MPDU contains the FCS field, and each MPDU can be confirmed separately through the Block Ack frame. Therefore, A-MPDU aggregation has better robustness than A-MSDU. However, when the MPDU is small, and the data rate is high, the A-MPDU aggregation will reduce transmission efficiency. Therefore, we can use the two-level aggregation mechanism to obtain appropriate robustness while reducing the performance loss caused by small data packets. The two-level aggregation structure is shown in Fig. 4.

In order to better explore the impact of different variables on the frame aggregation performance, this article uses NS-3[27] as the primary simulator. The following sections will change the simulation environment according to the specific situation, but in general, the basic simulation environment that this article will not modify is shown in Table. 2.

The experimental data generated by NS-3 is extracted and converted into several .plt file by FlowMonitor[28]. FlowMonitor can capture many network attributes such as: *timeFirstTxPacket*, *timeLastTxPacket*, *delaySum*, *jitterSum*, *txBytes*, *txPackets*,

TABLE 2 Basic Simulation Environment

Parameter	Value	Parameter	Value
MCS	VHT-9	Base Protocol	IEEE 802.11ac
Short GI	Enable	Routing Protocol	Static routing protocol
PHY Model	YansWifiPhy [26]	Transport Layer Protocol	UDP
Channel Width	80 MHz	Simulation Duration	20 s

lostPackets and so on. The mean delay (Delay), mean jitter (Jitter), mean received bit rate (Throughput) and lost packet rate (LPR) can be calculated by the following formula:

$$\overline{delay} = \frac{delaySum}{rxPackets} \tag{1}$$

$$\overline{jitter} = \frac{jitterSum}{rxPackets - 1} \tag{2}$$

$$\overline{throughput} = \frac{8 \cdot rxBytes}{timeLastRxPacket - timeFirstRxPacket} \tag{3}$$

4.2 | The effect of A-MPDU Aggregation on Linear WANET Performance

In this section, we will look at the impact of Frame Aggregation on Linear WANET Performance. Due to the poor performance of single A-MSDU aggregation, the A-MPDU aggregation and Two-Level aggregation with better performance are generally used at present, so let's first look at the effect of A-MPDU aggregation on Linear WANET Performance.

The A-MPDU aggregation frame sending process described in IEEE 802.11 is shown in Fig. 5.

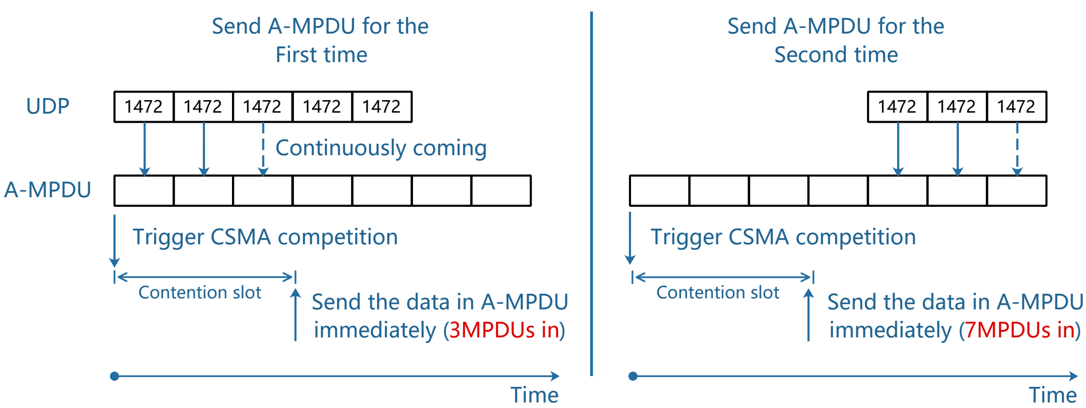

FIGURE 5 A-MPDU aggregation frame sending process

The length of the Ethernet data transmission unit must be between 46 and 1500 bytes, which is determined by the physical characteristics of Ethernet. The maximum transmission unit (MTU) in Ethernet is 1500 bytes. Because the first part of the IP packet is 20 bytes, the maximum length of the data area of the IP packet is 1480 bytes. Because of the first 8 bytes header of the UDP datagram, the maximum length of the data area of the UDP datagram is 1472 bytes. Therefore, the actual data bits that we can use in a UDP packet are 1472 bytes.

When the application layer has data to send, it will immediately trigger the CSMA channel competition process. Under normal circumstances, the request to send data is initiated by the application layer. The trigger here means that the application layer has data to send at the moment, so it delivers the data to the MAC layer and triggers the CSMA mechanism to operate. During the competition, the data will continue to reach the MAC transmission buffer. After the MAC successfully competes for the transmission time slot, the A-MPDU will be immediately framed and delivered to the PHY for transmission. At this time, the data in the MAC transmission buffer will be all aggregated into the A-MPDU, even if the buffer has only a few packets. Then the sender will perform the standard frame sending process and Block ACK process. During this transmission period, the data of the application layer will continue to reach the MAC buffer, waiting for the second sending opportunity.

As shown in Fig. 5, only 3 MPDUs are aggregated into A-MPDUs in the first transmission. In the second transmission, because there are unsent MPDUs stored in the buffer, 7 MPDUs will be aggregated.

Compared with the A-MSDU aggregation mechanism, the impact of A-MPDU on Linear WANETs is less complicated. Since each MPDU in the A-MPDU contains an FCS check field, this effectively improves the efficiency of error detection during retransmission. A-MPDU Limit is mainly used to limit the maximum length of A-MPDU. In IEEE 802.11ac, the maximum A-MPDU Limit is 1048575 Bytes. As mentioned in the previous analysis, Linear WANET rarely fills the A-MPDU Limit in normal transmission tasks. It is worth noting that, even if the A-MPDU Limit is large, the aggregation waiting delay will not increase because the MAC will send all the aggregated MPDUs before the end of the transmission time slot. Moreover, when the data rate increases sharply, a higher A-MPDU Limit will also give the system a more sufficient response time.

We use NS-3 to simulate A-MPDU aggregation under Linear WANET. The simulation results are shown in Fig. 6 and Fig. 7. The packets sending interval of the application layer used in the simulation is $Inv = 0.00025ms$.

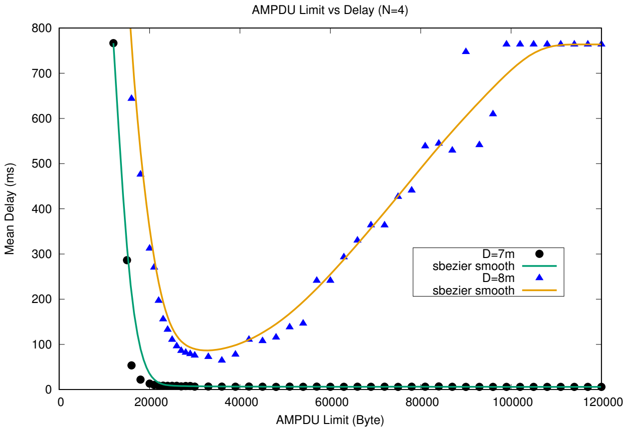

FIGURE 6 Mean Delay vs. A-MPDU Limit (D=7m)

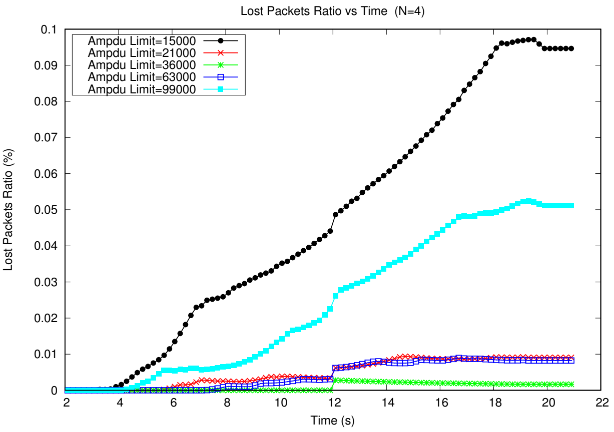

FIGURE 7 Change of packet loss rate under different AMPDU Limit (D=8m)

Fig. 6 compare the system delays under different channel conditions. We can see that, when the system is running in an environment with high-quality channel conditions ($D = 7m$), a higher A-MPDU Limit will bring about a lower average system delay. However, in an environment with low-quality channel status ($D = 8m$), a higher A-MPDU Limit will cause the average system delay to rise significantly. As shown in Fig. 6, when the A-MPDU Limit exceeds 36000 bytes, the average system delay will increase significantly with the increase of the A-MPDU Limit.

In an environment with low-quality channel status, a higher A-MPDU Limit will result in a larger A-MPDU for a single transmission, leading to a high probability of packet loss and retransmission. As shown in Fig. 7, the Linear WANET system is running in an environment with low-quality channel status (D=8m). Looking at Fig. 7 we can see that the lost packets ratio continues to grow as the simulation time increases and then plateaus. However, the growth rate of lost packets ratio and the plateau value are very different when comparing different A-MPDU Limits. When the A-MPDU Limit is greater than 36000 Bytes (A-MPDU Limit = 36000bytes, 63000bytes and 99000bytes), the growth rate of LPR will gradually increase as the A-MPDU Limit increases. The LPR plateau value at A-MPDU Limit = 99000 bytes is higher than the LPR plateau value at A-MPDU Limit = 36000 bytes. Excessive A-MPDU size will cause frequent packet loss and retransmission. Therefore, when the channel status is not good, blindly increasing the A-MPDU Limit cannot effectively improve the system performance.

However, when the A-MPDU Limit is less than 36000 Bytes (A-MPDU Limit = 15000bytes, 21000bytes and 36000bytes), the growth rate of LPR gradually decreases as the A-MPDU Limit increases. The LPR plateau value at A-MPDU Limit = 15000 bytes is higher than the LPR plateau value at A-MPDU Limit = 36000 bytes. The explanation for this phenomenon is that the

A-MPDU Limit is too small to hold a large amount of data transmission. If the A-MPDU Limit is too small, it will lead to the sending buffer overflow, which causes packet loss.

The previous discussion demonstrated the impact of the A-MPDU Limit on Linear WANET under poor channel conditions. However, as shown in Fig. 6, when the system is running in an environment with better channel conditions, the A-MPDU will have a smaller impact on the system. Next, we make the A-MPDU Limit extremely large, that is, do not limit the aggregate frame length, and observe the performance of the Linear WANET system when the channel conditions are good.

Generally, in the case of single A-MPDU aggregation, there is a minimum application layer data delivery interval μ_{amin} that the system can withstand. When the data delivery interval is lower than μ_{amin}, the system end-to-end throughput will no longer increase, and the delay and lost packets rate (LPR) will increase significantly. As shown in Fig. 8-10, we look for μ_{amin} by gradually reducing the application layer data delivery interval μ_a, which will lead to a higher throughput. The simulation parameters are: $AP_L = 1048575\ bytes$ (big enough), $UDP_S = 1472\ bytes$. The adjacent node spacing D is fixed at 7 m.

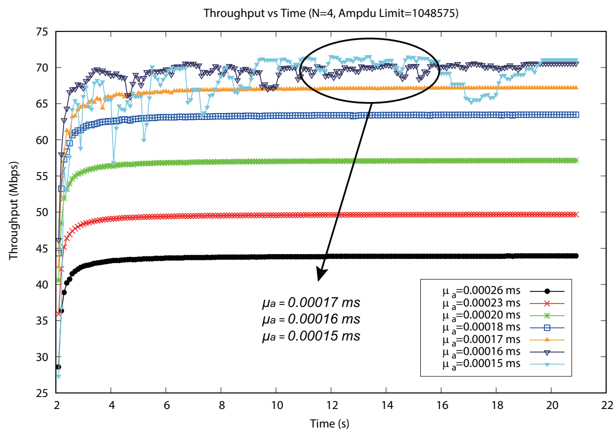

FIGURE 8 Throughput changes under single A-MPDU

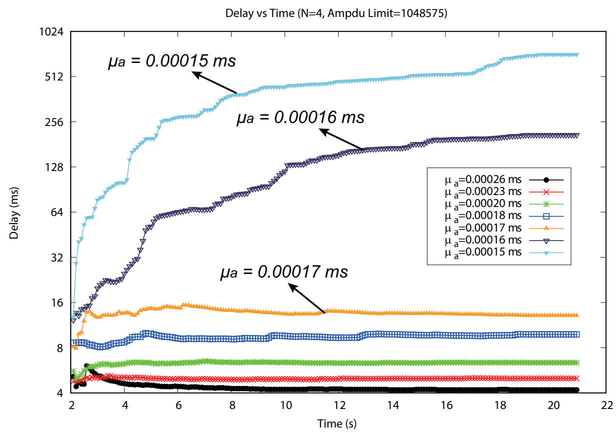

FIGURE 9 Delay changes under single A-MPDU

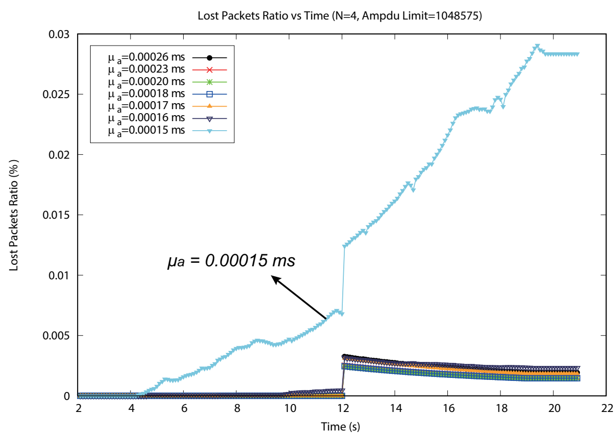

FIGURE 10 LPR changes under single A-MPDU

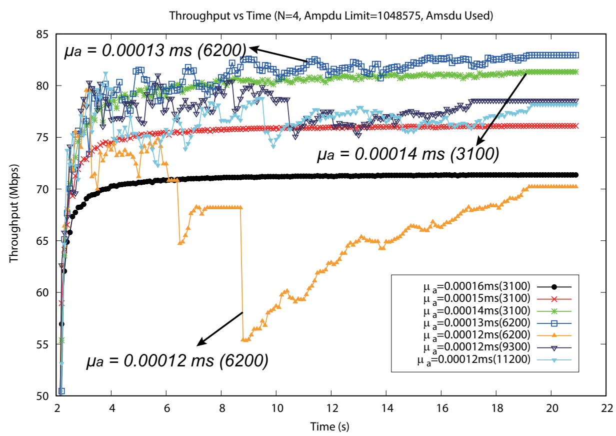

FIGURE 11 Throughput changes in Two-Level aggregation

We can see from Fig. 8-10, after $\mu_a < 0.00016\ ms$, the end-to-end throughput under A-MPDU aggregation will not increase. At the same time, after $\mu_a < 0.00016\ ms$, the system delay and packet loss rate both increase significantly. This phenomenon shows that the system cannot further improve the throughput by reducing the application layer data sending interval under the current parameters.

There are many reasons to explain why throughput does not continue to increase. Above all, the MAC parameter MCS value gives the upper limit of the system's throughput. This upper limit is jointly determined by the physical layer modulation mode and channel state. Besides, the Linear WANET characteristic of single-frequency and multi-hop cannot be avoided. Therefore, we need to find a solution to improve system performance based on the Linear WANET single-frequency and multi-hop characteristics, such as adding the A-MSDU mechanisms. We found that the addition of A-MSDU can further improve the overall performance of frame aggregation.

4.3 | The effect of Two-Level Aggregation on Linear WANET Performance

Below, we add the A-MSDU mechanism in the same simulation environment to observe the system performance changes at the throughput position ($\mu_a < 0.00016\ ms$). The simulation results under Two-Level aggregation mode is shown in Fig. 11-13.

We found that in a low FER channel environment, an appropriate increase in A-MSDU Limit can help improve the performance of Linear WANET. The A-MSDU can effectively increase the size of MPDU, which in turn can increase the efficiency of A-MPDU aggregation. To some extent, A-MSDU can provide a kind of additional buffer space for the data delivered from the application layer.

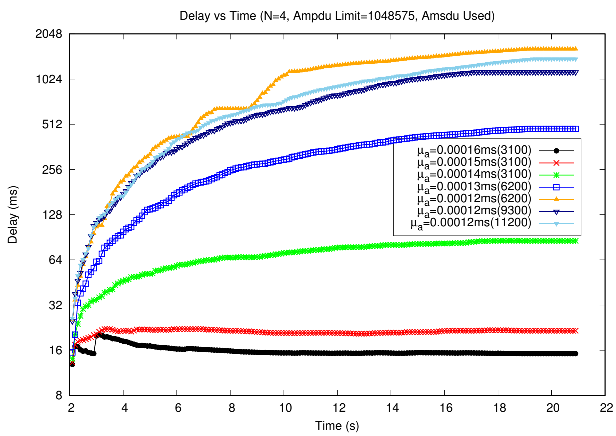

FIGURE 12 Delay changes under Two-Level aggregation

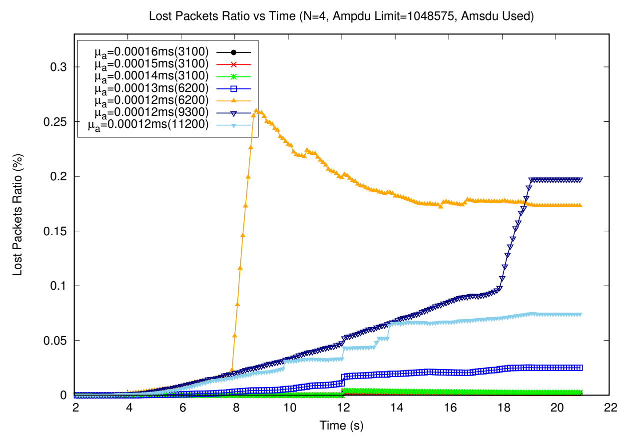

FIGURE 13 LPR changes under Two-Level aggregation

Comparing with Fig. 8, we can find that after adopting two-level aggregation, the maximum throughput of the system has been further improved. Moreover, the simulation results show that a higher A-MSDU Limit will bring more room to increase system throughput. The increase in throughput, from an aspect, reflects the increase in overall system performance. As shown in Fig. 11-13, after adding the A-MSDU mechanism, the system throughput can easily reach 70Mbps, and the system delay and LPR are both kept at a low level. Meanwhile, when A-MSDU Limit = 3100 bytes, the maximum throughput is about 80Mbps, and when A-MSDU Limit = 6200 bytes, the maximum throughput that the system can achieve increases to 83Mbps.

However, we also found that blindly increasing the A-MSDU Limit sometimes does not improve the system performance (from 6200 to 11200). Because of the lack of FCS verification mechanism, a higher A-MSDU Limit will increase system delay and LPR. An excessively high LPR will cause a decrease in system throughput. In Fig. 11 we can see that, under the same data interval $\mu_a = 0.00012ms$, from A-MSDU Limit = 6200 to 11200, the throughput decrease as the A-MSDU Limit increases. Moreover, the Delay and LPR both showed varying degrees of deterioration.

Fig. 14 shows the change of the maximum throughput with the length of the A-MSDU Limit in different channel BERs. We also use the Two-Level aggregation mode in this simulation. Furthermore, we increase the channel BER by increasing the spacing (D) of the adjacent nodes. The A-MPDU Limit is fixed to 65535 bytes. This experiment uses an approximation method to find the maximum system throughput (increase the data rate, and observe the change in throughput).

From Fig. 14, we can see that the maximum throughput will gradually decrease as the channel error rate increases. Meanwhile, the increase in A-MSDU Limit will also lead to a slight reduction in throughput. Simultaneously, by comparing the changes in throughput with channel status under different A-MSDU Limits, we can find that the larger the A-MSDU Limit, the more

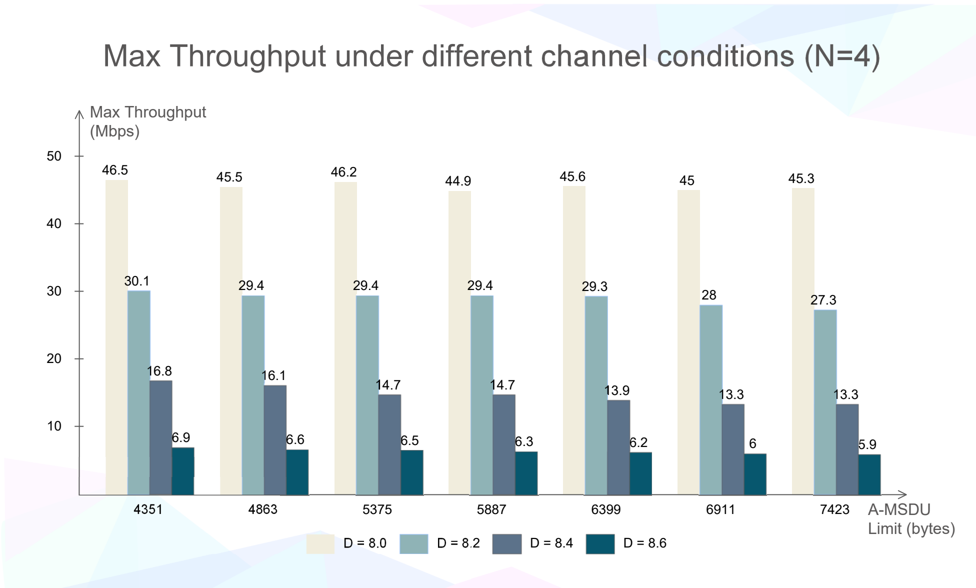

FIGURE 14 Max Throughput changes under two-level aggregation

pronounced the decrease in throughput. (The worse the channel state is, the lower the maximum achievable throughput will be.) This is in line with the conclusion we got earlier. Although A-MSDU can effectively increase the size of MPDU, it can increase the efficiency of A-MPDU aggregation. But, the increase of MPDU size will in turn lead to the increase of system retransmission cost. Once the channel environment deteriorates, the retransmission rate will increase, which will cause a large amount of packet loss and retransmission delay.

Therefore, we need to be careful when choosing the size of the A-MSDU Limit. The A-MSDU mechanism can improve the performance of the multi-hop system to a certain extent, but it will also bring higher system delay and LPR. The latter often severely weakens the system performance in the case of a poor channel condition.

Overall, we suggest that the A-MSDU mechanism can be used when the channel conditions are good, and the A-MSDU Limit should be appropriately increased to improve system performance. If the channel condition is time-varying, or the channel condition is not good, it is recommended to adopt the single A-MPDU aggregation mechanism in order to obtain better system stability.

In summary, the transmission period of the PHY layer (or the time slot obtained by competition) is relatively stable in a fixed structure network. The PHY layer sends the data delivered by MAC, and only one frame will be sent after the time slot is reached (if the TXOP mechanism is used, may send multiple frames). The length of this frame is related to whether frame aggregation is adopted. If the frame aggregation mechanism is not used, the data field length of the frame is fixed at 1472 Bytes (UDP). If frame aggregation is used, the data field length is variable according to the different delivery data rate of the application layer.

Multi-hop will affect the PHY layer transmission interval (the channel will be busier, resulting in increased contention time). Only when the aggregation limit is large, the PHY layer can transmit more data in one transmission opportunity to improve throughput. However, when the channel status is not good, too high A-MPDU Limit will cause frequent retransmissions and an increase in LPR. Therefore, the A-MPDU Limit needs to be adjusted appropriately according to the channel condition, the data rate of the application layer, and the Delay and LPR requirements.

5 | TXOP AND RTS/CTS PERFORMANCE ON LINEAR WANET

5.1 | The effect of TXOP Mechanism on Linear WANET Performance

Compared with frame aggregation, the TXOP mechanism has a much smaller impact on Linear WANET's performance. Transmission Opportunity (TXOP) is an essential part of the Enhanced Distributed Channel Access (EDCA) mechanism in IEEE 802.11e. The TXOP means that after a node obtains the channel access right, it can continuously send multiple data frames at

SIFS frame intervals without contention until the duration (TXOP Limit) runs out, or there is no data to send in the queue. When $TXOP\ Limit = 0$, it means that the MAC does not establish a TXOP period for transmission and will immediately send the data from the upper layer. The TXOP mechanism reduces the number of times that nodes compete for channels, and reduces the backoff time and probability of queue conflicts. This method can increase the channel utilization in P2P transmission.

The EDCA mechanism defines four types of service Access Categories (AC): Background (BK), Best-Effort (BE), Video (VI), and Voice (VO). Four types of ACs will establish their own MAC queues and map the data frames to the corresponding MAC queues according to different priorities. Each queue has its parameters, such as TXOP Limit, CW_{min}, CW_{max}, and AIFS. The CW_{min} and CW_{max} are the minimum and maximum values of the backoff window. When nodes compete for channel access, the competing nodes will randomly select a value between CW_{min} and CW_{max} as the backoff time. Thus, the smaller the CW_{min} and CW_{max} are, the shorter the backoff time, and the higher the priority of the frame will be. AIFS is the time node takes to perceive whether the channel is idle before performing backoff. The smaller the AIFS is, the higher the AC priority will be. The parameters of ECDA various ACs are shown in Table. 3.

TABLE 3 The parameters of ECDA various ACs

AC	TXOP Limit	CW_{min}	CW_{max}	AIFS
BK	0	31	1023	7 s
BE	0	31	1023	3 s
VI	3.008 ms	15	31	2 s
VO	1.504 ms	7	15	2 s

However, in multi-hop communication, the advantages of the TXOP mechanism are difficult to be reflected. In a multi-hop network, the sender's data is first sent to the Relay node and then forwarded from the Relay node to the receiver node. Therefore, the peer device that performs TXOP with the sender is Relay node. The Relay node only forwards the data and does not digest the data (the data will not be submitted to Relay's application layer). Moreover, the Relay will immediately perform the forwarding operation after receiving the first frame and stop receiving any frames in the subsequent backoff process. Meanwhile, due to the problem of hidden nodes, this backoff process may take a long time. It will dramatically affect the efficiency of the TXOP mechanism.

When we use Wireshark software to observe the packet transmission under saturated throughput, we found that the sender's sending interval is all within 3 ms. So in the system with $TXOP\ Limit = 3.008ms$ and above, the sender can use the TXOP time slot for continuous transmission. Nevertheless, in most cases, only two A-MPDU frames can be sent continuously (the sender's sending intervals are mostly 2ms or even higher). Besides, in unsaturated throughput cases, the sender's sending intervals are mostly 1ms or even higher.

As shown in Fig. 15 - Fig. 18, the simulation adopted the basic access categories BE, and manually modified its TXOP Limit to observe the effect of TXOP on Linear WANET system performance. The simulation parameters are: $N = 4$, $AP_L = 65535$, packet sending interval $Inv = 0.0003ms$, $UDP_S = 1472\ bytes$, unsaturated throughput.

From Fig. 15, we can see that after using the TXOP mechanism, the average delay is reduced by about 5 ms, but if the TXOP Limit is too small (1.504 ms), the delay will increase. Meanwhile, after using the TXOP mechanism, the LPR increased by 0.001%, the delay jitter increased by 0.01 ms, and the throughput remained unchanged. We further reduced the packet sending interval to $Inv = 0.0002ms$ to saturate the throughput. As a result shown in Fig. 18, we found that under the saturated throughput condition, the system throughput by using the TXOP mechanism did not increase significantly.

Therefore, the use of TXOP mechanism cannot effectively improve the performance of the Linear WANET system. Under the same conditions, a higher TXOP Limit can slightly reduce the average delay of the system, but the delay jitter and the LPR are both deteriorated. In a saturated throughput environment, the system throughput, which using the TXOP mechanism, has not improved significantly. Therefore, whether to choose the TXOP mechanism should depend on the user's delay requirements.

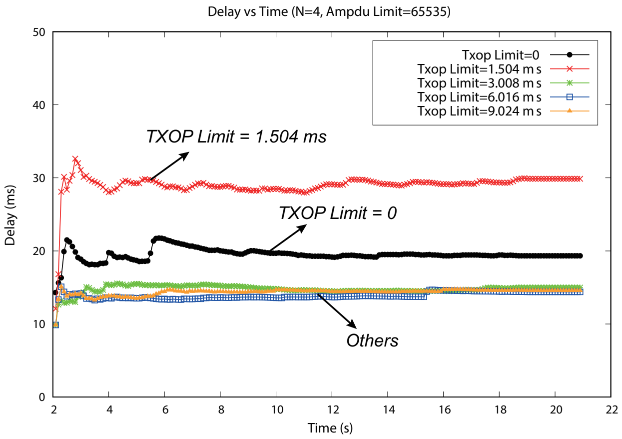

FIGURE 15 Change of Delay under different TXOP Limit (unsaturated)

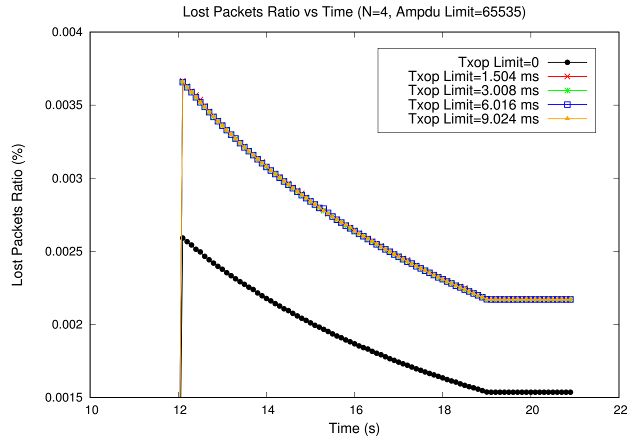

FIGURE 16 Change of LPR under different TXOP Limit (unsaturated)

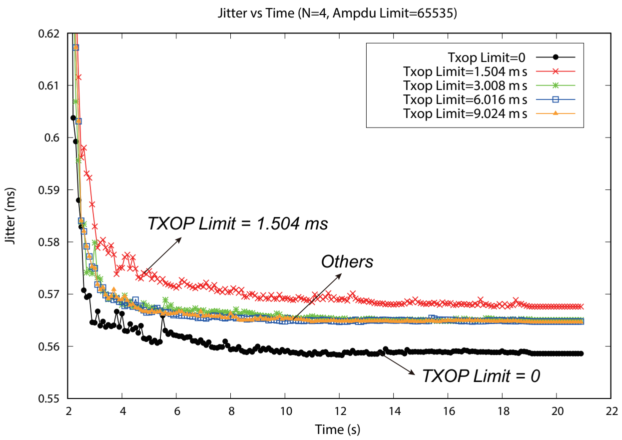

FIGURE 17 Change of Jitter under different TXOP Limit (unsaturated)

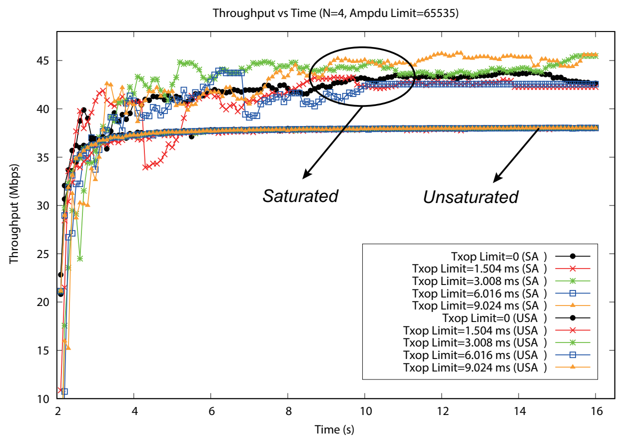

FIGURE 18 Change of Throughput under different TXOP Limit (saturated & unsaturated)

5.2 | The effect of RTS/CTS Mechanism on Linear WANET Performance

In Linear WANETs, system performance is mainly limited by multi-hop properties and retransmission problem. Therefore, it is possible to consider increasing the protection of data frames to avoid retransmission as much as possible. The RTS/CTS mechanism is an important measure to protect data frames.

IEEE 802.11 protocol introduced the RTS/CTS mechanism to alleviate the collision problem caused by hidden nodes. RTS/CTS mechanism performs a four-way handshake, which is similar to the ACK confirmation mechanism. Meanwhile, to ensure the successful transmission of the RTS or CTS frame, both RTS and CTS frames are modulated robustly.

Fig. 19 shows the RTS/CTS exchange process between nodes. Before preparing to send data, the source will first send an RTS frame to inform the surrounding nodes that it is ready to send data. The RTS frame contains the destination node information and reserved duration time information. All nodes that receive the RTS frame will set their Network Allocation Vector (NAV) value according to the reserved duration time given in RTS frame. NAV can be understood as a timer counter, indicating how long the channel will be occupied. Each node will maintain a NAV counter. The value of NAV continues to decrease over time. Before the value of NAV decreases to zero, the node will always consider the channel busy and suspend channel contention and data transmission.

After the destination node receives the RTS frame for itself, if the channel is not busy, it will broadcast a CTS frame as a response, and at the same time, informs surrounding nodes that it is ready to receive data. All nodes that notice the CTS frame

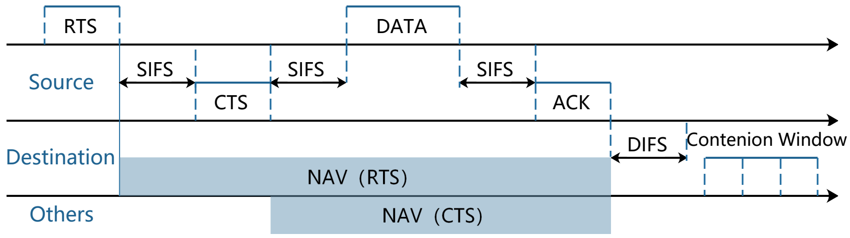

FIGURE 19 RTS/CTS mechanism

will set their NAV value according to the reserved duration time given in the CTS frame, to avoid sending data during this period. In this way, other nodes around the source and destination nodes are notified of the channel occupying period.

The RTS/CTS mechanism can expand the CSMA effective range and provide a further guarantee for the correct transmission of data frames. Meanwhile, the size of the RTS/CTS frame is as small as the ACK frame, and the effective range of RTS/CTS frame is within one hop. Thus, the RTS/CTS mechanism only occupies a few amounts of channel resources. Besides, the IEEE 802.11 protocol also defines a threshold parameter for the RTS/CTS mechanism. If the frame size is longer than the threshold, the RTS/CTS mechanism will be turned on automatically. This threshold avoids wasting channel resources caused by using the RTS/CTS mechanism when the transmitted frame is too small.

Fig. 20 - 22 compares the impact of the RTS/CTS mechanism on Linear WANET under saturated throughput ($\mu_a = 0.00013ms$) and unsaturated throughput ($\mu_a = 0.0002ms$). The simulation parameters are: $N = 4$, $AP_L = 1048575$ $bytes$, $AS_L = 6200$ $bytes$, $D = 7$ m, $UDP_S = 1472$ $bytes$. In order to avoid using the RTS/CTS mechanism for non-data frames, we set the RTS/CTS threshold to 500 bytes. For comparison, the simulation that does not use RTS/CTS mechanism fixes the threshold to 1048575 bytes.

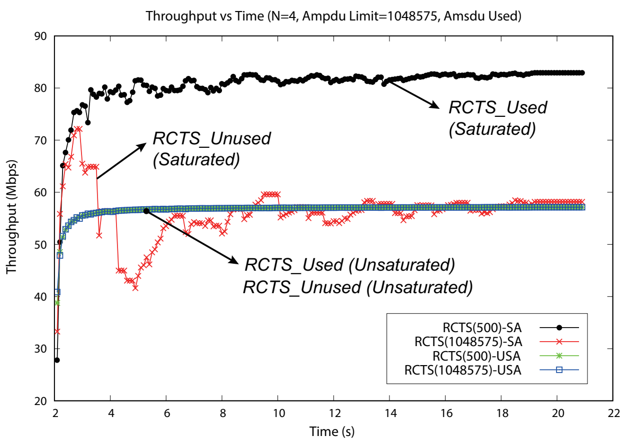

FIGURE 20 The impact of RTS/CTS mechanism on throughput

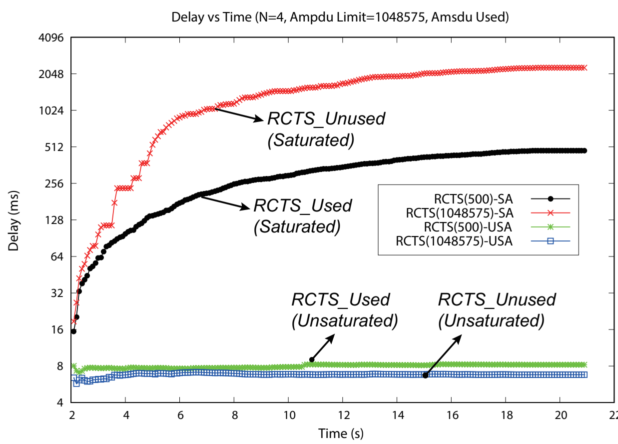

FIGURE 21 The impact of RTS/CTS mechanism on Delay

From Fig. 20 - 22, we can see that in a saturated throughput environment, the system throughput which using the RTS/CTS mechanism is 25 Mbps higher than the throughput without the RTS/CTS mechanism. And, the simulation curve is more stable, which means that the system performance using the RTS/CTS mechanism is more robust. Meanwhile, the system using the RTS/CTS mechanism has a lower delay (saturated) and a lower system LPR. This reflects the good effect of the RTS/CTS mechanism on the performance of the Linear WANET system in a saturated throughput environment. In a saturated throughput environment, the sending buffer runs at full capacity, the packet loss and retransmissions will significantly affect the data transmission efficiency. Therefore, a high LPR will inevitably lead to a sharp drop in throughput. The RTS/CTS mechanism reduces the packet loss and retransmission caused by collision to a certain extent so that the throughput curve can be more stable. Moreover, the reduction of retransmission will also reduce the average delay of the system.

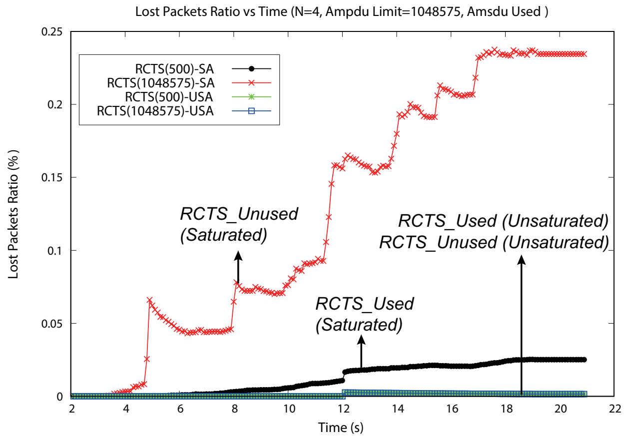

FIGURE 22 The impact of RTS/CTS mechanism on LPR

In the unsaturated throughput environment, the difference between use and not use the RTS/CTS mechanism is smaller. From Fig. 20 - 22 we can see that under the unsaturated throughput environment, the curves between use and not use the RTS/CTS mechanism almost overlap. However, in the delay comparison, the average delay with the simulation that not use RTS/CTS mechanism is smaller, which shows that in an unsaturated environment, the increased handshake rule of the RTS/CTS mechanism does bring some delay in a certain degree.

In general, the RTS/CTS mechanism has a better effect on the performance of the Linear WANET system. The main reason is that the RTS/CTS mechanism can effectively reduce the packet loss caused by collisions during frame transmission and, meanwhile, reduce the number of retransmissions. This property is essential for the Linear WANETs. However, this does not mean that the RTS/CTS mechanism should be fully used in all situations. The performance improvement effect of the RTS/CTS mechanism can only be reflected when system throughput is saturated. In an unsaturated throughput environment, the increased handshake rules of the RTS/CTS mechanism will reduce the data exchange efficiency and increase the average system delay. Therefore, we suggest that the system decide whether to enable the RTS/CTS mechanism according to the current data rate and channel environment. If the channel status is not good, the RTS/CTS mechanism must be enabled to suppress the lost packets rate. If the channel status is good, and the data rate is low (unsaturated environment), the RTS/CTS mechanism can be turned off to enhance the efficiency of data exchange. At the same time, the RTS/CTS threshold should be selected lower than the length of most data frames, to ensure that the RTS/CTS mechanism only takes effect for data frames.

6 | CONCLUSION

In this paper, we have studied the performance of the Aggregation mechanism, the TXOP mechanism, and the RTS/CTS mechanism for Linear WANET. The final goal of this paper aims to explore the operational status of various performance improvement mechanisms in Linear WANETs. And, to ascertain how to adjust and optimize the mechanisms mentioned above according to the characteristics of Linear WANETs. Through the simulation research of various mechanisms, we found that the linear multi-hop characteristic has a significant impact on the performance of the frame aggregation mechanism. Researchers need to adjust the aggregation frame length limit and determine which frame aggregation mode to use based on the current channel status, data rate, and payload size. The RTS/CTS mechanism has a good effect on the performance of Linear WANETs. The main reason is that the RTS/CTS mechanism can effectively reduce the packet loss caused by collisions during frame transmission and reduce the number of retransmissions. Due to the forwarding characteristics of multi-hop networks, the advantages of the TXOP mechanism cannot be effectively reflected in Linear WANETs.

The performance analysis discussed in this paper has referential significance for various multi-hop wireless networks that adopt the IEEE 802.11 protocol. In the future, we plan to develop an adaptive frame aggregation optimization mechanism for Linear WANETs, which can adaptively adjust the aggregation mode and aggregation level according to the current channel status and service requirements. This mechanism will enable the Linear WANETs to obtain a better network performance. Meanwhile, in most real-world application scenarios, the channel state between nodes cannot be kept consistent. Therefore, one of our future research directions is to consider performance optimization schemes for Linear WANETs in the case of non-uniform channel states.

ACKNOWLEDGMENTS

This work was supported by the Fundamental Research Funds for the Central Universities, and the national sci-tech support plan, digital media technology development. (CUC200D056, 2015BAK05B00, 2015BAK05B01).

CONFLICT OF INTEREST

The authors have no conflict of interest relevant to this article. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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