# Network Layer Challenges of IEEE 802.11n Wireless Ad Hoc Networks

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**Abstract.** Recent demands toward high-speed wireless networks are growing. IEEE 802.11n, as the latest standard toward achieving higher speeds, aims to enhance IEEE 802.11 for higher throughputs. There are few works which analyze performance of this protocol in single-hop networks in terms of MAC layer-based parameters. Most of these works suggest disabling the RTS/CTS handshake to reduce MAC layer overheads. However, the effects of this protocol on the upper layers, especially the network layer, are still unknown. This paper deals with investigating performance of the network layer over IEEE 802.11n. Through extensive simulations performed in NS-2 we show that although network throughput is improved using IEEE 802.11n, it suffers from the problem of fairness among receivers. We also show that enabling RTS/CTS improves fairness but may lead to bandwidth inefficiency. In addition, it is shown that even at high physical rates, the end-to-end delay does not meet delay requirements of these networks.

**Keywords:** IEEE 802.11n, Routing, Network Layer, High-Speed Wireless Ad hoc Networks.

## 1 Introduction

IEEE 802.11n is the next generation wireless LAN technology that promises higher data rates, longer range and more reliable coverage than 802.11 a/b/g networks. In order to provide such gains, it introduces a variety of mechanisms such as physical layer diversity (using Multiple Input Multiple Output (MIMO) technology), channel bonding, and frame aggregation [1]. It also defines two modes of operation: *Distributed Coordination Function* (DCF) which is ad hoc and based on CSMA/CA, and *Point Coordination Function* (PCF) which is centralized.

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An ad hoc network is a dynamically reconfigurable wireless network with no fixed wired infrastructure. Ad hoc networks have numerous practical applications such as military applications, emergency operations, and wireless sensor networks. In many applications, ad hoc networks carry diverse multimedia applications such as voice, video and data. In order for delay sensitive applications such as voice and video to provide quality of delivery, it is imperative that protocols of ad hoc networks provide quality of service (QoS) support [3]. Due to the dynamic nature of ad hoc networks, traditional fixed network routing protocols are not viable. For this reason, several proposals for routing protocols have been presented.

On-demand routing is one of the most popular routing approaches in ad hoc networks. Instead of periodically exchanging routing messages in proactive routing protocols that results in excessive routing overheads [16] [17], on-demand routing algorithms discover routes only when a node needs to send data packet to a destination and does not have any route to it. Most of the existing on-demand routing protocols, e.g., Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV), build and rely on single path for each data session. Therefore, route recovery process is required after each route failure that causes loss of transmitted data packets in such protocols. Multipath routing allows the establishment of multiple paths between a single source and single destination node. It is typically proposed in order to increase the reliability of data transmission (i.e., fault tolerance) or to provide load balancing [18], [19], [20], and [21].

In a data transmission flow from a sender to a receiver, MAC layer overheads affect network throughput; hence most of researches on IEEE 802.11n suggest disabling the RTS/CTS handshake to increase throughput [10, 4]. These works analyze the performance of this protocol in single-hop networks in terms of MAC layer-based parameters. Although disabling RTS/CTS may lead to more efficiency at the MAC layer, due to the ad hoc and multi-hop nature of theses networks, its effects are still unknown on upper layers, especially the network layer. The main issue of this paper is to investigate performance of the network layer over IEEE 802.11n.

Owing to the significance of routing protocols in communications of an ad hoc network, in this paper, we investigate performance of routing protocols such as Destination Sequenced Distance Vector (DSDV) [15], as a table driven protocol, and Ad hoc On demand Distance Vector (AODV), as an on demand protocol, at the network layer over IEEE 802.11n. We simulated various scenarios on the IEEE 802.11n MAC layer which were executed on NS-2 [22].

In our simulations, we investigate the two different modes of operations: the RTS/CTS handshake and basic access which disables RTS/CTS control packets. Results show that although network throughput is improved using IEEE 802.11n while RTS/CTS is disabled, it suffers from the problem of fairness among receivers. We also show that enabling RTS/CTS improves fairness. In addition, several working scenarios under which each of the handshake methods performs better are introduced.

In addition, we study the performance of DSDV at high physical rates. It is shown that even at high physical rates, the end-to-end delay does not meet the delay requirements [7] of these networks.

Section 2 reviews related works. In Section 3, we discuss network layer issues over the IEEE 802.11n MAC layer. Simulation results are presented in Section 4, and finally, we conclude the paper in Section 5.

## 2 Related Works

Approaches such as Burst and Block acknowledgements are proposed to improve efficiency at the MAC layer [6] [8] [9] [12] [13] [1]. In Burst ACK, the backoff process is performed once for a series of data packets and ACK frames. Block ACK uses a single ACK frame for multiple data frames, thus reducing the number of ACKs and SIFS. Aggregation schemes such as [1] [4] transmit multiple data frames together to reduce overheads. This is achieved by aggregating packets in a single large frame at the physical layer.

In [5] the authors present a theoretical model to evaluate the saturation throughput for the burst transmission and acknowledgment (BTA) scheme under error channel conditions in the ad-hoc mode show some advantages of BTA over the legacy MAC. The author in [11] proposes two enhancement mechanisms to reduce the overhead, concatenation (CM) and piggyback (PM). CM concatenates multiple frames into a single transmission. By PM a receiver station is allowed to piggyback a data frame to the sender station once if the receiver station has a frame to send to the sender.

In the AFR scheme [4], multiple packets are aggregated into and transmitted in a single large frame. If errors occur during transmission, only the corrupted fragments of the frame are retransmitted.

The aforementioned works consider a single-hop network to analyze their proposed methods. Network layer problems, however, are more crucial in the presence of mobile nodes as one the main characteristics of these networks. Since all of the works on high-speed wireless ad hoc networks concentrate on improving MAC efficiency in terms of throughput, performance of the network layer has not been investigated in these networks. This paper deals with this problem.

## 3 Network Layer Issues of IEEE 802.11n

The IEEE 802.11n protocol supports appropriate bandwidth and supplies suitable throughput for most of the applications in wireless communications. Unfortunately, because of its wireless infrastructure and resultant inherent problems, we cannot utilize the whole bandwidth efficiently in this protocol. Therefore, providing a reliable connection between a pair of source and destination in wireless networks is difficult because of many problems such as bandwidth limitation, energy consumption, hidden and exposed terminal problems and etc. There are many algorithms proposed for network routing and solving the above problems. They also use control packets to find stable routes.

During transmission of control packets, network bandwidth will be wasted and nodes cannot receive data packets. Moreover, higher priority of control packets may cause increasing delay in sending actual data packets; therefore, we lose bandwidth capacity. Sending control packet is one of the principle steps in routing algorithms; therefore, we cannot eliminate these packets. In addition, increasing raw bandwidth at the physical layer will not solve the inefficiency problem and the performance will not increase accordingly.

When the routing algorithm uses more control packets over the IEEE 802.11n MAC layer, due to node movements, route recovery or new path detection; the efficiency of IEEE 802.11n may decrease. Results presented in the next section confirm this problem.

In the next session, we show simulation results of DSDV routing protocol on the MAC layers of IEEE 802.11 and IEEE 802.11n, and discuss more regarding the characteristics of IEEE 802.11n which may affect routing protocols.

# 4 Simulation Results

In this section, we show performance results of DSDV and AODV in IEEE 802.11n networks using NS-2 simulator. In the simulation, we modeled a network of 50 mobile hosts which are placed uniformly in a 1000*1000 $m^2$ area. Radio propagation range for each node is 225 meters. Each simulation scenario runs for 300 seconds of simulated time. Also we use other conventional parameters of NS-2 in our simulations. Result of each scenario is averaged over 10 different runs with confidence level of 95% lower than 0.02.

Network improvement is calculated by the following metrics which are used by [4]:

- Throughput: is equal to the total amount of data, in bits, transmitted in the network over the simulation time. It represents the maximum rate at which the MAC layer can forward packets from senders to receivers. It can be seen as the rate achieved by the whole system rather than by a single station (STA).
- Average delay: This metric represents the delay a packet experiences in average until it is successfully received by the destination.
- Efficiency: is equal to the achieved throughput of the channel over the physical rate.
- Fairness: To measure fairness for all the STAs, we use Jain's fairness index. In particular, given $n$ STAs in the system, Jain's fairness index, $I$, is defined as

$$I = \frac{\left(\sum_{i=1}^{n} S_i\right)^2}{n\sum_{i=1}^{n} S_i^2} \tag{1}$$

where $n$ stands for the number of STAs and $S_i$ is the throughput of the STA $i$. When every STA achieves exactly the same throughput, $I$ is equal to 1. If only one STA happens to dominate the channel entirely, $I$ approaches 1/n.

## 4.1 Mobility Effects on IEEE 802.11 and IEEE 802.11n

In this section, we compare performance results of the two MAC protocols IEEE 802.11 and IEEE 802.11n for different node speeds. We modeled a network of 50 mobile hosts which are placed randomly in a 1000*1000 $m^2$ area. Radio propagation range for each node is 225 meters. Each simulation scenario runs for 300 seconds of the simulation time. Data packet sizes, number of data flows, routing protocols, data rate and control rate are 2048 bytes, 15, AODV and DSDV, 54Mbps, and 8Mbps, respectively. We use random waypoint movement model with 10 seconds paused time. Queue size is 70, and the maximum aggregation size is 40000 bytes. We use block ACK mechanism while using IEEE 802.11n, and packet rate is 200 packets per second like the scenario used in [14].

Throughput of AODV and DSDV routing protocols are shown in Fig. 1 for IEEE 802.11 and IEEE 802.11n. This figure indicates that IEEE 802.11n has better performance results in contrast to IEEE 802.11. In addition, any increase in the speed results in throughput decrease due to increase in the number of links failures.

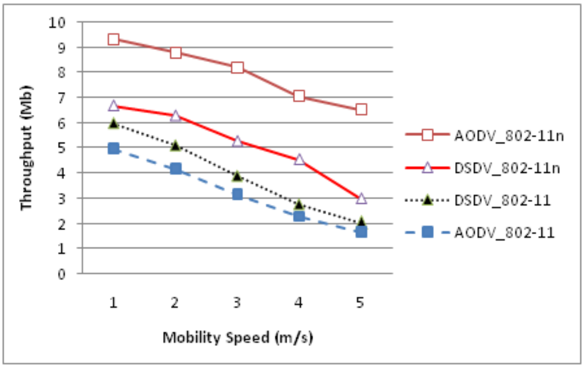

**Fig. 1.** Throughputs of IEEE 802.11 and IEEE 802.11n vs. mobility speed

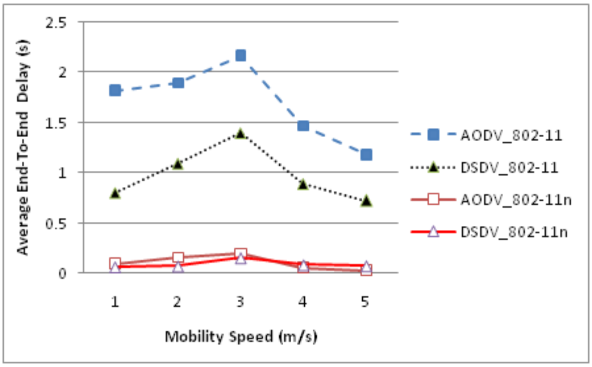

**Fig. 2.** End-to-end delays of IEEE 802.11 and IEEE 802.11n vs. mobility speed

Referring to Fig. 2, the end-to-end delay of IEEE 802.11n is shorter than that of IEEE 802.11 due to the use of aggregation in IEEE 802.11n. This confirms the idea of packet aggregation to decrease channel access overhead.

From Fig. 1 and Fig. 2, it can be observed that IEEE 802.11n increases throughput while it also decreases delay in contrast to IEEE 802.11. After careful log investigation, it is found that the other reason of these improvements is due to unfairness channel allocation to traffic flows. This means that IEEE 802.11n is not able to allow all flows to deliver their packets to their corresponding receivers.

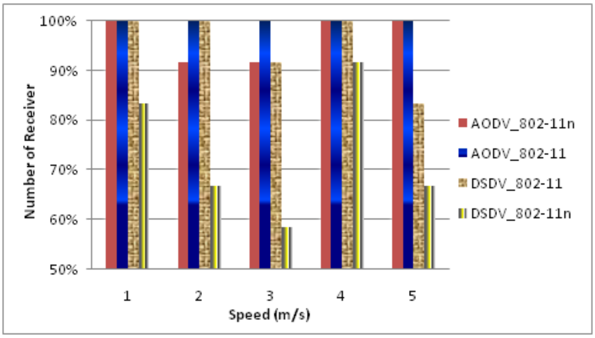

**Fig. 3.** Receiving percentage of IEEE 802.11 and IEEE 802.11n for various speeds

Fig. 3 shows the percentage of the flows were able to deliver their packets for each scenario. Since the aggregation scheme of IEEE 802.11n results in larger packets sizes and longer transmission durations in comparison with IEEE 802.11, and due to more failures in the network that happen when the speed increases, some receivers do not receive any packets; therefore, the average end-to-end delay of delivered packets decreases in IEEE 802.11n.

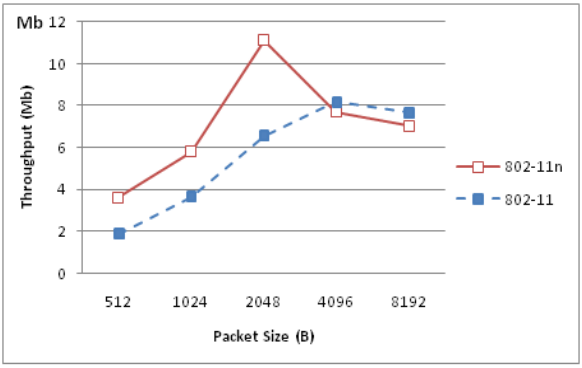

**Fig. 4.** Throughput of IEEE 802.11 and IEEE 802.11n for various packet sizes

## 4.2 Packet Size Effects on IEEE 802.11 and IEEE 802.11n

In this section, we compare IEEE 802.11 and IEEE 802.11n protocols using the AODV routing algorithm. The mobility speed is 1 meter per second and the other simulation parameters are the same as before.

Fig. 4 shows throughputs of IEEE 802.11 and IEEE 802.11n. It can be observed that the IEEE 802.11n protocol has a better throughput than IEEE 802.11 for small and medium packet sizes.

Fig. 5 shows that by increasing the packet size, the number of receivers decreases due to the same reason for the previous scenario. Referring to Fig. 6, the end-to-end delay of IEEE 802.11n is shorter than that of IEEE 802.11 because the number of receivers decreases.

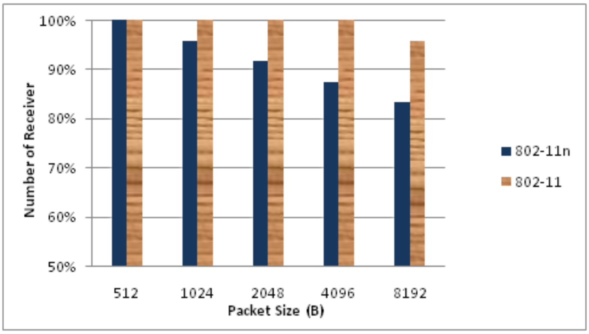

**Fig. 5.** Receiving percentage in IEEE 802.11 and IEEE 802.11n for various packet sizes

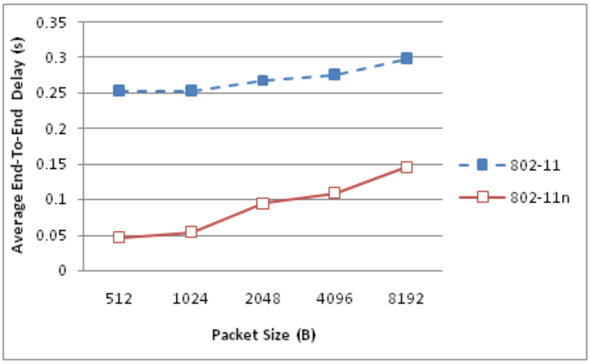

**Fig. 6.** End-to-end delay of 802.11 and 802.11n for various packet sizes

### 4.3 DSDV Performance in High-Speed Physical Rates

In order to compare performance of IEEE 802.11 and IEEE 802.11n in the previous sections, we used physical rates of up to 54Mbps. In this section, we only evaluate performance of DSDV on IEEE 802.11n for higher speeds than 54Mbps. The aforementioned metrics are also utilized to investigate the performance.

The simulation scenario used in this part is the same as that of the previous part. The major difference is that physical rate and aggregation size are increased up to 648Mbps and 64KB, respectively.

Fig. 7 shows the achieved throughput for various aggregation sizes. As it indicates, increasing the aggregation size improves throughput, especially for higher physical rates. If the physical rate increases, control packet durations dominate data packet transmission times that lead to lower throughput and losing efficiency. A compensation method is to aggregate more data and generate a larger frame. Results of the figure imply that for higher physical rates, more packets should be aggregated to improve throughput.

Efficiency of the protocol for various aggregation sizes is shown in Fig. 8. It shows that IEEE 802.11n performs less efficiently in higher speeds due to protocol overheads although increasing the aggregation size helps improve the efficiency. The best achievable efficiency is approximately 40% for 648Mbps, and this value will definitely degrade more as the number of nodes increases.

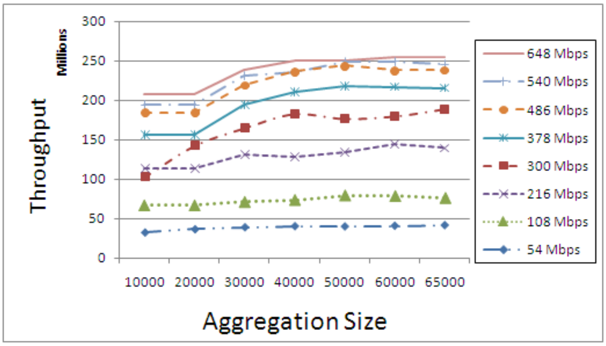

**Fig. 7.** Throughput of 802.11n for various aggregation sizes

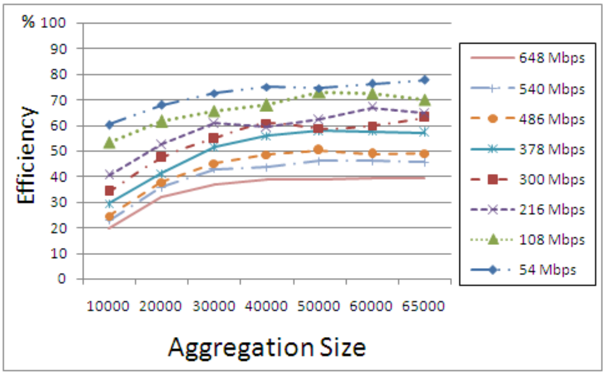

**Fig. 8.** Efficiency of 802.11n for various aggregation sizes

Fairness and delay values of the above simulated scenario are shown in Table 1 for different physical rates. As the rate increases, delay decreases due to shortened transmission durations, and fairness increases as well. It can be seen that the end-to-end delay is longer than the value specified in [7] for traffics such as HDTV, even at the rate 648Mbps. The fairness is still a problem although it is improved by increasing the physical rate.

**Table 1.** Fairness and delay for various physical rates

| Physical rate (Mbps) | Fairness (%) | Delay (s) |
|---|---|---|
| 54 | 80.85 | 0.7779 |
| 108 | 82.53 | 0.6363 |
| 216 | 83.52 | 0.5371 |
| 300 | 83.68 | 0.4817 |
| 378 | 84.88 | 0.4445 |
| 486 | 85.92 | 0.3913 |
| 540 | 86.53 | 0.3832 |
| 648 | 87.33 | 0.3801 |

### 4.4 Handshake Effects on IEEE 802.11n

It is obvious that control packets have significant roles in wireless network operations although they may waste the bandwidth. During transmission from a sender to a receiver, MAC layer overheads adversely affect the network throughput; hence most of researches on IEEE 802.11n such as [10, 4] consider disabling the RTS/CTS handshake during data transmission to increase network throughput.

In the following simulation scenario, we evaluate performance of IEEE 802.11n in two different handshake modes: RTS/CTS handshake and basic mode that disables RTS/CTS control packets. Simulation parameters are similar to the previous section. The RTS/CTS threshold is 300 bytes that allows RTS/CTS handshake before each data transmission.

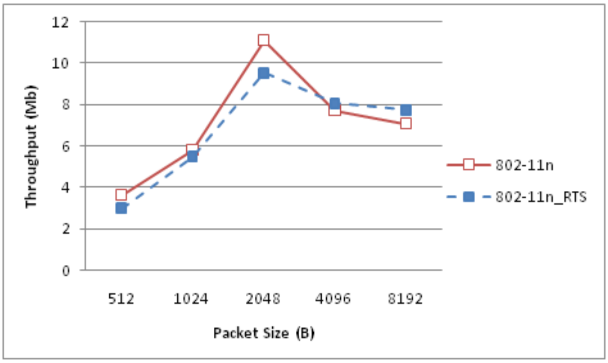

**Fig. 9.** Network throughput in RTS/CTS handshake and basic access for various packet sizes

Fig. 9 shows throughput variation in the two modes. Referring to this figure, when the packet size is small, sending RTS decreases throughput. In other words, when the packet size increases, sending RTS results in increase in throughput.

Referring to Fig. 10, when the RTS/CTS handshake is disabled, the number of receivers increases due to small data packet sizes and shorter transmission durations. When the RTS/CTS handshake is enabled, it wastes the bandwidth by RTS and CTS frames to transmit small data packets that results in lower receiver percentage. By increasing the packet size, the RTS/CTS handshake causes that more receivers receive data packets.

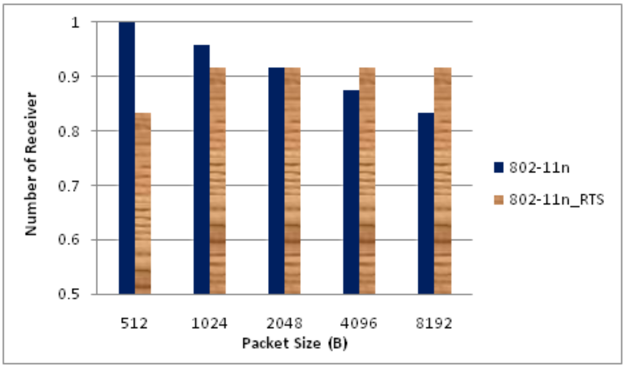

**Fig. 10.** Receiving percentage in the two handshake modes of IEEE 802.11n

Fig. 11 shows the end-to-end delay in the two access modes. The figure indicates that by using RTS, when we have small packet sizes, the end-to-end delay is shorter than that of Basic access because in this case, fewer receivers are able to receive data packets and their corresponding traffic flows dominate the channel. By increasing the packet size, the end-to-end delay increases too because more traffic flows can deliver their packets and fairness improves. It is worth noting that only delivered packets are considered for delay and throughput calculations.

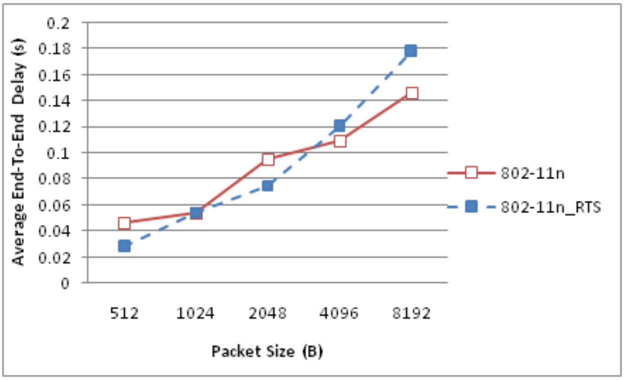

**Fig. 11.** Average end-to-end delay for various packet sizes

Some works such as [10, 4] claim that RTS/CTS handshake is not suitable in high speed networks due to its adverse effect on network throughput. On the contrary, as we showed in our simulation results, when packet size increases and because of inherent problems of wireless networks such as collision, hidden stations, and limited buffer size of receivers, throughput decreases without using the RTS/CTS handshake.

It can be seen that using the RTS/CTS handshake we can overcome some of the problems discussed above such as fairness. As a result, it can be inferred that the RTS/CTS handshake is not always useful, especially for smaller packet sizes. On the contrary, disabling RTS/CTS may cause problems such as throughput decrease for large packet sizes, and unfairness for smaller sizes. Therefore, the above result necessitates a revision in the RTS/CTS handshake which is out of the scope of this paper.

## 5 Conclusion

As technology trends toward multimedia applications over wireless LANs, it is very important that we have reliable and delay-sensitive wireless networks. With the increasing use of high-speed wireless networks, need to further improvement of these networks has been raised. Although IEEE 802.11n is suitable for broadband wireless applications, due to the intrinsic overheads of the protocol, we cannot utilize bandwidth effectively in data transfer. This protocol is also backward compatible with it pervious protocol, IEEE 802.11, because of the extensive use of Wi-Fi tools all over the world.

Simulation results show that IEEE 802.11n improves throughput and delay in comparison with IEEE 802.11 due to the aggregation method, but the in some cases such as small packet sizes, it suffers from fairness problems. Moreover, using the RTS/CTS handshake improves fairness although it imposes overhead at the MAC layer.

Performance study of DSDV for high-speed physical rates shows that delay decreases due to shortened transmission durations, and fairness increases as well, but the end-to-end delay is longer than HDTV requirements, even at the highest rate.

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