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Mixture of Half-duplex and Full-duplex Wireless Network Considering Hidden Terminal Problem

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Abstract The full-duplex (FD) wireless is one of the key drivers for realizing the 5G cellular systems, which can initiate the mixture of FD and half-duplex (HD) wireless networks simultaneously. Many research works have been studied to improve the medium access control (MAC) performance of the mixture of HD and FD wireless networks. However, the hidden terminal problem still remains unsolved today. Therefore, the paper aims to revisit and evaluate this problem explicitly. This paper depicts the numerical evaluations of HD, FD and mixture of HD and FD wireless networks in terms of conditional collision probability, transmission probability and saturation throughput.

Keywords Half-duplex, full-duplex, MAC protocol, hidden terminal problem, Markov chain.

1. Introduction

Nowadays, one of future wireless trends is 5G technology that can be a potential core network of Internet of Things (IoT) concept as well as its applications which bring many benefits for society. One of the required techniques in this technology is full-duplex (FD) wireless. Because of its outstanding features such the improvement in terms of throughput and significantly reducing the end-to-end delay. In the field of wireless research, not only half-duplex (HD) but also FD transmission has a problem, i.e. the hidden terminal problem. To overcome this problem, many solutions based on MAC protocol had already been studied. However, the hidden terminal problem still remains unsolved and need to be considered more explicitly.

The hidden terminal is a node that cannot sense the ongoing transmission but is able to introduce enough interference to corrupt the reception if it transmits [1], [2]. In the hidden terminal problem, packet collision happens at the intended receiver if there is a transmission from a hidden terminal. For example in Fig. 1, there are three nodes, like A, B and C. Node B is within the transmission range of node A and node C, while node C is outside the transmission range of node A, and correspondingly, node A is outside the transmission range of node C. Here, the transmission range of a node is defined as the area inside which other nodes are able to correctly receive its packets. Without loss of generality, we suppose that every node in Fig. 1 has the same transmission range (represented by a dash circle). In this situation, if there is an ongoing transmission from node A to node B, meanwhile, node C will not be able to detect it and may transmit during the ongoing transmission from node A, which leads to collision at node B. Because node C does not know whether node A is transmitting or not, it can occupy the channel at any time and the quality of the flow from node A to node B cannot be guaranteed whenever there are any packets from node C to other nodes. Therefore, this degrades the performance of wireless networks systems.

For long duration of wireless communication networks, the HD technique is used. In the HD system, a wireless transceiver can either transmit or receive wireless signals in a given bandwidth but not both at the same time, where two orthogonal time or frequency channels are allocated for the respective reception and transmission at the relay. Therefore, there is an advantage of HD technology that is no co-channel interference. Besides, in current wireless network, both frequency division duplex (FDD) and time division duplex (TDD) require two separate channels to realize orthogonal transmission and reception, which wastes half of radio resources. FD can double spectrum efficiency by simultaneous transmission and reception on the same frequency and time resource. In addition, FD also helps to reduce end-to-end packet delay and improve network efficiency, FD is widely considered as one of the promising techniques in 5G systems. FD technology can solve the hidden terminal problem. That is, in Fig. 1, node A transmits data to node B, while the node B can simultaneously transmit data to node C. Note that node C can successfully receive the data transmitted by node B without collision. This technique requires a new medium access control (MAC) protocols that can exploit the additional capabilities. However, the difference in HD technology, the problem already exists on FD technology as the overwhelming nature called self-interference (SI), which is generated by transmitter to its own collocated receiver. There are some solutions that related to SI cancellation were studied, such as passive SI suppression,

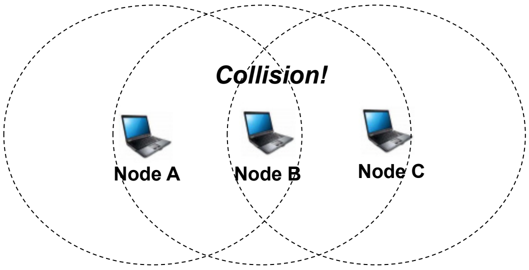

Fig. 1: The hidden terminal problem.

analog cancellation, or digital cancellation. These solutions were explicitly presented in [3]. Moreover, there are still some technical obstacles to be overcome before FD is really put into practice. The current studies mostly focus on theoretical analysis and experiments based on very simple models.

The mixture of HD and FD wireless networks is combination of HD and FD modes into wireless network systems. The aim of this proposition is to improve the end-to-end throughput of wireless networks. The requirement of this scheme is related to a new MAC protocol and the hidden terminal problem need to be analyzed and considered, because they directly affect to the performance of wireless network system.

The rest of this paper is organized as follows. Section 2 is presented with three nodes in system model. The model with the HD, mixture of HD and FD and FD wireless network. Next, Section 3 is the analysis of system model with the detail of mixture of HD and FD wireless network in various solutions to solve hidden terminal problem and the Markov Chain (MC) modeling to consider the conditional collision probability. Section 4 is simulation setting and evaluation results of system model in terms of saturation throughput, conditional collision probability and transmission probability. Finally, Section 5 is concluding remarks of this paper and discussion about future works.

1.1. Related Works

The hidden terminal problem can be observed easily in transmission with many nodes that use directional antennas and have high upload. This situation leads to the difficulties in MAC layer over wireless networking. To overcome these problems, in previous research works, many solutions have been studied.

For HD transmission, a request-to-send (RTS)/clear-to-send (CTS) handshake was implemented in conjunction with the carrier sense multiple accesses with collision avoidance (CSMA/CA) scheme [4]. Before transmitting a packet, a transmitter station send a special RTS short frame. The destination stations acknowledges the receipt of an RTS frame by sending back a CTS frame, after which normal packet transmission and ACK response occurs. In this case, the collision may occur only the RTS frame, and it is detected by the lack of CTS response. Moreover, Ref. [5] accurately revisited the hidden terminal problem in a CSMA/CA wireless network. This research analyzed the limitations of previous modeling methods and proposed a method of modeling that related to using a fixed-length channel slot as the unit of time. The evaluation results based on the saturation throughput and conditional collision probability

For FD transmission, there are a few solutions based on MAC protocol like shared random backoff (SRB), header snooping, virtual contention resolution (VCR) were discussed in [6]. These solutions proposed a new message structure which being used for the FD-MAC protocol. In addition, the collision avoidance with RTS/FCTS exchange also have been mentioned in [7]. However, the hidden terminal problems still have not been solved completely yet.

Besides, there are very few papers on the combination of HD and FD modes into wireless network system. In previous research [8], the optimal transmission scheduling for a hybrid of FD and HD relaying was discussed. K. Yamamoto *et al.* analyzed and proved the achievement of spectral efficiency, improvement of end-to-end throughput that is higher than that achieved when using FD and HD relaying individually. However, the hidden terminal problem has not discussed in this research.

The limitation of the solutions in the solving of hidden terminal problem is still an open issue for researchers who continue to concentrate how to solve it completely and how to make the mixture of HD and FD wireless network becomes more common and practical.

1.2. Motivation and Objective

To focus on solving hidden terminal problem, this paper revisits the previous research work [5], which be used as a preliminary study. Although the main method is concentrated on the hidden terminal problem in a CSMA/CA wireless network under both RTS/CTS and Basic access mechanism, we analyze and extend its system model in case of RTS/CTS mechanism. The main contribution is modeling the system model for mixture of HD and FD wireless network considering hidden terminal problem. The model that is considered includes three nodes and display like chain model.

In Ref. [5], the analysis of system model based on Bianchi's bidimensional Markov Chain (MC) modeling [4]. This method is used in this paper. However, the extension is explicit considering of three states inside one node, like success, collision and freeze.

The evaluation results of HD, FD and mixture of HD and FD wireless network are in terms of saturation throughput, conditional collision probability and transmission probability. Besides, the solutions that are applied in the mixture of HD and FD to solve hidden terminal problem are evaluated.

The expected outcomes can show the effectiveness of the mixture of HD and FD wireless network in the improvement of saturation throughput. The objective of this paper is to explicitly model and analyze the impact of the hidden terminal problem in not only the HD, but also both the mixture of HD and FD and FD wireless network. Thus, this research will open a new way to continue to solve the hidden terminal problem completely.

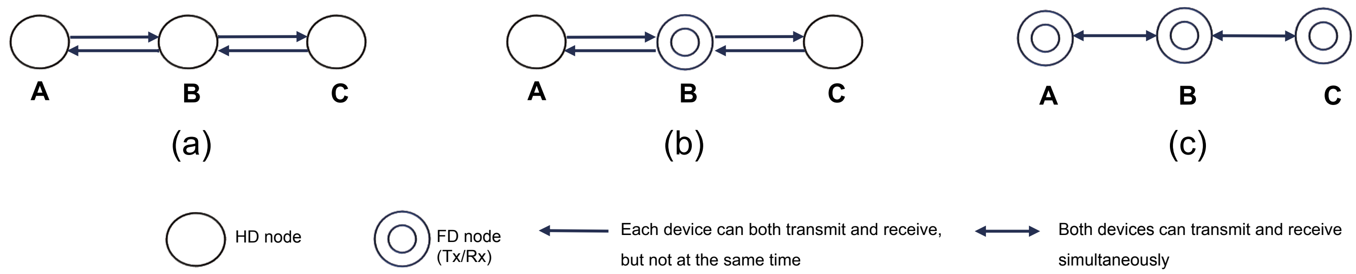

Fig. 2: The chain topologies: (a) HD, (b) Mixture of HD and FD, (c) FD.

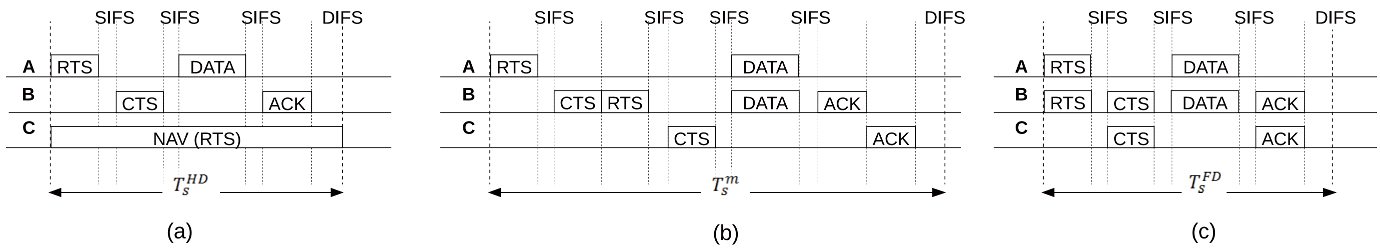

Fig. 3: The frame exchange in the time of successful transmission: a) HD, (b) Mixture of HD and FD, (c) FD.

2. System Model

In this section, we introduce the system model with three nodes for HD transmission, mixture of HD and FD transmission and the ideal case of FD transmission in wireless network.

As illustrated in Fig. 2, there are three nodes and among them, we assume the HD node and FD node with transmission Tx and reception Rx simultaneously. In this figure, node B is within the transmission range of node A and node C, while node C is outside the transmission range of A and vice versa. In other words, node A and node C are hidden nodes each other. Node B is applied the FD-MAC protocol in [6].

Figure 2(a) illustrates the three HD nodes. The RTS/CTS mechanism is applied to analyze and evaluate the throughput of system.

Figure 2(b) illustrates the mixture of HD and FD wireless network. The FD transmission is at node B. There are two potential actions for FD node. First, node B starts a new reception session, while transmitting. Let us assume that node B is transmitting to node A, when node C initiates the transmission of packet. Then node B has to estimate the channel between node C and itself so as to decode node C's packet. Second, node B starts a new transmission session, while receiving. When node B has already commenced receiving a packet from node A and intends to send a packet to node C.

Figure 2(c) illustrates the idea case with all nodes are FD mode. This model can be called as bidirectional full-duplexing. All transmission and reception are simultaneous at the same time and frequency. However, the transmission is made a pair of nodes, node A and node B or node B and node C. Node A and node C are hidden node each other.

3. Modeling and Derivation

In this section, we describe the mixture of HD and FD wireless network by analyzing the transmission time that is considered with three states, like success, collision and freeze. This paper uses the RTS/CTS mechanism to analyze and evaluate. This mechanism is very effective in terms of system performance, especially the hidden terminal problem can be solved.

3.1. Modeling

First, we revisit the definition of time slot in [4]. The slot is of variable length depending on the state of the channel. For RTS/CTS mechanism, the time of successful transmission T_s is defined in Fig. 3 with three cases, T_s^{HD} for HD transmission, T_s^m for mixture of HD and FD transmission and T_s^{FD} for of FD transmission.

$$\begin{aligned} {T_s}^{HD} &= \mathrm{RTS} + \mathrm{CTS} + \mathrm{DATA} + \mathrm{ACK} + 3\mathrm{SIFS} + \mathrm{DIFS} \\ {T_s}^{m} &= 2\mathrm{RTS} + 2\mathrm{CTS} + 2\mathrm{DATA} + 2\mathrm{ACK} + 4\mathrm{SIFS} + \mathrm{DIFS} \\ {T_s}^{FD} &= \mathrm{RTS} + \mathrm{CTS} + 2\mathrm{DATA} + \mathrm{ACK} + 3\mathrm{SIFS} + \mathrm{DIFS} \end{aligned} \tag{1}$$

Besides, the slot has the length of a collided transmission, T_c = RTS + DIFS, for all stations. When the node is in backoff time, it has slot time length σ, is $20\mu s$.

In Fig. 3(a), we consider the transmission between node A and B. Node A send the preliminary frame, RTS to node B. At node B, when it detects an RTS frame, it responds, after an SIFS time, with a CTS frame. Node A is allowed to transmit its packet only if the CTS frame is correctly received. The RTS and CTS frames carry the information of

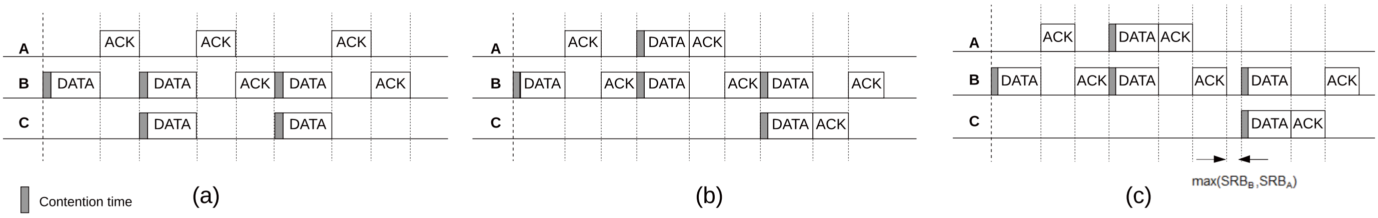

Fig. 4: The schemes for mixture of HD and FD: a) Header Snooping, (b) Virtual Contention Resolution, (c) Shared Random Backoff.

the length of the packet to be transmitted. This information can be read by any nodes in its transmission range. In the ongoing transmission between node A and B, node C updates the a *Network Allocation Vector* (NAV) containing the information of the period of time in which the channel remains busy [4]. Therefore, when a node is hidden from other nodes, by detecting just one frame among RTS and CTS frames, it can suitably delay further transmission, and thus avoid collision.

Figure 3(b) is the mixture of HD and FD transmission with node B is FD node. In this situation, node B starts a new transmission session, while receiving. Node B has already received a packet from node A, however it also has a packet that is prepared in order to send to node C. The RTS/CTS mechanism is like HD transmission. After completing the detection of RTS/CTS, node B is set to be in full-duplex, receive a packet from node A and send a packet to node C simultaneously.

Figure 3(c) is ideal case of FD transmission. This situation is transmission for all frames or packets at the same time between two FD nodes. The time of successful transmission is same with HD transmission, however the number of packets (Data) is twice as much.

Moreover, Fig. 4 shows the scheme of transmission time for three solutions: header snooping, virtual contention resolution (VCR) and shared random backoff (SRB) that are used for solving the hidden terminal problem in the mixture of HD and FD wireless network. These solutions were explicitly discussed in [6], which based on a new proposed FD-MAC protocol. In this figure, we concentrate on the transition of the packets in FD mode and ignore the detail of contention time that includes the time of initialization and finish for successful transmission.

Figure 4(a) is a case of header snooping, node B has packets that are sent to node A, while node C also has packets and want to send to node B. This scheme is another action of system model in Fig. 3(b). The VCR solution is illustrated in Fig. 4(b). The notation is an ACK frame before an FD transmission at node B. In this situation, physical layer needs to train its self-interference channel in FD mode, so an ACK frame that includes information was sent. This was also discussed with an FD-MAC protocol in [6]. The requirement of this solution is the depth of the buffer that keeps all packets for FD node. The method that is operated is first-in, first-out (FIFO) in FD node. Figure 4(c) is the scheme for SRB. In this solution, after one FD mode, each node will pick a random backoff value in contention window size and wait in this maximum time until it equals 0, the new transmission is initialized.

3.2. Derivation

The modeling of system models are presented, now we need to analyze their effectiveness in performance of system by the evaluation of throughput. To observe this, the parameters that related to calculate throughput need to be revisited.

First, we concentrate on the analysis of transition states among three nodes in system model. In order to facilitate the analysis, the intermediate steps $(\mathrm{I_{AB}}, \mathrm{I_{BC}})$ that can incorporate and accurately describe the joint behavior of the senders are used. The $\mathrm{I_{AB}}$ is decision on state between node A and node B, similarly $\mathrm{I_{BC}}$ is decision on state between node B and node C. The intermediate step observes a collision when (both) the transmitters attempt to transmit and collision. It observes a successful transmission when one of them is successful. Conversely, it observes a freeze state when both the transmitters do not transmit. The detail of analysis is shown in Fig. 5. We have two intermediate steps and three states, so there are nine patterns for totally.

According to the analysis in [5] with the states of collision and success that were considered, the conditional collision probability p is calculated as follows:

$$p = \frac{2p'}{1+p'} \tag{2}$$

where p' is probability that the receiver observes a collision.

Besides, we easily see that the condition to collision occurs in Fig. 5 that is analyzed with full three transition states: success, collision and freeze. The conditions are the same conditions as were analyzed in [5]. Therefore, this paper still use (2) to calculate the conditional collision probability p.

A	Collision	Collision	Collision	Success	Success	Success	Freeze	Freeze	Freeze
$\mathrm{I_{AB}}$	Collision	Collision	Freeze	Collision	Success	Freeze	Success	Freeze	Freeze
B	Collision	Success	Freeze	Collision	Success	Freeze	Success	Collision	Freeze
$\mathrm{I_{BC}}$	Freeze	Success	Freeze	Collision	Collision	Success	Success	Collision	Freeze
C	Freeze	Freeze	Freeze	Success	Collision	Success	Success	Collision	Collision

Fig. 5: The transition states of the intermediate step of the joint senders.

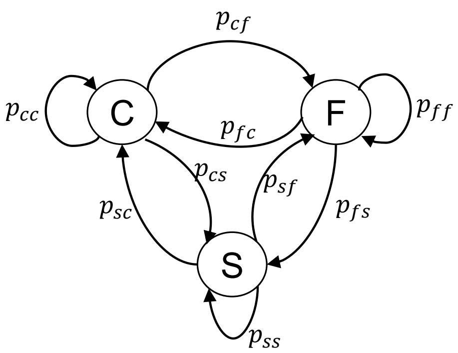

Fig. 6: The transmitting states of the channel around common receivers based on Markov Chain.

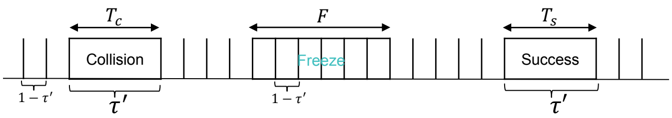

Fig. 7: The channel model with collision, freeze and success states.

Moreover, the Discrete Time Markov Chain (DTMC) was used for modeling that has only the two states, success and collision [5]. We extend this scheme by addition the freeze state (shown in Fig. 6). There are nine transition probabilities, correspondingly with three states. Here, collision (C) state, p_{cc}+p_{cf}+p_{cs} = 1; success (S) state, p_{ss}+p_{sc}+p_{sf} = 1 and freeze (F) state, p_{ff}+p_{fs}+p_{fc} = 1.

The purpose of this part is to verify the probability p' to calculate the conditional collision probability p in (2).

$$p' = \frac{p_{sc} + p_{fc}}{1 - p_{cc} + p_{sc} + p_{fc}} \tag{3}$$

where p_{cc} and p_{sc} were explicitly discussed in the schematic analysis of the transitions between system transmitting states [5]. We need to concentrate on the derivation of the transition probability p_{fc} that related to freeze state. The freeze states occur around intermediate steps ($\mathrm{I_{AB}}, \mathrm{I_{BC}}$) when all nodes do not transmit, or in other words, the probability of freeze state is remaining probability after probabilities of success and collision states occurred. For calculation, we follow the formulas for probabilities in [5] and then calculate the probability of freeze state.

Furthermore, the previous research [5] defined the model of transmission time, Fig. 7. In there, the probability τ' is an intermediate transmission probability, as follows:

$$\tau' = \frac{2}{2 + (W-1)[1 + p_f F]} \tag{4}$$

Here, W is window size; F is the length of the freezing period in fixed-length slots, $F = L - (\mathrm{RTS} + \mathrm{SIFS})/\sigma$, where L is successful period (an integer multiple of σ) and p_f is the frequency with which the counter freezes divided by the average number of backoff slots, as follows:

$$p_f = \frac{2(1-p)}{W-1} \tag{5}$$

The transmission probability (P_T) is as follows:

$$P_T = \frac{\tau'}{\tau' + Q(1-\tau')} \tag{6}$$

where τ' is given in (4) and $Q = \frac{1}{(1-p)L + pC}$, with C is collision period (an integer multiple of σ).

The throughput (S) is defined as the number of packets transmitted during a specific period of time divided by the duration of that period. S is calculated as follows:

$$S = P_T . \frac{(1-p)L}{(1-p)L + pC} . \frac{1}{L} \tag{7}$$

4. Numerical Simulations

Based on the system models, which are described in Section 2 and the modeling and derivation of system model with the conditional collision probability, transmission probability and the throughput, which are described in Section 3, this section shows the simulation setting and the evaluation results in comparison among system models.

4.1. Simulation Scenario and Setting

The scenario is shown in Fig. 2, where node A and node C are hidden each other and node B is in FD mode that can transmit and receive simultaneously.

Table I shows the parameters of system model that have been presented in Section 3. We assume that TDD method is used to fix the length of slot-time for initialization in order to calculate the conditional collision probability of transmission states, success, collision and freeze.

4.2. Evaluation Results

The analysis of system model is explicitly presented in Section 3. The conditional collision probability p is a parameter that needs to be calculated firstly. After that, we can calculate the transmission probability and the saturation throughput of system.

TABLE I: The list of simulation parameters and setting.

Parameters	Values
Packet length (bytes)	[256, 512, 1024, 1536, 2048, 2294]
Contention window size	[32, 64, 128, 256, 512, 1024]
Basic rate (Mbps)	1
Data rate (Mbps)	[1, 2, 11]
PLCP header	192 bits
MAC header	272 bits
PHY header	128 bits
RTS size	160 bits
CTS size	112 bits
ACK size	112 bits
SIFS length	10 µs
DIFS length	50 µs
Slot time length	20 µs
EIFS length	DIFS + CTS + SIFS

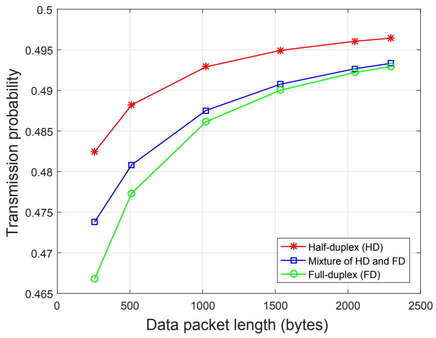

Fig. 8: Comparison of transmission probability with W = 32, basic rate = 1 Mbps and data rate = 2 Mbps.

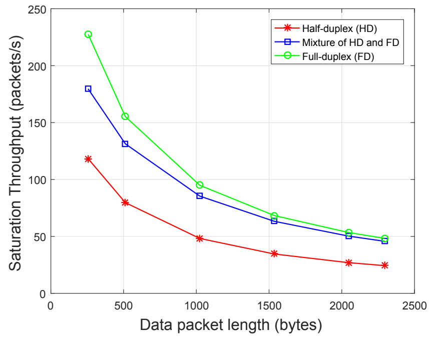

Fig. 9: Comparison of saturation throughput with W = 32, basic rate = 1 Mbps and data rate = 2 Mbps.

The maximum of slot-time for calculation the conditional collision probability is approximately 0.02 seconds. Meanwhile, the slotted time is 20 μs. Therefore, the fixed-length slot-time can be fixed on 1000 slots.

Figure 8 illustrates the comparison of transmission probability among various system models. We can easily see that the HD transmission is higher than those of FD transmission. Meanwhile, the mixture of HD and FD are close to those of FD transmission.

Figure 9 illustrates the comparison of saturation throughput among them. The FD transmission can double the throughput as compared with HD transmission. The mixture of HD and FD transmission is better than HD and close to the FD transmission.

Moreover, Fig. 10 shows the results in comparison of three solutions in the mixture of HD and FD wireless network. The evaluation results based on the same successful packets among the solutions. The header snooping is the best solution.

As a result, we can say that the mixture of HD and FD is more effective than HD wireless network in the improvement in the saturation throughput of system. Besides, the effectiveness of the mixture of HD and FD wireless network is close to the ideal case that is FD wireless network. The system models that consider hidden terminal problem and full transition states (collision, success, freeze) are discussed. The results have already shown the improvement in the saturation throughput of

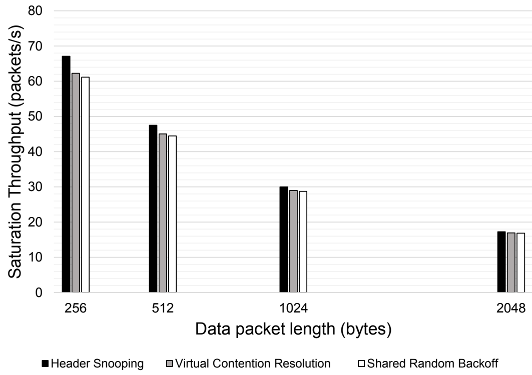

Fig. 10: Comparison of solutions in the mixture of HD and FD with W = 32, basic rate = 1 Mbps and data rate = 2 Mbps.

the mixture model. However, the optimization of freeze state and its effectiveness need to be discussed more explicitly.

5. Concluding Remarks

In this paper, we revisited the hidden terminal problem in HD wireless network (CSMA/CA) and extended the system model not only the mixture of HD and FD, but also the FD wireless network. In addition, we also discussed the solutions that are used to solve the hidden terminal problem in the mixture of HD and FD wireless network. Besides, the transition states have already considered with full states, collision, success and freeze. The evaluation results were explicitly presented by comparison among various system models and solutions.

For future works, this research needs to be extended and improve more to continue to completely solve the hidden terminal problem. Especially, we need to concentrate on MAC protocol, analyze and propose a novel MAC protocol for the mixture HD and FD wireless network in order to solve hidden terminal problem. Because, this existing problem is still challenging for researchers. This research is as an open key to researchers in the near future.

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