An IBFD MAC Mechanism Considering Capture Effect for Centralized Wireless Networks

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ABSTRACT

In this paper, we provide an In-band Full-duplex (IBFD) medium access control (MAC) mechanism in centralized wireless networks, considering capture effect. The proposed mechanism reinforces capture effect from the MAC point of view so that it contributes to suppress the influence of inter-node interference and improve network throughput. Analytical saturation throughput of the proposed mechanism is derived in the presence of capture effect, where we fully consider that AP and nodes have different interference sources. Numerical results demonstrate the superiority of our proposed scheme in terms of IBFD wireless networks.

KEYWORDS

in-band full-duplex, capture effect, medium access

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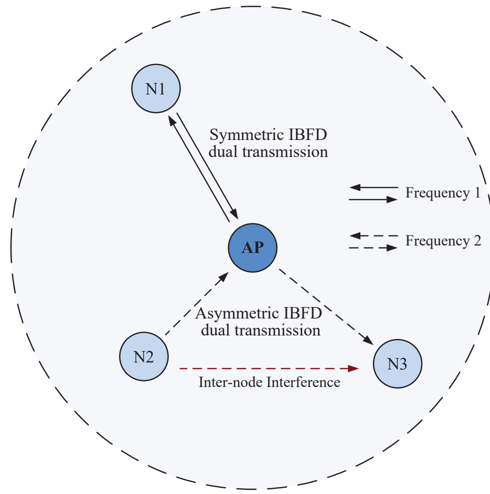


Figure 1: Symmetric/asymmetric dual transmissions in centralized IBFD wireless network.

1 INTRODUCTION

Recent self-interference cancellation technologies have been able to allow In-band Full-Duplex (IBFD) signaling, in which nodes transmit and receive simultaneously in the same frequency band [1, 9, 12]. To further realize IBFD communication among multiple nodes, supportive MAC protocols are needed to achieve the true benefits of IBFD wireless networks.

In this paper, we focus on a centralized IBFD wireless network, where n nodes (defined as N1,N2,...,Nn) are randomly located within the communication range of AP, as shown in Figure 1. AP and all the nodes support IBFD wireless communication and have equal access priority. The IBFD transmission can be divided into symmetric dual transmission (e.g. N1→AP→N1) and asymmetric dual transmission (e.g. N1→AP→N2).

based on RTS/CTS to access channel for symmetric dual packets transmission. Doost-Mohammady et al. [5] used CSMA/CA in centralized IBFD wireless networks. The destination node returns packet of its own to source node immediately after receiving the header of the coming packet, or sends out busytone to occupy channel if having no packet back to source node. However, these two mechanisms cannot reserve downlink of asymmetric dual transmission. For the above problem, Zuo et al. [14] proposed an IBFD mechanism, named as RTS/SRTS (Second RTS)/CTS, which can both establish symmetric or asymmetric dual link by single channel access. The SRTS frame includes the expected duration of the two packets for dual transmission, which will be obtained by neighbor nodes. Then, this mechanism no longer uses busytone to occupy channel during packet transmission, which consumes less energy compared to the scheme in [5].

However, the IBFD MAC protocols in [3, 5, 7, 14] did not take inter-node interferences (INI) into consideration. When multiple nodes contend channel simultaneously, the frames from other nodes, namely INI, have a bad effect on the reception of the destination node. Some MAC-layer researchers have considered utilizing physical (PHY) layer technologies to increase the possibility of successful access in the presence of INI [6, 8, 11, 13]. Among the studies, Zorzi et al. [13] proposed that the capture capability of a node can decrease the effect of INI. When several nodes simultaneously transmit frames to AP, a packet collision occurs. But one of the collided frames can still be correctly decoded, as long as its SINR obtained by AP is high enough. This phenomenon is known as capture effect. Later Hadzi-Velkov et al. [6] demonstrated both AP and nodes have capture effect, and Lee et al. [8] verified on the platform that the capture effect can indeed improve network performance. To better increase the successful transmission probability, we endeavor to utilize capture effect of PHY when we design MAC protocols in the presence of INI.

In this paper, we extend the MAC mechanism in [14] for further throughput improvement. We proposed an IBFD MAC mechanism considering capture effect (FDMAC-CE) in the presence of INI. Besides to establish dual link, we design the medium access and packet transmission to explore capture effect at both AP and node sides during IBFD transmission and further contribution to increase the probability of a successful transmission and throughput. Then, we derive a Markov model incorporating capture effect to determine the throughput of FDMAC-CE. Here we analyze respectively the frame capture probability of AP and nodes since they have different INI sources.

2 FDMAC-CE MECHANISM

The MAC protocol determines the time and order of medium access and packet transmission of nodes. Proper empowerment of MAC protocols could assist PHY layer to judge whether the coming packet can be received correctly. Considering this, we elaborate medium access and packet transmission of FDMAC-CE for better use of capture effect.

2.1 Control Frame Structures

The function of control frame is important for medium access. We design the structure of SRTS frame in [14]. Besides source address, destination address and packet duration of SRTS, SRTS retains the source address and packet duration of RTS. A node uses RTS, SRTS and CTS in turn to access medium. SRTS, who is used in the second handshaking, acts as not only a reply frame to answer source node of RTS, but also a request frame to access destination node of SRTS.

We consider that if a node receives multiple frames simultaneously, it can still hopefully receive the frame of the node whose received power is the strongest among all frames [8]. Then the node requires a criterion for correct reception. Define γ as the ratio of the power of the strongest frame P_u and the sum of the powers P_k ($k = 1, 2, \ldots, x$) of the other x frames which interfere the reception of the strongest one. It can be expressed as

$$\gamma = \frac{P_u}{\sum_{k=1}^{x} P_k}, \tag{1}$$

The node calculates the value of γ and determines whether it can capture successfully. If γ is greater than the predefined threshold, the node will be able to decode the strongest frame. It can be seen that γ is an important parameter for capture effect. If a node can obtain the value of γ during the establishment of asymmetric dual link, its PHY layer may adjust transmit power for dual packet transmission based on this value, which can decrease the probability of collision caused by INI. Thus, we consider to add the information of γ in SRTS and CTS frame and deliver it by medium access, which will assist a node to determine whether to adjust transmit power for better capture effect.

Frame Control	Packet2 Duration	Packet1 Duration	Packet2 DA	Packet2 SA	Packet1 SA	γ	FCS
2	2	2	6	6	6	1	4 bytes

Figure 2: The SRTS frame structure of FDMAC-CE mechanism.

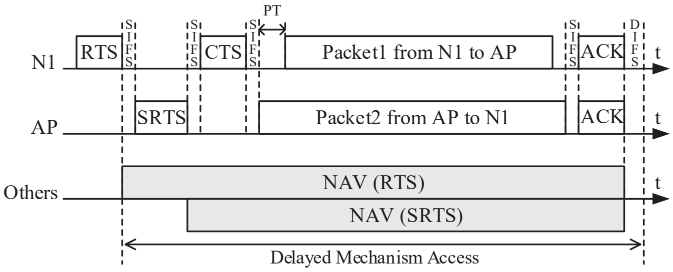
The frame structure of SRTS is shown in Figure 2, where SA and DA represent the source address and destination address respectively, and γ only occupies 1 byte. SRTS also includes the durations of the two packets which will be transmitted simultaneously during dual packet transmission. Then the nodes in the network can obtain this durations information by medium access. Therefore, the communication node who firstly finishes packet transmission no longer need to use busytone to occupy channel. Compared with the MAC protocols in [5, 10], FDMAC-CE has a lower node energy consumption for dual packet transmission.

2.2 Medium Access and Packet Transmission

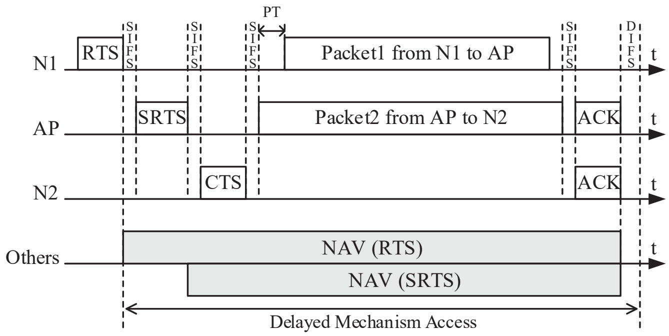
If the strongest frame reaches a destination node earlier than interference frames, the destination node would have more opportunities to capture this frame since it would synchronize with the earliest frame. Moreover, when the strongest frame arrives earlier by a PHY preamble time, the successful possibility of capture effect can be further improved [8]. Considering this, we design FDMAC-CE as shown below.

The successful IBFD dual transmission is shown in Figure 3. The packets that a node and AP want to transmit are defined as Packet1 and Packet2 respectively. The definitions of SIFS (Short Inter Frame Space) and DIFS (Distributed Inter Frame Space) and network environment are the same as [14]. When a node (N1) has Packet1 to AP, it initiates a RTS request to AP. If AP has packet2 to N1, it plans to form symmetric dual link with N1 and then sends SRTS back to N1, as shown in Figure 3(a). After receiving SRTS, N1 knows the request of AP and then sends CTS to AP to finish symmetric dual link establishment. While if AP has no packet to N1 but has Packet2 to another node N2, it expects to establish asymmetric dual link with N1 and N2 and then transmits SRTS to N2, as shown in Figure 3(b). Here SRTS both replies the request of N1 and asks for the agreement to access N2. After receiving SRTS, N2 transmits CTS to AP to complete asymmetric dual link establishment.

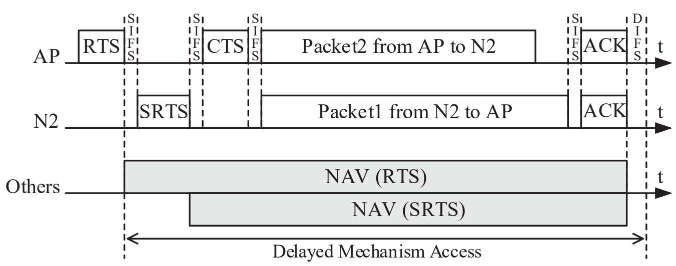
Remarkably, in asymmetric dual packet transmission, N2 may be interfered by the packet from N1. Then we consider that if the desired Packet2 from AP reaches N2 a PHY preamble time earlier than Packet1 from N1 (which is INI for N2), it would be easier for N2 to receive Packet2 correctly. To assist N2 to capture the packet from AP, we design the case of a node initiating a RTS to AP that AP firstly transmits Packet2 and then after a PHY preamble time (PT), N1 starts Packet1 transmission to AP. Moreover, to reduce the judgment complexity of a node, we design that in the case of a node initiating a RTS, both the symmetric and asymmetric dual links have the same packet transmission procedure. Since neighbor nodes have known the transmission duration of both Packet1 and Packet2, the node that firstly finishes packet transmission does not need to send busytone for channel occupation. At last, the destination



(a) A node initiates a transmission in symmetric dual link.



(b) A node initiates a transmission in asymmetric dual link.



(c) AP initiates a transmission in symmetric dual link.

Figure 3: Successful IBFD wireless transmissions with FDMAC-CE mechanism.

nodes transmit ACK frames to their source nodes to finish dual packet transmission.

For the case of AP initiating a RTS request, as shown in Figure 3(c), the medium access is similar to what occurs when N1 initiates a RTS to AP. But these two cases have different packets transmission procedures. AP can only communicate with a node in symmetric dual transmission mode. Thus, we set AP and its destination node to transmit their respective packets to each other simultaneously after establishing symmetric dual link successfully.

3 THROUGHPUT ANALYSIS IN PRESENCE OF CAPTURE EFFECTS

We analyze the network throughput of FDMAC-CE with a Markov chain model [2] in presence of capture effect, as shown in Figure 4. All the nodes in the IBFD wireless network can listen to the channel, contend IBFD transmission opportunities and detect collisions, and always have packets to transmit. In FDMAC-CE, AP and nodes have different backoff parameters. The maximum contention windows of a node and AP are defined as $2^m W$ and $2^{m_0} W_0$ respectively, where W and W_0 is the minimum contention window, m and m_0 is the maximum backoff stage.

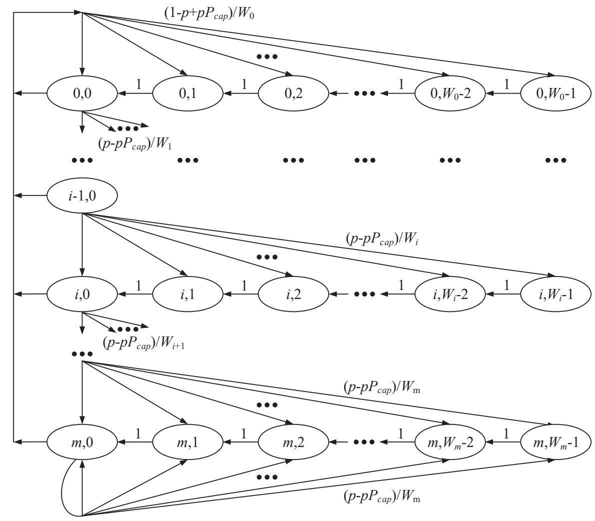


Figure 4: Markov chain for contention model with capture effect.

Define τ and τ_0, p and p_0, P_{cap} and P_{cap0} as the transmission probability, condition collision probability and capture probability in a random slot time of a node and AP respectively. Let $p_{eq} = p - pP_{cap}$, $p_{eq0} = p_0 - p_0 P_{cap0}$, and then, we can express the probabilities above as :

$$\tau = \frac{2(1-2p_{eq})}{(1-2p_{eq})(1+W) + p_{eq}W(1-(2p_{eq})^m)}, \tag{2}$$

$$p = 1-(1-\tau)^{n-1}, \tag{3}$$

$$\tau_0 = \frac{2(1-2p_{eq0})}{(1-2p_{eq0})(1+W_0) + p_{eq0}W_0(1-(2p_{eq0})^{m_0})}, \tag{4}$$

$$p_0 = 1-[(1-\tau)^n + \binom{n}{1}\frac{1}{n}\tau(1-\tau)^{n-1}]. \tag{5}$$

Here, we assume that p, p_0, P_{cap} and P_{cap0} are constant and independent of each transmission. Before calculating network throughput, we need to get the expression of P_{cap} and P_{cap0}.

Considering a propagation model with deterministic power attenuation and Rayleigh fading, the local mean received power of a node is given as:

$$P_0 = Ar_k^{-n_p}P_t, \tag{6}$$

where, P_t is the transmit power, n_p is the path-loss exponent (which is usually set as 3.5 in indoor propagation conditions [4]), r_k is the distance between source node and destination node, $Ar_k^{-n_p}$ is the deterministic path-loss. A, n_p and P_t are identical for all the nodes. When signal transmission is attenuated by Rayleigh fading, the instantaneous power of a received frame is exponentially distributed as:

$$f(x) = \frac{1}{p_0}e^{-\frac{x}{p_0}}, x > 0. \tag{7}$$

We assume that when a node initiates a RTS to AP, there are other j ($j \in [1, n-1]$) nodes contend channel simultaneously. In this case, the condition probability of this node capturing channel can be expressed as [6]:

$$P_{ca}(\gamma > z_0 g(S_f) \mid j) = \int [I(r_1)]^j h(r_1) dr_1, \tag{8}$$

where γ has been given in (1), and

$$I(r_1) = \int \frac{h(r_v)\mathrm{d}r_v}{1 + z_0 g(S_f)(\frac{r_v}{r_1})^{-n}}, \tag{9}$$

z_0 is the capture threshold at the receiver, $g(S_f)$ is processing gain of the correlation receiver, which is inversely proportional to the spreading factor S_f. For Direct Sequence Spread Spectrum (DSSS) using a 11-chip spreading factor, $g(S_f) = \frac{2}{3S_f}$ [6]. We determine the capture capability of a node with the consideration of $g(S_f)$ that if $\gamma > z_0 g(S_f)$, the node can capture channel successfully. r_1 and r_v are the normalized distances from the contending node and other interfering nodes to the destination node (AP), which are given by:

$$h(r_1) = 2r_1, 0 < r_1 \leqslant 1, \tag{10}$$

$$h(r_v) = 2r_v, 0 < r_v \leqslant 1. \tag{11}$$

The probability of generating $j+1$ frames over n contending nodes in a random slot time, denoted as R_j, is calculated as:

$$R_j = \binom{n}{j+1} \tau^{j+1} (1-\tau)^{n-j-1}. \tag{12}$$

Then, P_{cap} can be computed as:

$$P_{cap} = \sum\nolimits_{j=1}^{n-1} R_j P_{ca}(\gamma > z_0 g(S_f) \mid j). \tag{13}$$

Assume that when AP initiates a RTS to a node (N1), there are j_0 ($j_0 \in [1, n-1]$) nodes except N1 contend channel simultaneously. In this situation, we can express the condition probability of AP capturing channel as:

$$\begin{aligned} & P_{ca0}(\gamma > z_0 g(S_f) \mid j_0) \\ & = \int \left(\int \frac{h(r_u)\mathrm{d}r_u}{1 + z_0 g(S_f)(\frac{r_u}{r_1})^{-n}} \right)^{j_0} h(r_1) dr_1. \end{aligned} \tag{14}$$

Here r_u are the normalized distance from other interfering nodes to the destination node (N1), which are given by:

$$h(r_u) = \frac{1}{2} \frac{1}{B(2, 2.5)} \frac{r_u}{2} (1 - \frac{r_u}{2})^{\frac{3}{2}}, 0 < r_u \leqslant 2, \tag{15}$$

where $B(.,.)$ is the Beta function [6]. The probability of generating j_0 frames over $n-1$ other contending nodes except N1 in a random slot time, denoted as R_{j0}, is calculated as:

$$R_{j0} = \tau_0 \binom{n-1}{j_0} \tau^{j_0} (1-\tau)^{n-1-j_0}. \tag{16}$$

Then, P_{cap0} can be computed as:

$$P_{cap0} = \sum\nolimits_{j_0=1}^{n-1} R_{j_0} P_{ca0}(\gamma > z_0 g(S_f) \mid j_0). \tag{17}$$

Based on the above equations, we can calculate out the values of τ, τ_0, p, p_0, P_{cap} and P_{cap0}.

The next analysis step is the computation of the normalized system throughput S, defined as the fraction of time the channel is used to successfully transmit payload bits:

$$S = \frac{(P_{sa} + P_{ss})E[P]}{(1 - P_{tr})\sigma + P_{sa}T_{sa} + P_{ss}T_{ss} + P_c T_c}, \tag{18}$$

where

- P_{tr} is the probability that there exists at least one transmission during the considered slot time:

$$P_{tr} = 1 - (1-\tau_0)(1-\tau)^n, \tag{19}$$

and then, the probability of idle time during this slot time can be expressed as $1 - P_{tr}$.

- P_{sa} is the successful transmission probability of AP initiating a RTS frame. This event corresponds to the case in which only AP transmits in a given slot time, or two or more nodes transmit simultaneously but the frame from AP is captured by the desired node. These conditions yield the following probability:

$$P_{sa} = \tau_0 (1-\tau)^n + P_{cap0}, \tag{20}$$

and the transmission time lasts: $T_{sa} = T_{RTS} + T_{SRTS} + T_{CTS} + T_{Hdr} + T_{E[P]_a} + T_{ACK} + 4T_{SIFS} + T_{DIFS}$, where $Hdr = PHY_{hdr} + MAC_{hdr}$ is the length of PHY and MAC header of a packet, $E[P]_a$ is the longer payload size of Packet1 and Packet2.

- P_{ss} is the successful transmission probability of a node initiating a RTS frame. This event occurs when exactly one node transmits in the given slot time, or two or more nodes transmit simultaneously but capture effect of AP achieves. Thus, this probability is given as:

$$P_{ss} = \binom{n}{1} \tau (1-\tau)^{n-1} + P_{cap}, \tag{21}$$

and the transmission time lasts: $T_{ss} = T_{RTS} + T_{SRTS} + T_{CTS} + T_{Hdr} + T_{E[P]_s} + T_{ACK} + 4T_{SIFS} + T_{DIFS}$, where $E[P]_s$ is the longer payload size of PT+Packet1 and Packet2. The main difference between Tsa and Tss are the different transmission durations of $E[P]_a$ and $E[P]_s$.

- P_c is the failed transmission probability:

$$P_c = P_{tr} - (P_{sa} + P_{ss}), \tag{22}$$

and the corresponding time lasts: $T_c = T_{RTS} + T_{DIFS}$.

- $E[P]$ is the total packet payload length.
- σ is the duration of a slot time.

4 NUMERICAL RESULTS

We use MATLAB to evaluate the performance of the FDMAC-CE mechanism for centralized IBFD wireless networks and validate our analytical model. The basic parameters for simulation are listed as shown in Table 1. Moreover, we also compare the performance of FDMAC-CE (with capture effect) to that of RTS/SRTS/CTS (without capture effect) [14] and RTS/FCTS [3] for IBFD wireless networks.

Figure 5 and Figure 6 show the failed transmission and successful transmission probabilities of the three IBFD MAC mechanisms depend on the number of contending nodes. Here z_0 is set to 5dB. We can see that the failed and successful transmission probabilities of the mechanisms all increase as the number of contending nodes increases. But with the same network scale, FDMAC-CE obtains

Table 1: Parameters for Numerical Simulations

Packet1/Packet2 payload	8184 bits
PHY header	128bits
MAC header	272 bits
RTS	160 bits + PHY header
SRTS	232 bits + PHY header
SRTS [14]	224 bits + PHY header
CTS	120 bits + PHY header
CTS [14]	112 bits + PHY header
FCTS [3]	400 bits + PHY header
ACK	112 bits + PHY header
PT	288 bits
Channel Bit Rate	1 Mbit/s
Slot Time (σ)	50 μs
SIFS	28 μs
DIFS	128 μs
W	16
W_0	16
m	6
m_0	3

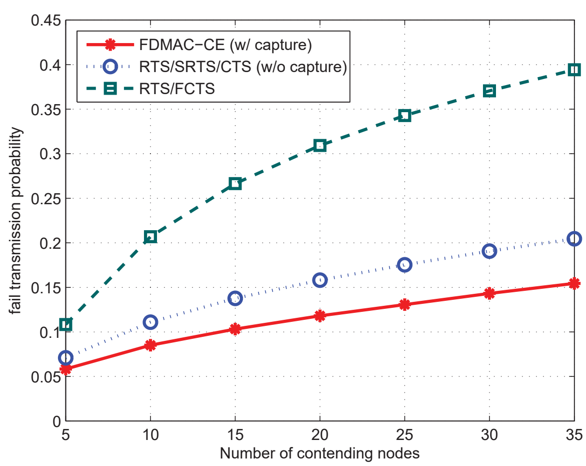


Figure 5: The fail transmission probability versus number of contending nodes.

lowest failed transmission probability and highest successful transmission probability compared to the other two schemes. This is because with capture effect, though collision occurs in the channel, FDMAC-CE still tries to receive a frame correctly, which can further improve network performance.

Figure 7 shows the throughput depends on the number of contending nodes for different mechanisms, wireless networks and capture thresholds. It is clear to see the advantage of IBFD network that it nearly twice the throughput of HD network. The throughput of the two IBFD mechanisms both decrease as the number of nodes increases. But under the same conditions, the throughput of the

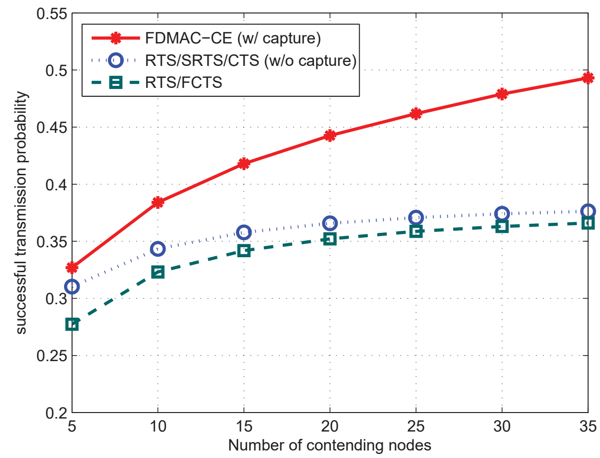


Figure 6: The successful transmission probability versus number of contending nodes.

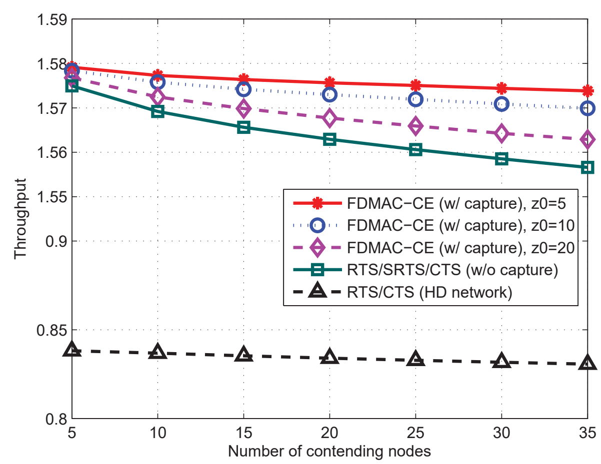


Figure 7: The throughput versus number of contending nodes for different access mechanisms.

former decreases slowly and is always higher than that of latter. Thus, FDMAC-CE remains more stable performance gain for IBFD wireless network. Moreover, for the same network scales, with the increase of capture threshold z_0 which determines whether a node can capture a frame successfully, the throughput of FDMAC-CE reduces. We can deduce that as $z_0 \to \infty$, FDMAC-CE will work in absence of capture effect and the throughput predicted by our model tends to the throughput of RTS/SRTS/CTS.

5 CONCLUSION

In this paper, we proposed a FDMAC-CE mechanism considering capture effect for centralized IBFD wireless networks, which enables symmetric and asymmetric dual links establishment by only a single channel access. By FDMAC-CE, the communication nodes can get better use of the captured frames, which improves successful transmission probability in a collision caused by simultaneous arrival of multiple frames. Comparison between FDMAC-CE and RTS/SRTS/CTS shows the enhancement of throughput and stability in performance evaluation.

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