A Simulation Study of CSMA/CA Performance in 60 GHz WPANs

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Abstract— **Recently, there has been an increasing interest in developing 60 GHz wireless personal area networks (WPANs) for short-range high-speed wireless communications. Both industrial and standardization organizations such as IEEE 802.15.3c and IEEE 802.11ad are making considerable efforts to bring the very high data rate (up to several Gbps) WPANs into reality. In this work, we develop an NS-2 extension for simulating 60 GHz WPANs, based on which we conduct a comprehensive simulation study to investigate the impacts of antenna directivity and CSMA/CA operation modes on the throughput of 60 GHz WPANs. Observations from extensive simulation results provide valuable insights and guidelines in designing future MAC schemes for 60 GHz WPANs with directional antennas.**

I. Introduction

The rapidly increasing demand for the development of high-speed WPANs is presenting new challenges in communications research area. Potential market targets a wide variety of home and office applications such as gigabit wireless peer-to-peer file transfer, high definition uncompressed video streaming and wireless data bus for HDMI and PCIe cable replacement.

The 60 GHz wireless spectrum is an ideal candidate for high-speed wireless where bandwidth requirement is crucial to meet end-user application needs. Operating at the unlicensed 57-64 GHz (millimeter-wave) bands, the 60 GHz radio is capable of supporting short range, high data rate applications with speeds of 5 Gbps or higher. The 60 GHz technology offers various advantages over existing unlicensed communications systems (e.g., 2.4 or 5 GHz) such as very high data rates and wide, largely un-congested frequency bands. Moreover, the remarkable advances in Silicon-based technologies such as Complementary Metal-Oxide-Semiconductor (CMOS) and Silicon-Germanium (SiGe) enable single chip solutions for gigahertz frequencies, which makes the 60 GHz technology more commercially interesting. The IEEE has started standardization initiatives, such as IEEE 802.15.3c [1] and IEEE 802.11ad [2], for developing millimeter-wave-based alternative physical (PHY) and MAC layers for 60 GHz radios.

The unique characteristics of 60 GHz radios, such as high propagation loss in the millimeter-wave spectrum, make 60 GHz links more fragile than those operating at lower frequencies (e.g., 2.4 or 5 GHz). Omni-directional antennas, which are commonly used in WiFi, are not suitable for 60 GHz WPANs for the following reasons. Firstly, it is difficult to achieve a high antenna gain with omni antennas to ensure a good Signal to Interference and Noise Ratio (SINR) for 60 GHz links. Secondly, interferences among adjacent links are inevitable due to omni transmissions.

Directional antenna is a natural solution to the above issues and has been considered feasible for 60 GHz radios. Based on beam switching or phase array technologies, the transmission power is focused in an intended direction, which not only mitigates the random multi-path reflections but also improves the SINR required in the intended direction significantly. Moreover, the antenna directivity enables multiple wireless links to use the same frequency and operate in close proximity without interfering with each other, while simultaneously increasing the radio range. IEEE 802.15.3c has proposed to use directional antennas at both ends of a communication link.

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The IEEE 802.15.3c is the enhanced version of the IEEE 802.15.3 MAC protocol [3]. It specifies the operation of a WPAN piconet. A piconet consists of a number of independent devices (DEVs) that communicate with each other under the coordination of a piconet coordinator (PNC), which provides basic timing, performs scheduling and manages the quality of service (QoS) of the piconet. Once a piconet is formed, all data transmissions and timing are based on superframes. As shown in Fig. 1, a superframe consists of three parts: Beacon, Contention Access Period (CAP) and Channel Time Allocation Period (CTAP). The PNC broadcasts beacons at the beginning of a superframe to all DEVs with synchronization, management and time allocation information. The CAP adopts Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for channel access and is used for command exchange and asynchronous data transfer. During the CTAP, the PNC allocates channel time to DEVs in an orderly manner, which provides contention-free access and thus can provide a certain level of QoS to DEVs. Such a Time Division Multiple Access (TDMA) based MAC protocol guarantees interference-free channel access within a piconet. However, the system throughput is still limited because the channel time is allocated mutually exclusively to the DEVs.

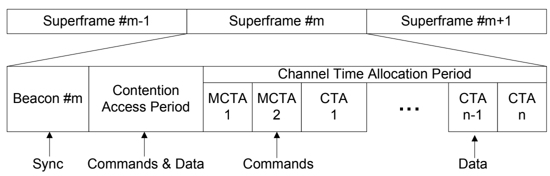

Fig. 1. Structure of an IEEE 802.15.3 superframe

Previous works have shown that spatial-reuse capabilities of directional antennas may be fully exploited when incorporating appropriately designed MAC schemes. In [4], a simulation study of the IEEE 802.15.3 MAC is presented to investigate the performance of real-time, best-effort traffic with various superframe lengths and different ACK policies. In [5], the authors study the relationship between the CAP duration and the number of contending DEVs. MAC schemes designed for directional antennas have been studied in the context of extending the IEEE 802.11 MAC protocol [6]–[9]. Unfortunately,

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most of these schemes are designed for WLANs and do not consider the unique characteristics of WPANs.

Though there are some existing works on MAC protocol design for 60 GHz WPANs [10]–[12], they mainly focus on the impact of configurable parameters (e.g., CTAP and superframe length) in 802.15.3c. To our knowledge, there has been few works addressing the potential throughput improvement with antenna directivity and refined CSMA/CA operations in the 60 GHz domain, which are studied in this paper. The main contributions of the paper are:

- We have developed a simulation framework for 60 GHz WPANs based on NS-2 [13].
- We conduct a comprehensive simulation study on the CSMA/CA performance with antenna directivity.
- We propose and evaluate two new CSMA/CA operation modes during the CAP and compare their performances with those proposed in the IEEE 802.15.3c standard draft. Simulation results may serve as guidelines in designing proper MAC protocols for 60 GHz WPANs.

The rest of the paper is organized as follows. In Section II, we present the NS-2 extension which we developed for simulating 60 GHz WPANs. In Section III, we evaluate the CSMA/CA performance with directional antennas and spatial reuse. In Section IV, we discuss and compare four CSMA/CA operation modes. The paper concludes in Section V.

II. NS-2 Extension for 60 GHz WPANs

In order to have an accurate simulation environment for investigating 60 GHz WPANs, we have developed an NS-2 (version 2.33) extension that incorporates new features such as effective SINR calculation for modeling co-channel interference, support of directional antennas, and the caching function. Our development is based on an NS-2 extension called *IEEE 802.11 Overhaul* [14] which rectifies the shortcomings in the default NS-2 MAC and PHY modules.

A. IEEE 802.15.3c HSI PHY

To simulate bi-directional, high speed communications in the 60 GHz bands, we have tuned NS-2 PHY layer parameters according to the High Speed Interface (HSI) mmWave PHY modes defined in the IEEE 802.15.3c standard draft. We also have tuned the *wireless-PhyExt* module to support 8 Modulation and Coding Schemes (MCSs) defined in the same standard draft. The timing and MCS parameters are listed in Table I.

TABLE I
IEEE 802.15.3c HSI PHY Parameters

SymbolDuration	SIFS	CCADetect	Slot	Preamble
222 ns	2.5 μs	2 μs	4.5 μs	4.47 μs

MCS	Data Rate (Mbps)	MCS	Data Rate (Mbps)
0 (CONTROL)	59	1	1416
2	2124	3	2478
4	2832	5	4248
6	4602	7	4965

B. Effective SINR Calculation

The default *wirelessPhy* module in NS-2 simply passes all the packets with power greater than the carrier sense threshold to the *mac-802.11* module, where packet collisions are handled. Such an over-simplified implementation does not consider SINR or model the interference when multiple packets arrive at the same time. Consequently, packet (or frame) reception, collision and capture are not modeled properly. The *IEEE 802.11 Overhaul* extension provides a new *wireless-PhyExt* module which supports cumulative SINR computation, preamble/PLCP header processing and frame capture. During the frame reception process, once the preamble and PLCP header of an incoming frame, say *Frame Rx*, have been received and decoded successfully, the receiver transfers to the receiving state and tracks the SINR throughout the duration of frame body reception.

However, there is a limitation in this implementation. That is, if the monitored SINR of *Frame Rx* drops below the threshold required by the MCS used for frame body transmission at any time during the receiving state, the PHY will mark the frame with an error flag and drop it as corrupted. This is not always true in practice since most wireless devices implement Forward Error Correction (FEC) techniques such as convolution, turbo and LDPC coding. These techniques improve the coding gain by adding redundancy to the transmitted information using a predetermined algorithm. This allows the receiver to lock onto the transmitter's clock even when the monitored SINR drops below the threshold. In order to model such behaviors properly, we modify the *PowerMonitor* component in the *wireless-PhyExt* module to enable effective SINR calculation. Once the reception of a frame starts, the *PowerMonitor* at the receiver monitors all other transmissions in the wireless medium and then calculates the effective SINR. For example, the effective SINR of *Frame Rx* shown in Fig. 2 can be calculated as:

$$\text{SINR} = \sum_{i}^{5} (t_i \cdot v_i) \Big/ \sum_{i}^{5} t_i. \quad (1)$$

If the calculated SINR meets the threshold required by the MCS used for frame body transmission, the receiver is considered to have "captured" *Frame Rx* successfully. Otherwise, the frame is considered "corrupted" due to interference and dropped. This extension enables us to accurately model the interference, collision and captures behaviors, especially in the congested wireless environment.

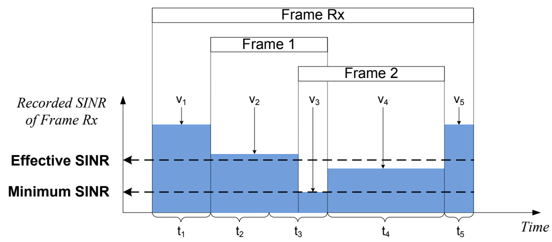
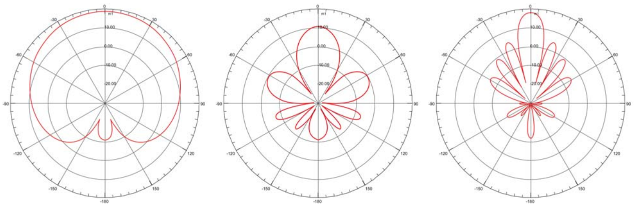


Fig. 2. An example of effective SINR calculation

C. Support of Directional Antenna and Caching Function

We have implemented a flexible directional antenna module in NS-2. In Section III, we assume that all nodes are equipped with an ideal conical-shape directional antenna. Therefore, the simulation results provide optimistic throughput evaluation, while our simulation study can be extended easily to adopt other realistic antenna models. In Section IV, we consider three realistic antenna models provided by Ansoft Corporation [15] with a beamwidth of 90, 60, 15 degree and a maximum gain of 8.6, 12.1 and 17.7 dB, respectively, which are referred to as ant-90/60/15 in the rest of the paper for simplicity. Fig. 3 plots the radiation patterns of ant-90, ant-60 and ant-15. These antenna propagation patterns enable our simulation framework



(a) ant-90 (b) ant-60 (c) ant-15

Fig. 3. The simulated antenna models with different beamwidth

to capture the behaviors of realistic directional antennas with side lobes and back lobes.

We also have developed a Sector Queue Coordinator (SQC) module between the Link Layer and Interface Queue (IFQ). When the PNC receives a packet from MAC, it forwards the packet immediately if the receiver is in the current sector. Otherwise, the packet is passed to the SQC which stores the packet in the sector queue which the receiver corresponds to.

III. Study of CSMA/CA Performance with Antenna Directivity

In this section, we present the simulation study of CSMA/CA performance with directional antennas in 60 GHz WPANs.

A. Simulation Setup

We consider typical indoor WPAN scenarios where multiple pairs of nodes are exchanging data using 60 GHz radios. All nodes are static. In our simulation, we use the *TwoRayGround* propagation model with a path loss exponent of 3.5, which is commonly used to model signal propagation in the 60 GHz Non Line-of-Sight (NLOS) indoor environment [1]. The minimum and maximum contention window sizes (CW_{min} and CW_{max}) are set according to the IEEE 802.15.3c standard draft. For the physical layer, we simulate the IEEE 802.15.3c HSI PHY with data rates up to 4.9 Gbps as described in Section II-A. For the MAC layer, we simulate CSMA/CA with all timing-related parameters adjusted based on the HSI PHY settings. Rate adaptation is disabled and the maximum transmission rate is determined by the distance between the transmitter (Tx) and the receiver (Rx).

As mentioned in Section II-C, we assume that all nodes are equipped with an ideal conical-shape directional antenna in this study. In addition, we assume that beamforming has been accomplished so that Tx and Rx antennas' main-lobe beams point to each other with a sufficient degree of accuracy before directional communications. This can be achieved by adopting Direction of Arrival (DOA) estimation or sector sweeping techniques, which is a part of future work of this study. Other simulation parameters are listed in Table II. We evaluate the system performance from three aspects:

- *System Throughput*: aggregate throughput of all flows.
- *Packet Loss*: number of packets dropped during preamble processing or frame body reception due to interference.

TABLE II

Simulation Parameters

Antenna Type	Ideal Conical	PHY	802.15.3c HSI
Beamwidth	15 degree	MAC	CSMA/CA
Main-lobe Gain	17.7 dB	CW_{min}	8
Outside Gain	-24 dB	CW_{max}	64
Tx Power	15 mW	Retry Limit	3
Path Loss Exponent	3.5	Traffic	CBR
Rate Adaptation	Disabled	Packet Length	32768 bytes

- *Capture*: number of packets that are received successfully even in the presence of interference.

B. Scenario I: Random Deployment – Varying Application-Layer Flow Rate

We first study the effects of the antenna model on the system throughput. We compare the performances of a variety of antenna combinations, which are listed in Table III. In Group 1, Tx and Rx use the same antenna combination for Data/ACK and RTS/CTS transmissions. In Group 2, Tx and Rx may use different antenna combinations for Data/ACK and RTS/CTS transmissions. Note that there are several other antenna combinations that belong to Group 2. However, according to our preliminary study, they are not practically meaningful and hence not considered in this work.

TABLE III

Antenna Combinations in the Simulation Study

Group	Mode	Data	ACK	RTS	CTS
Group 1	OO+OO	O	O	O	O
	OD+OD	O	D	O	D
	DO+DO	D	O	D	O
	DD+DD	D	D	D	D
	Note: we also evaluate the cases when RTS/CTS is disabled, i.e., OO, OD, DO, DD.				
Group 2	DD+OO	D	D	O	O
	DD+OD	D	D	O	D
	DD+DO	D	D	D	O
	OD+OO	O	D	O	O
	DO+OO	D	O	O	O
Comments	D = transmitted using a directional antenna		O = transmitted using an omni antenna		

In the simulation, we randomly deploy 9 pairs of Tx/Rx in a (25m×25m) square area. The distance between each pair varies from 0.5 to 2 meters, which allows all links to operate at the highest possible data rate (i.e., 4.9 Gbps) if no interference is present. We vary the application-layer CBR rate from 80 Mbps to 3.2 Gbps (which saturates the link considering MAC and upper-layer overheads). Each simulation run lasts for a minute. Results are averaged over 100 randomly generated scenarios and shown in Fig. 4. We have the following observations on the impact of antenna directivity on throughput:

- DO suffers the highest packet loss. This is because a directional Tx is not aware of other ongoing transmissions while an omni Rx may be interfered with by signals coming from all directions.
- OO, OO+OO and DD+OO perform well in reducing collisions and hence packet losses. However, transmitting RTS/CTS and/or Data/ACK with omni antennas sacrifices the spatial reuse and hence affects the system throughput.
- DD+DD reduces collisions effectively while minimizing the impact on other transmissions, thus yielding a relatively high system throughput.
- DD achieves the highest system throughput. Although Rx may suffer a large number of collisions, it also can capture a large number of packets in the presence of interference thanks to the high directional antenna gain.

As for the effects of using RTS/CTS in directional communications, we have the following observations:

- The effectiveness of RTS/CTS on collision avoidance varies with the antenna directivity due mainly to the deafness and hidden node problems [16].
- Since RTS/CTS are always transmitted at the low rate of 59 Mbps, noticeable impacts can be observed on the

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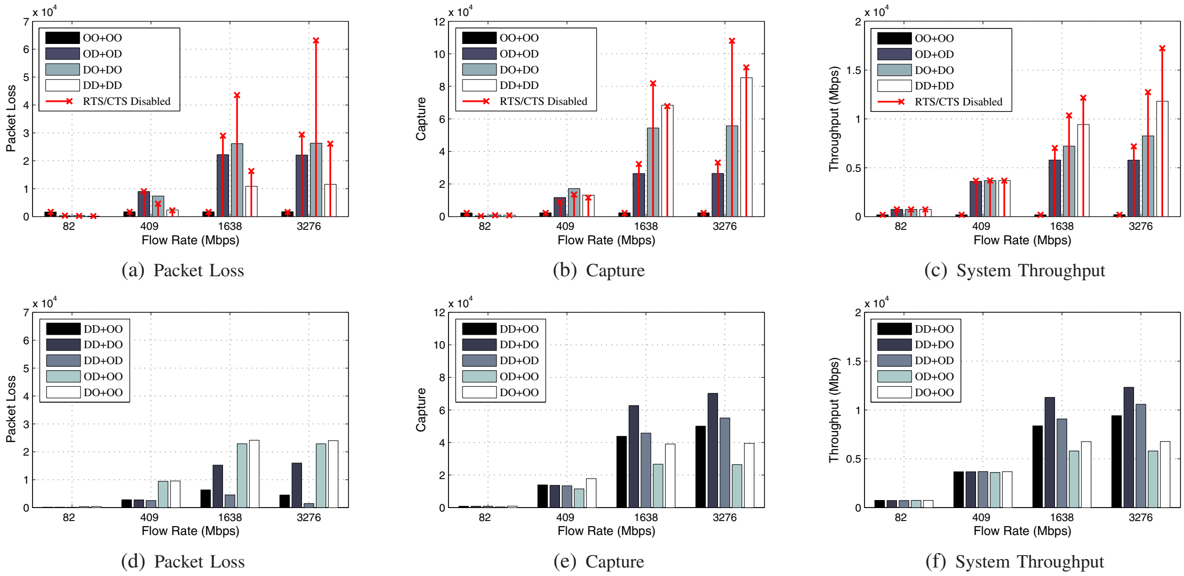


(a) Packet Loss (b) Capture (c) System Throughput

(d) Packet Loss (e) Capture (f) System Throughput

Fig. 4. Performance comparison of using different antenna combinations in a 60 GHz network

system throughput, particulary when the data transmission rate is high (e.g., 4.9 Gbps).

In general, the schemes that transmit Data/ACK packets using directional antennas yield higher system throughput, such as DD+OO, DD+DO, DD+OD, DD+DD and DD. In the following sections, we evaluate these five schemes further at other network scenarios.

C. Scenario II: Random Deployment – Varying Node Density

In this simulation, we keep the CBR rate at 3.2 Gbps and vary the number of node pairs from 6 to 18. We evaluate the system performance and the per-flow performance. Results are plotted in Fig. 5. We have the following observations:

- Although the usage of directional antenna can improve spatial reuse and system throughput effectively, the results of per-flow performance indicate that the performance gain becomes less significant with the increasing node density.
- DD and DD+DD outperform others significantly, which conform to our observations in *Scenario I*.
- When Tx/Rx both use directional antennas, DD+DO performs the best in terms of collision avoidance because a directional RTS could inform all other Rx that potentially may be interfered with, while an omni CTS could inform all other Tx that have a directional antenna pointing to this Rx. However, this does not necessarily improve the system throughput due to the lack of spatial reuse.

D. Scenario III: Chain Deployment

We simulate two cases of chain deployment as shown in Fig. 6, which represent two of the worst-case scenarios for a network that uses directional antennas. In Case 1, all 6 DEVs communicate with the PNC, while in Case 2, 6 pairs of Tx/Rx are lined up with the PNC. Adjacent nodes are 0.4 meters apart. Tx and Rx are beamformed to each other and send CBR flows at 3.2 Gbps. Throughput comparison results are shown in Fig. 7. In Case 1, all schemes that use RTS/CTS perform similarly. When DD is used, the PNC suffers more packet losses because the transmitters are not aware of other transmissions and attempt their transmissions blindly. In Case 2, DD achieves higher throughput since the receivers on the left (e.g., R1) could "capture" the packets in the presence of interference from Tx(s) on the right (e.g., T6). As a result, multiple directional communications may take place simultaneously and hence a higher system throughput may be achieved. The schemes that use RTS/CTS yield much lower system throughput because it is almost impossible to support multiple simultaneous communications under a chain deployment when RTS/CTS are used to reserve the medium.

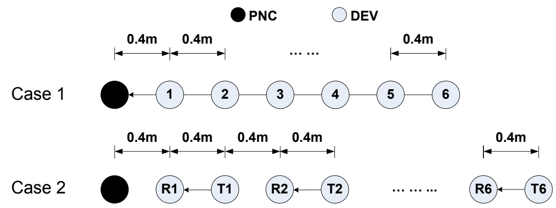
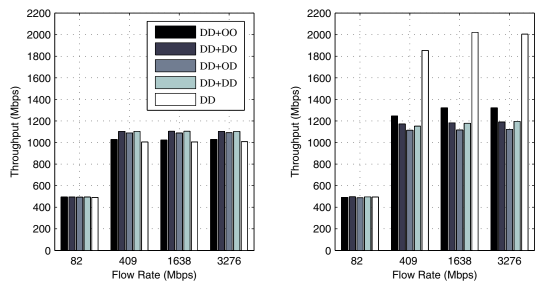


Fig. 6. Two cases of chain deployment



(a) Case 1 (b) Case 2

Fig. 7. Throughput comparison under chain deployment

E. Summary

We summarize the key conclusions from the above simulation study as follows:

- In general, using directional antennas improves the spatial reuse effectively and hence the system throughput.
- In random deployment scenarios, DD achieves the highest throughput thanks to high directional antenna gains and packet captures.

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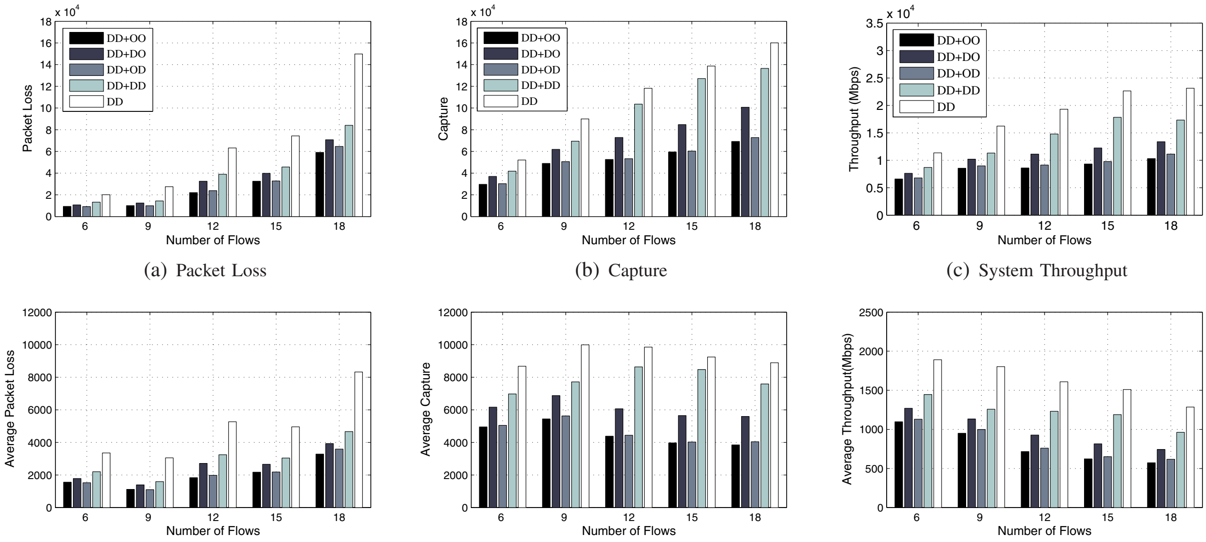

(a) Packet Loss (b) Capture (c) System Throughput

(d) Per-flow Packet Loss (e) Per-flow Capture (f) Per-flow Throughput

Fig. 5. Performance comparison with different node densities in a 60 GHz network

- If energy conservation is a critical concern, DD+DO may be a reasonable option since it reduces collisions effectively while maintaining a reasonably high throughput.
- DD+DD may be a good option if both system throughput and energy conservation are concerned.

So far, we have studied the CSMA/CA performance with various antenna combinations in 60 GHz WPANs. In the next section, we will investigate different CSMA/CA operation modes during the CAP.

IV. Study of CSMA/CA Operation Modes in CAP

The simulation study in Section III helps understand the potential throughput improvement in 60 GHz WPANs with directional antennas. In practice, the WPAN performance is affected by many other factors, among which the CSMA/CA operation mode during the CAP is a critical one. In this section, we study four different CSMA/CA operation modes and compare their performances in terms of system throughput, power consumption and implementation complexity.

A. CSMA/CA Operation Modes

The four CSMA/CA operation modes in the simulation study are summarized in Table IV. Mode 1 is proposed in the IEEE 802.15.3c standard draft, where CSMA/CA is used during the CAP to communicate commands and asynchronous data. A DEV sends a special RTS packet to the PNC with the intended destination specified in target address. The PNC responds with special CTS packet(s) indicating a preparatory call to the intended destination. Tx and Rx communicate with each other directly after beamforming. This mode requires that the PNC is always on which may be costly for battery-powered PNCs when the wireless medium is serving excessive bursty traffic. Moreover, simultaneous communications are not possible due to the omni antenna at the PNC, and hence the system throughput is limited in this mode. Mode 2 is the same as Mode 1 except that the PNC is equipped with a directional antenna and sector sweeping is required for the PNC to communicate with DEVs. In general, sector sweeping is energy consuming and incurs extra delay.

We propose Mode 3 and Mode 4 as follows. Mode 3 is proposed for DEVs which are not capable of sector sweeping. In this mode, DEVs simply beamform to the PNC, which uses a directional antenna to sweep all sectors continuously and is responsible for relaying all the data packets. The PNC is capable of data caching if a data packet is received but Rx is not in the current sector. The caching function is implemented using the SQC as discussed in Section II-C.

Mode 4 is proposed to allow simultaneous communications in the piconet. The PNC uses ant-90 to announce the CAP to "activate" each sector periodically. DEVs in an active sector perform sector sweeping and communicate with their destinations directly upon successful exchange of RTS/CTS. DEVs in an inactive sector use ant-90 to point to the active sector and keep listening till the beginning of their assigned CAP. Once RTS/CTS have been exchanged successfully, Tx and Rx beamform to each other using ant-15 and start data transmissions for a during of TxOP. After that, Tx resumes sector sweeping and Rx resumes listening. In this mode, DEVs do not rely on the PNC for exchanging RTS/CTS and hence the PNC does not have to be always on. A limitation of this mode is that DEVs in the active sector have to sweep and monitor all the directions continuously.

B. Performance Evaluation

1) Simulation Setup: In this simulation, we use the same PHY and MAC layer settings as in Section III. In addition, we have implemented sector sweeping and abstracted beamforming functionalities in the *mac-802.11Ext* module to simulate the antenna behaviors at the PNC and DEVs. We simulate a piconet consisting of a PNC at the center and m DEVs evenly distributed in the n (= 4) sectors surrounding the PNC. Based on our observations in Section III, we set the PNC and DEVs to operate DD+DO in Mode 1 and DD+DD in Modes 2, 3 and 4. We assume that all DEVs are beamformed to the PNC using ant-15 at the beginning of the simulation. Other simulation parameters are listed in Table V.

2) Simulation Results: We simulate two different scenarios: *Scenario 1* with 8 DEVs and 24 CBR flows, and *Scenario 2* with 16 DEVs and 64 CBR flows. Results are shown in

TABLE IV
FOUR CSMA/CA OPERATION MODES IN THE SIMULATION STUDY

Mode	For Control Packet Exchanges		For Data Transmissions			
	PNC Antenna	DEV Antenna	Traffic	Tx/Rx Beamforming	Node Position Information	Multiple Transmissions
1	omni	ant-15 to PNC	directly between communicating PNC/DEVs	required	required	no
2	sector-sweeping using ant-90/60/15	ant-15 to PNC	directly between communicating PNC/DEVs	required	required	no
3	sector-sweeping using ant-90/60/15	ant-15 to PNC	relayed through PNC	not required	required	no
4	sector-sweeping using ant-90	sector-sweeping using ant-90/60/15	directly between communicating PNC/DEVs	required	not required	possible

TABLE V
SIMULATION PARAMETERS

CAP	4 ms	TxOP	500 μs
Sweep Interval	60 μs	PCP buffer	3276800 bytes
Scenario 1	8 DEV, 24 CBR	Scenario 2	16 DEV, 64 CBR

Table VI. As expected, with Mode 1, 2 or 3, the system throughput is low since none of them supports simultaneous communications. Mode 3 yields a slightly higher throughput than Modes 1 and 2 due mainly to less contention in each sector. Moreover, in Modes 2 and 3 where the PNC uses a directional antenna, the beamwidth has a noticeable impact on the system throughput, particularly when the node density is low. This is because the PNC has to sweep all sectors even if some of them do not have any intended Tx or Rx.

By allowing multiple DEVs in the active sector to communicate simultaneously, Mode 4 with ant-90 yields a throughput that is more than 55% higher than Mode 1 in *Scenario 1*. The difference becomes more significant in *Scenario 2* since the numbers of nodes and CBR flows increase. It should be noted that the performance gain is achieved at the expense of continuous sector sweeping of all DEVs in the active sector. In general, the usage of an antenna with a larger beamwidth may sacrifice the spatial reuse. On the other hand, it may reduce the discovery time between Tx and Rx. So there is a tradeoff. In our simulation setup, it seems more beneficial by using an antenna with a larger beamwidth (i.e., ant-90 outperforms ant-60 and ant-15), although antennas with smaller beamwidth may be preferred in other network scenarios.

C. Summary

Based on the above simulation study, we conclude that Mode 4 is a more plausible solution for throughput improvement than other modes because it allows simultaneous communications. In addition, we can see that Mode 3 yields comparable system throughput as Modes 1 and 2 and may be a good option for DEVs that are not capable of sector sweeping.

TABLE VI
PERFORMANCE COMPARISON OF CSMA/CA OPERATION MODES

Mode	Antenna Model		Aggregate Throughput (Mbps)	
	PNC	DEV	Scenario 1	Scenario 2
1	omni	ant-15	2083	2286
2	ant-90	ant-15	1879	2363
	ant-60		1690	2021
	ant-15		1378	1863
3	ant-90	ant-15	2130	2549
	ant-60		1371	2138
	ant-15		672	1362
4	ant-90	ant-90	3229	3860
		ant-60	2560	3174
		ant-15	1902	2899

V. CONCLUSIONS AND FUTURE WORKS

In this work, we conduct a comprehensive simulation study of CSMA/CA performance in 60 GHz WPANs. It consists of two parts: study of CSMA/CA performance with antenna directivity and study of CSMA/CA operation modes during the CAP. To facilitate these studies, we developed an NS-2 extension for simulating 60 GHz WPANs. Results from the first part of the study suggest that using directional antennas improves the spatial reuse and hence the system throughput in general. In the second part of the study, we propose two new operation modes for CSMA/CA and compare them with those proposed in the IEEE 802.15.3c standard draft. Results indicate that a properly-designed CSMA/CA operation mode may improve the system throughput significantly. Future works include the design of an efficient beamforming scheme for neighbor discovery using directional antennas and the design of an enhanced CSMS/CA for 60 GHz WPANs.

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