Robust 60 GHz Indoor Connectivity with Cooperative Access Points

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***Abstract*— the 60 GHz frequency band achieves very high data rate (in the order of Gb/s) since it has 7-9 GHz unlicensed bandwidth. However, high free-space path loss and penetration loss necessitate use of steerable directional antennas to overcome these losses by additional antenna gain. The directional nature of 60 GHz links makes them sensitive to misalignment that can cause by nodal movement. In this paper, we propose and evaluate a novel method for improving the connectivity of indoor 60 GHz links. The key idea is to allocate multiple coordinated Access Points (AP) for each transmission in downlink. Since these APs are widely spaced in the environment and transmit simultaneously, the link remains stable by the translational or rotational movement of the client or obstacles. There are many challenges related to this method that need to be addressed. The exhaustive research protocol for discovering the best "sector" for a pair of nodes require more time with increasing the number of APs. This large amount of overhead time may affect the throughput significantly. Having more transmitters is not sufficient enough since there are other parameters like beamwidth that affect the link robustness. We built a Matlab simulator to evaluate the performance of our proposed method and compare it with normal point to point data transmission as defined in IEEE 802.11ad standard. Our simulation results show that by having three APs transmitting concurrently to a mobile client whose antenna beamwidth is 90°, packet delivery ratio is 99% while in a similar situation with one AP this ratio is 61%.**

Keywords— 60 GHz, wireless network, mm-wave communication, Mobility, Connectivity, Indoor.

I. INTRODUCTION

The next generation of wireless technologies will apply millimeter-wave (mm-wave) spectrum for providing multi gigabit data rate since it has large amount of unlicensed bandwidth (from 57 up to 64 GHz). The free-space path loss in 60 GHz frequency band is more than 20 dB greater than legacy bands. Furthermore, the small wavelength (5 mm) results in high penetration attenuation through the most solid materials in an indoor environment. Therefore, the poor link budget in 60 GHz spectrum necessitate the use of electronically steerable antennas arrays. In directional transmission, the antenna gain in the transmitter (TX) and the receiver (RX) compensate the aforementioned losses and improve the range of the transmission. Therefore, links in 60 GHz band are highly directional and require alignments of antennas at both TX and RX for their establishment. As defined in IEEE 802.11ad standard [8, 9], Beam Forming Training (BFT) procedure has to be done in order to establish a link between a pair of nodes. Figure 1 shows details of this procedure. At the end of BFT, both nodes know the direction or virtual sector which is the best for data transmission.

The link between two nodes is highly vulnerable to mobility and blockage as reasons of misalignment. Having robust 60 GHz connectivity is our ultimate goal because link failure significantly affects the performance of the system.

In this paper, we suggest a novel solution for improving connectivity in 60 GHz networks using coordinated APs. The key idea is to use multiple APs transmit to a single client simultaneously. These APs are spatially separated from each other and compromise movement resilience for the users. Many questions required to be answered:

- How APs coordinate with each other?
- How many APs are needed?
- How to choose a group of APs for a particular transmission?
- What is the effect of client's beamwidth on link robustness?
- What is the effect AP's beamwidth on the link's robustness?

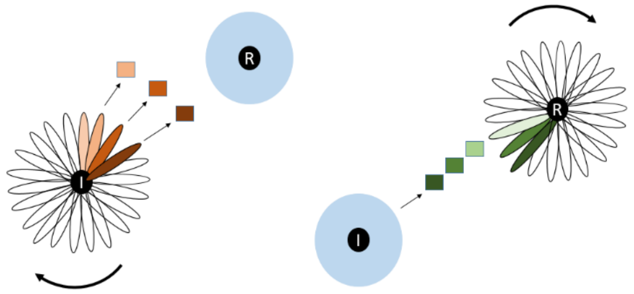

Figure 1. A pair of nodes discover the best sector to transmit to each other via a procedure called sector level sweep. The initiator and responder can do either transmit sector sweep or receive sector sweep. In this phase one of the nodes transmits/receives directionally and the other one has the pseudo-omni pattern.

- How overhead time will increase and how this time affects total throughput?

These issues are well studied in this paper. It is worth mentioning that we will focus on indoor environment here because there we have more NON-Line-Of-Sight (NLOS) components due to reflections. Measurements show that the strongest NLOS components are at least 10 dB below the Line-Of-Sight (LOS) one [1]; however, in [2] authors claimed that NLOS components in 60 GHz are able to overcome the blockage due to walls and cubicles although their coverage range is much lower relative to LOS scenarios.

The remainder of this paper is organized as follows: related works are described in Section 2. Our proposed system model is presented in Section 3. We explained the details of our Matlab Simulator and important simulation parameters in the fourth section. Then, we analyze the performance of our suggested method by introducing different metrics in Section 5. Last section is dedicated to conclusion.

II. Prior Work

Previous related works can be classified into three categories.

A. Multi-hop communication via relaying nodes

A solution to preserve 60 GHz connectivity in case of blockage is multihop communication via relaying nodes. Relaying has been well studied in the literature like [4] and [5]. To determine which node(s) should act as relaying node for specific transmission, the AP needs to have a network map of all existing stations [5] Therefore, all stations including AP have to build a network map by sector sweeping and sending a "Hello" message to other nodes. Based on the received ACKs, each station builds its own network map and transmits the information to AP as well. This procedure must be repeated after a singular movement; therefore, a very high overhead time is needed to build this network map and keep it updated. This large amount of overhead time will decrease the throughput terrifically since this protocol cannot be used in the mobile networks.

B. Radio-over-Fiber based architecture for seamless wireless communication

In RoF systems, wireless signals are transported via a fiber link between base stations before being radiated through the air. Using RoF based architecture to have a seamless communication for in-building networks have been studied in literature [10], [11], [12] and [13]. For example in [10], authors assumed that each room and corridor of a building is covered with one AP. Then they proposed the concept of Extended Cells (EC). They claimed that they can reduce the number of essential handovers and overcome the shadowing effects to ensure a seamless communication. The prior work in this area does not address the directional nature of 60 GHz, blockage, reflection and rotational movement. In another word, there is an assumption that in each cell, there is always a LOS link between AP and the client.

C. Sensor assisted movement identification

Another related work in this area is [3] in which authors claim that the reason of link degradation can be found by using sensors like accelerometers and gyroscopes. Based on the sensor information they predicted the next beam-pair so that link quality remains stable with the goal of minimizing number of re-beamforming. There are serious issues with this paper, first of all it does not address the case when there is no LOS path between TX and Rx. Second, the methods explained in the paper can predict a linear forward movement so if the RX turns around their protocol fails.

III. System Model

We consider a wireless network consists of multiple APs connected to each other via a fiber link.

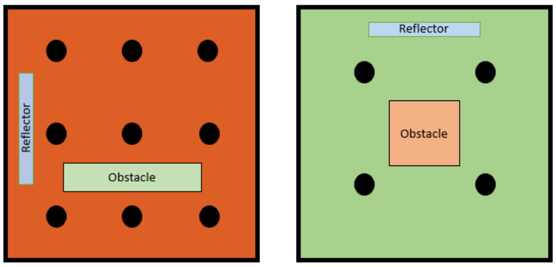

Figure 2. Two sample indoor environment with 9 and 4 APs respectively.

In figure 2, two sample scenarios have been depicted where you can find an environment with one absorber, one reflector and 4 or 9 APs respectively. The room is surrounded with four walls. We assume that all the APs are fixed but all the clients, obstacles and reflectors are capable of translational and rotational movement. In this paper we are focusing on the downlink data transmission.

The APs can be synchronized through the fiber link in the time order of Nano second. In fact, they operate as a large distributed multi-antenna AP [6]. Furthermore; all APs have one RF chain meaning that they can only transmit in one direction at each moment.

Directional transmission makes the opportunity of channel reusing meaning that in an infrastructure network, multiple APs can transmit simultaneously to their desired clients without any spatial interference. On the other side, directional nature of 60 GHz spectrum induces deafness whereby neighboring nodes are hidden from each other due to differences in the orientation of their directional antenna beams. In general, we categorize the major causes of channel degradation into two groups. First, sector misalignment due to nodal mobility and second, blockage by mobile obstacles [3]. Details can be found in figure 3.

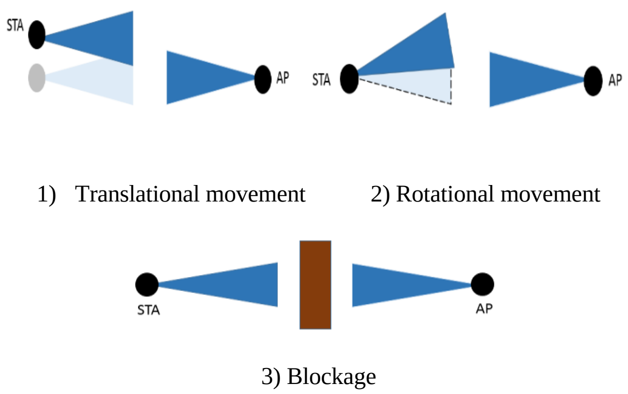

Figure 3. Major causes of link degradation

A. Amendment to IEEE 802.11ad beamforming

As described in the introduction, electronically steerable antenna arrays are used to compensate the extra losses of 60 GHz band. A procedure called BFT is used to determine the appropriate antenna sectors for a pair of stations. BFT consists of two phases: 1- Sector Level Sweep (SLS), 2-Beam Refinement Phase (BRP).

Figure 4 shows an example of BFT procedure. All nodes keep sensing the channel in pseudo-omni mode until receiving Request to Send (RTS) or data packet. The STA which initiates the beamforming (BF) by transmitting a BF frame is called initiator and another STA is called responder. During a SLS, the initiator switches across all sectors and transmits BF frames while the responder receives with a quasi-omnidirectional pattern. Then, the responder sends frames from each sector containing the information of the initiator's best sector ID.

The SLS phase can be followed by BRP based on the STAs' request. The sectors found in the SLS may be sub-optimal since one of the STAs have quasi-omni pattern. The BRP refines the sectors determined in SLS phase. It means that after the BRP the sectors are tuned in order to receive the highest energy at the middle of the sector.

We use the same basic concepts for beamforming; however, we have to adjust them so that these procedures can be used in multi-AP scenario.

In the sector level sweep phase, all the APs send the BF frames first. Each frame has the information of AP ID and sector ID. Then the responder sends frames consist of information about which APs have been selected for the further data transmission. The frames also contain the sector ID of the selected APs.

In the beam refinement phase, the sector will not be adjusted to strongest beam anymore. The new BRP refines the sectors by considering all received beams. This amendment provides us with better rotation resilience.

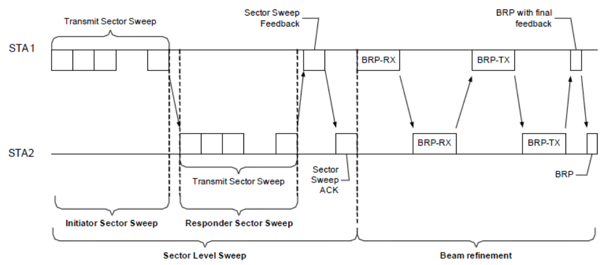

Figure 4. Beamforming Training (BFT) procedure

B. Design Parameters

According to IEEE 802.11 ad standard, the maximum possible number of sectors is 128. Therefore, the minimum beamwidth would be 3 degrees. Narrower beamwidth at the TX or RX improve the antenna gain and the link budget in general.

An approximation for calculating the directivity gain as a functional horizontal beamwidth θ°_{HP} and vertical beamwidth ϕ°_{HP} is:

$$D \cong 10 \times \log_{10} \frac{32400}{\theta^{\circ}_{HP}\phi^{\circ}_{HP}} \qquad \text{dBi} \qquad (1)$$

Link budget is calculated based on (2) in which P_{Tx} is the transmit power, $PL(d)$ is the path loss at the distance of d and M is the order of reflections. We consider reflections up to the order of three. The beamwidth used at the TX and RX is θ°_{Tx} and θ°_{Rx} respectively and ϕ°_{vert} is the vertical beamwidth which is fixed to 60° in our simulations.

$$LB = 10\log\frac{32400}{\theta^{\circ}_{Tx}\phi^{\circ}_{vert}} + 10\log\frac{32400}{\theta^{\circ}_{Rx}\phi^{\circ}_{vert}} + P_{Tx} - PL(d) - \sum_{i=1}^{M} loss\ (obstacle\ i) \quad dBm \qquad (2)$$

Path loss can be calculated as follows:

$$PL(d) = PL(d_0) + 10n\log_{10}(d) \qquad (3)$$

For the LOS link *n=2* and $PL(d_0) = 68\ dB$ and for the NLOS *n=4* and $PL(d_0) = 80\ dB$.

Therefore, narrower beamwidth at the TX and RX, provide higher link budget and data rates. However, narrower beamwidth require more time for the beamforming training.

Considering the 802.11ad timing values, the length of a BFT slot can be calculated as (4).

$$BFT_{time} = (\frac{13320}{\theta_{Tx}} + \frac{13320}{\theta_{Rx}} + 145.31)\ \mu s \qquad (4)$$

Where θ_{Tx} and θ_{Rx} are the beamwidth of transmitter and receiver respectively.

It is worth mentioning that the time calculated in (4) is the time needed for beamforming training between two STAs; however, in our amendment we can estimated the time for our modified BFT to be n times greater than calculated BFT_{time} where n is the number of APs that are active for a particular transmission and participate in SLS.

Equation (4) indicates that BFT time changes with beamwidth drastically. For example by choosing the TX and RX beamwidth to be 3° the exhaustive research requires *9 ms* while the maximum data transmission time in 802.11 ad is *2 ms*. This amount of overhead time can reduce the total throughput of the network significantly. In the section 5, we investigate the effect of beamwidth as well as number of APs on the throughput.

Moreover, narrower beamwidth is more susceptible to misalignment and link breakage due to small motion of either the TX or RX.

There is a wide aperture transmission for a single user since multiple APs which are widely spaced transmit to a particular RX. Therefore, the wider the RX beamwidth, the more APs may catch the RX. Therefore, the probability that at least one AP can establish a link with a mobile client will increase by the wider beamwidth. So there is a tradeoff between received Signal to Noise Ratio (SNR) and movement resilience. Figure 5 shows this fact.

We simulate the effect of the beamwidth on SNR and movement resilient with our Matlab Simulator which is described in the next section.

C. Method Description

When there is packet to be send to a particular RX, all free APs participate in modified BFT procedure as in section A. RX sends back acknowledgement to the *m* best APs which have the maximum received signal strength. And those *m* APs start sending data simultaneously to the RX. The question that how the amount of *m* influence the link quality is answered in performance evaluation part.

Moreover, simulation results show that using signal strength factor to simply choose the APs is good enough that it does not worth to spend more overhead time to find a group of APs per each transmission. In fact, by this method we only use the information attained in the BFT.

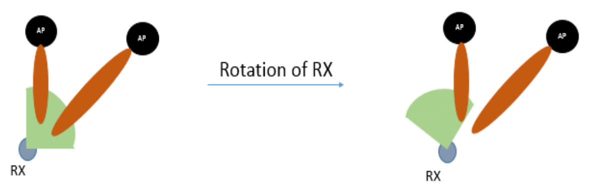

Figure 5. The wider beam is resilient to mobility since more APs reach the Rx with wider beamwidth.

IV. MATLAB SIMULATOR

We built a Matlab simulator for modeling the transmission in 60 GHz networks. We used 2D ray tracing technique and considered up to third-order reflected path components. In the simple case there is one reflector and one obstacle in a rectangular shape room with four walls as depicted in figure 2. The reflection losses are matched with 802.11ad measurement study [7]. The locations of APs are fixed as well as their configurations. All APs and users are assumed to have one RF chain so they only can transmit toward one direction in a time.

By assuming bandwidth to be 1.7 GHz the noise power can be calculated as follows:

$$N[dB] = 10 \log 4KTB \cong -105\ dB \qquad (5)$$

Where K is Boltzmann's constant and equals to $4.138 \times 10^{-23} J/_K$, T is temperature in Kelvin and B is bandwidth.

Table 1 shows some parameters that have been used in our simulations.

Simulation Parameter	Value
Environment Dimensions	6*6
Vertical Beamwidth	60 degree
Transmission Power	0 dB
Noise Figure	7 dB
Max. transmit slot	2 *ms*
Beacon Interval	100 *ms*
Max. translational velocity	1 m/s
Max. rotational velocity	10pi rad/s
Number of APs	1-9

Table 1. Important Simulation Parameters

Our simulator models object with rectangles of arbitrary length and width which are capable of translational and rotational movement.

V. PERFORMANCE EVALUATION

In this section, we investigate the effect of beamwidth and number of APs per transmission on the received SNR and link robustness. In order to have a through comprehension of the existing tradeoffs and see the effect of all impressive factors, we evaluate the performance of our network with different simulation metrics.

A. SNR Experiments

In this subsection, we aim to analyze how beamwidth of either AP or user can change the SNR in the receiver. As mentioned previously, wider beamwidth decrease the antenna gain and link budget of the signal, but more APs can cover the client.

We set 9 APs uniformly distributed over the environment (see figure 2) and fixed the AP's beamwidth to 10 degrees. We chose the location and dimensions of reflector and absorber randomly. Also we chose the location and orientation of the client randomly.

The beamwidth at the client changes from 5° to180°. To show how number of transmitters influence on the SNR, we consider three scenarios in which after completing modified BFT, the client sends ACK to the best AP (among 9), three best APs and all APs. By best AP, we mean the AP that provide best signal power at the receiver. Figure 6 shows the result of the simulation.

From this figure, we can conclude that as long as only one AP transmits, the SNR is decreasing by incrementing the RX beamwidth. Therefore, when the SNR concerns and there is only one active AP for transmitting, it is reasonable to have the minimum possible beamwidth in the RX.

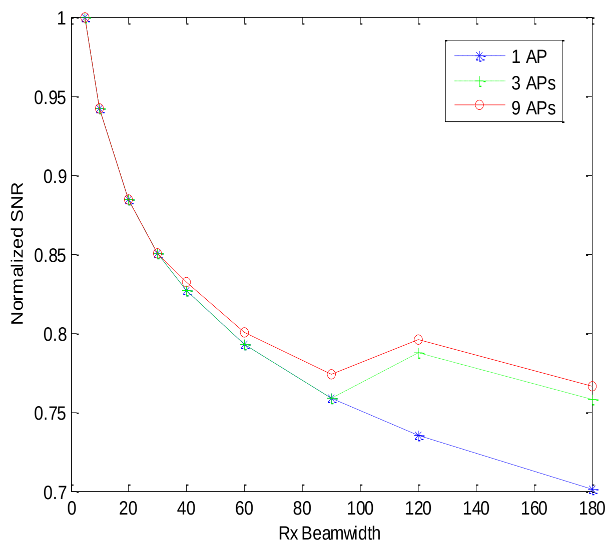

Figure 6. Normalized SNR versus Rx beamwidth when one, three and nine APs transmit to a single user simultaneously.

In addition, comparing red and blue curve when RX beamwidth is between 5 and 90 degrees proves that the effect of NLOS components is not significant in received signal power. In general, by increasing the Rx beamwidth, the SNR decrease until the beam becomes wide enough (120° here) that is capable of capturing another LOS component from another AP transmitting.

The comparison between green and red curve reveals that, improving the number of transmitter from 3 to 9 has not great impact on SNR. The reason is that, APs located uniformly in the environment and there is huge amount of free-space path loss, so signal releasing from farther APs have low signal power (almost below the threshold which is -78 dBm) when hitting the RX even if they have LOS link and are within the RX selected sector.

Next, we consider one AP in the middle of the 2D model of the room. We fixed the receiver beamwidth while changing the AP's beamwidth from 4° to 180°. Again the location and dimensions of obstacles as well as the location of the client are chosen randomly. Figure 7 is the outcome of the simulation.

When AP has wider beam, the chance of multiple separate NLOS and LOS rays hitting the Rx increases. On the other side, the link budget of the signals is reduced due to lower antenna gain. Figure 7 shows that the decrease of link budget overweight the signal power carried by additional rays. Therefore, the normalized SNR is reduced by extending the beam.

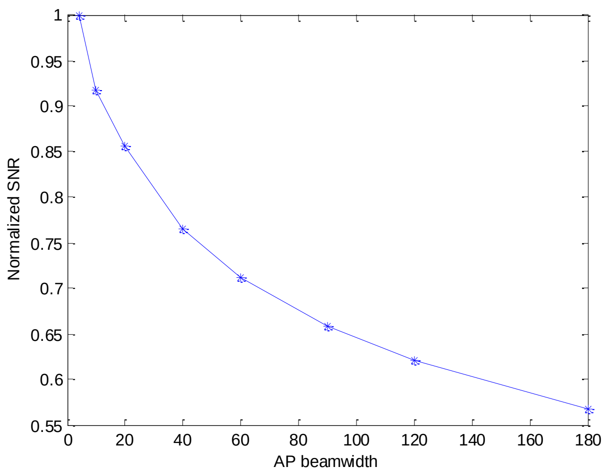

Figure 7. Normalized SNR versus AP beamwidth.

To conclude, as long as there is no goal of multicasting in 60 GHz networks in which one AP covers multiple clients concurrently, it is better to have minimum possible beamwidth for the AP.

B. Nodal Mobility Experiments

60 GHz links are susceptible to link breakage due to misalignment of TX and RX sectors. This misalignment results from nodal mobility. In this section, we study the performance of coordinated APs in mobile networks. Another factor that is expected to influence the link resilience is beamwidth of the RX (see figure 5). In this section, we study this factor as well.

Here like previous section, the transmitters are fixed. In order to have fairness, the locations of reflector and absorber are chosen randomly but remain stationary in the whole scenarios.

First, we set an AP in the middle of the environment, choose a random location an orientation for the receiver. We find the SNR after beamforming training. If this amount be above the threshold meaning that a link is established between two nodes, the data transmission starts. Then client has random rotational and translational movements that may lead to misalignment. We find the SNR after the data transmission time. If the SNR is still above the threshold, we count this packet as a successfully received packet; otherwise, we assume this packet as a lost packet and start BFT procedure again. In order to study the effect of beamwidth at the receiver we select different values for RX beamwidth and per each value repeat the abovementioned process for 100 packets to find the data delivery ratio.

Then we change the number of APs to nine. To see how multi-AP scenario improve the link robustness, we repeat the simulation in order to find data delivery ratio for 3 cases when a group consists of 3, 6 and all 9 APs transmit simultaneously. Figure 8 shows the data delivery ratio vs. beamwidth for different scenarios.

From this figure we observe that as expected in all cases the data delivery ratio improves as beamwidth at receiver antenna increases.

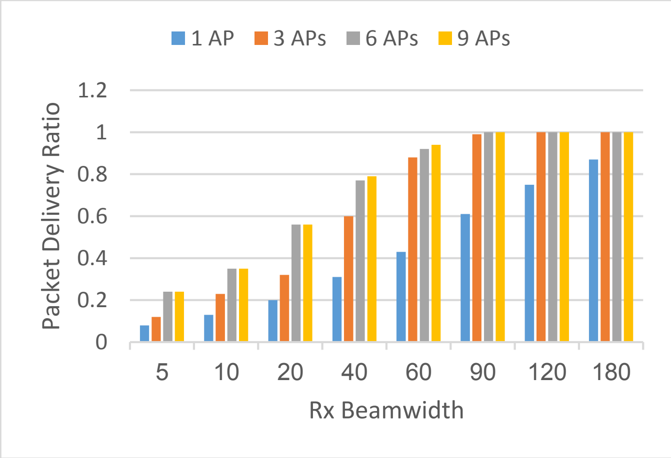

Figure 8. Packet Delivery Ratio vs. Rx beamwidth for multi- AP scenarios as well as single AP scenario.

The considerable point is that concurrent transmission of three APs improve the packet delivery ratio by 45 %, 38%, 25% and 13% when the receiver's beamwidth is 60, 90, 120 and 180 degrees respectively.

Furthermore, based on figure 8, increasing number of selected APs from 3 to 6 and 9 does not have a serious impact on link robustness. So, it is better that we allocate only three APs for each transmission and use others to serve another client simultaneously in a multi-user scenario. The negligible difference between data delivery ratio when using 3 APs or 9 APs proves that the method we suggested in Section 3.C for AP selection is pretty good and simple that it does not worth to use any other complex and time consuming methods for AP selection.

C. Throughput Experiment

We have explained in our system model that there is an inverse relationship between beamwidth and BFT time (see equation 4). Moreover, we mentioned that the approximate time for modified BFT in coordinated APs scenario is n times greater than BFT_{time} as in equation (4) where n is the number of APs participate in SLS phase.

To understand the effect of this overhead time on throughput, we need to explain some MAC Layer specifications as defined in 802.11ad. Channel time is divided into Beacon Intervals (BI), with a structure that is depicted in Figure 9. Each BI has intervals for beacon frame transmission, BF and data transmission. The Data Transmission Interval (DTI) is divided into n slots and supports both random access and scheduled access.

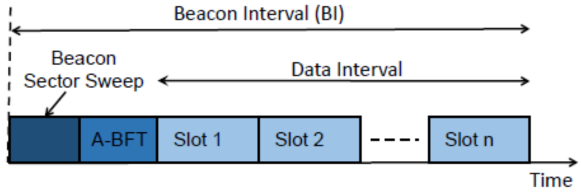

Figure 9. Structure of Beacon Interval as defined in 802.11ad.

In general, there is two strategies for data transmission in DTI. First strategy is to BFT once and keep sending data till *k* packet losses. Then for reestablishing the link another BFT is needed. Second strategy is to do training before each transmission. It is obvious that the overhead time in the first one is lower but the loss of retransmitting the lost packets may overcome the throughput gains due to lower overhead time.

We use the first strategy for data transmission with *k* equals to 1 since the large amount of overhead time is needed to establish a link in coordinated multi-AP scenario. Besides, figure 8 proves that the probability of link breakage within one packet transmission time (which is max. 2 *ms*) is small.

Using simple timeline analysis and renewal reward theorem, the throughput for given Rx beamwidth θ_i is as follows:

$$\eta(\theta_i) = \frac{(1-P_{break}(\theta_i))*(t_{trans})}{(1-P_{break}(\theta_i))*(t_{trans})+P_{break}(\theta_i)*(t_{M-BFT})} \quad (6)$$

Where t_{trans} is the transmission time, t_{M-BFT} is time needed for modified BFT and $P_{break}(\theta_i)$ is the probability of link breakage when the beamwidth at receiver is θ_i.

It is worth mentioning that when there is only one AP to transmit, the modified BFT and normal BFT act the same.

When three best cooperative APs transmit simultaneously, the link is more robust and the probability of link breakage is lower. Therefore, the frequency of beamforming training is lower. But on the other hand the time needed for BFT is almost nine times of the single AP scenario. To study this tradeoff, we simulate the throughput for different RX beamwidth values. Figure 10 shows the result.

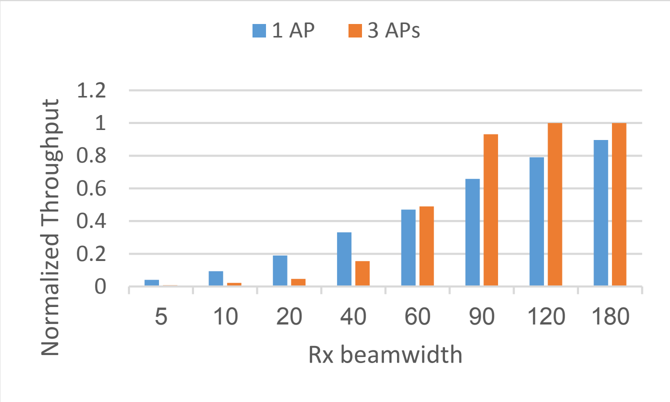

Figure 10. Normalized throughput vs. Rx beamwidth in two scenarios. First, when there is only one AP in the room and second when a group of three APs have been selected among nine existing APs in the environment.

As depicted in figure 10, for the narrower beams, the link is more susceptible to breakage; therefore, beamforming training is more frequent. Since modified BFT procedure is more time consuming when there is multiple APs in the environment, the overhead time for the second scenario is much greater than the first one. This huge overhead time decrease the throughput drastically; therefore, as figure 10 shows, the throughput of the first scenario is greater than coordinated multi-AP transmission case for the narrower beams.

For the wider beams, multi-AP scenario provides more robustness, so in a fully backlogged network several packets are received successfully before a link breakage. This large amount of data transmission with one BFT results in higher throughput by 28%, 21% and 11% when the beamwidth is 90˚, 120˚ and 180˚ respectively.

VI. CONCLUSION

We have proposed a novel method for building robust links in 60 GHz systems. Since the directional nature of the 60 GHz, the link which is established during BFT procedure is susceptible to breakage due to nodal mobility. The key idea is allocating multiple coordinated APs for each transmission. As explained in the paper, the beamwidth selection for the RX antenna plays an important role in link robustness as well.

For each downlink data transmission, a group of three best APs which are coordinated with each other via a fiber link and have been selected during a procedure called modified beamforming training, transmit simultaneously to a single client and provide movement resilience for the user. For the receiver to be capable of capturing the selected APs, it requires to have the sector beamwidth of 90˚ in most cases. The simulation results prove by applying this method for data transmission, both data delivery ratio and throughput of the network will be improved significantly in comparison to single AP-STA transmission method defined in the 802.11ad standard.

VII. FUTURE WORK

In this paper we only considered the downlink transmission; however, the nature of uplink is completely differs from downlink and requires separate investigation. In the uplink scenario, the transmission is not wide aperture anymore. As the beamwidth of the client increases, the transmitted data will be received by more than one AP which gives us resilience; however, the link budget of transmitted signal is reduced due to lower antenna gain. In the future, we are going to study the movement resilience for uplink transmission. In this paper we mentioned that it is possible to have multiple groups of APs transmitting to different clients simultaneously but we did not talk about the details. In future, we are going to design a protocol for multiple concurrent transmissions of groups of APs and consider both downlink and uplink data transmissions.

VIII. ACKNOWLEDGMENT

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