Exploiting Unique Polarisation Characteristics at 60 GHz for Fast Beamforming High Throughput MIMO WLAN Systems

Djamal E. Berraki, Simon M. D. Armour and Andrew R. Nix

Communication Systems & Networks, University of Bristol
Merchants Ventures Building, Woodland Road, BS8 1TJ, Bristol UK

Email: {d.berraki, simon.armour, andy.nix}@bris.ac.uk

Abstract— **A 2x2 60 GHz MIMO solution combined with polarisation diversity is proposed for high throughput WLAN applications. In addition to a PHY throughput of more than 12 Gbps, this scheme is robust against polarisation mismatch and antenna tilting due to the adoption of circular polarisation. It also offers the possibility to detect LOS/NLOS conditions for antenna adaptation. A fast beamforming ability that exploits the MIMO architecture is presented. Results show that the proposed beam switching procedure outperforms existing prior art schemes in terms of its ability to track a time varying channel.**

Keywords **—60 GHz, circular polarised antennas, MIMO, Polarisation diversity, beamforming**

I. Introduction

The 60 GHz millimetre-wave band is a perfect candidate for short-range Gbps wireless communications. IEEE 802.11ad is widely seen as the most developed standard in this area, offering link speeds of up to 6.7 Gbps [1]. Despite remarkable potential, millimetre-wave WPAN systems face several serious challenges originating from the unique propagation characteristics in this band. In order to compensate for the high free space path loss and provide appropriate coverage, directive antennas with a minimum 15 dBi gain are required [2]. Another major issue affecting 60 GHz systems is the problem of dynamic human body shadowing. This can introduce up to 40 dB of rapid attenuation [3]. Beamforming techniques have been proposed to work around the human body or other obstacles by switching beams into NLOS paths.

At 60 GHz the transmission is mainly sustained by a single cluster that can be the LOS path or one of the main reflected clusters [4]. Therefore, the polarisation information of the cluster is of crucial importance. Polarisation mismatch can cause poor system performance and some studies have reported a drop of 20 dB in the received signal power [5].

Driven by data hungry applications, such as the streaming of uncompressed 4K resolution video, data rates of 12 Gbps and beyond are envisaged to be required. The current channelisation adopted in the present standard does not allow a single user to aggregate two frequency channels to double their throughput [1]. Hence, MIMO techniques are seen as a solution for high throughput (>10 Gbps) operation in the millimetre bands. Using directive antennas in a LOS channel can be problematic since it can create high spatial correlation in the MIMO channel, which generally leads to poor system performance. To alleviate this issue, the use of two orthogonally polarised antennas is proposed. Any two polarisations that are symmetrical in the Poincaré sphere can be used. This study is limited to linear or circular orthogonal polarisations. Two circular cross-polarised antennas at both sides of the link are suggested for the following reasons. Circularly polarised signals reverse their handedness once reflected. This unique feature can be exploited to detect whether the propagation condition is LOS or NLOS. Another benefit from using circular polarisation is that, unlike linear polarised antennas, they are insensitive to tilting of the device.

Circular polarised steerable antennas are viable from a design viewpoint. Several studies have presented antenna designs for 60 GHz applications. In [6] an electrically steerable dual polarised 16 element antenna design with a gain of 17 dBi was presented. An example of a dual polarised directive antenna was presented in [7], which was characterised by a high cross-polar discrimination of more than 20 dB and permitted electrical switching between different polarisations (linear/circular, vertical/horizontal).

In addition to the sudden fading caused by human body shadowing (which can attenuate the signal by up to 40 dB in less than 100 ms), it was shown in [8] that sudden signal attenuation is also observed when devices are rotated and displaced. This implies that the beamforming training protocol has to respond quickly to adapt the beams in order to maintain Quality of Service (QoS). For this reason a very fast beamforming technique that fully exploits the 2x2 proposed MIMO configuration is introduced here.

II. Circularly polarised antennas: 2x2MIMO

A. Description

The proposed 2x2 polarisation MIMO system is illustrated in fig. 1. Each terminal is equipped with two left and right handed circular polarised (LHCP/RHCP) antennas spaced at a distance of 5 wavelengths from one another. A maximum received power beamforming technique was adopted to align each set of antennas. The beamforming procedure uses the code book defined in the IEEE 802.15.3c standard [9].

B. 3D ray tracing

In order to analyse the performance of the proposed system, a 3D ray tracing tool (including antenna array and diffuse scatter models) was developed in compliance with the 802.11ad conference room channel model [10].

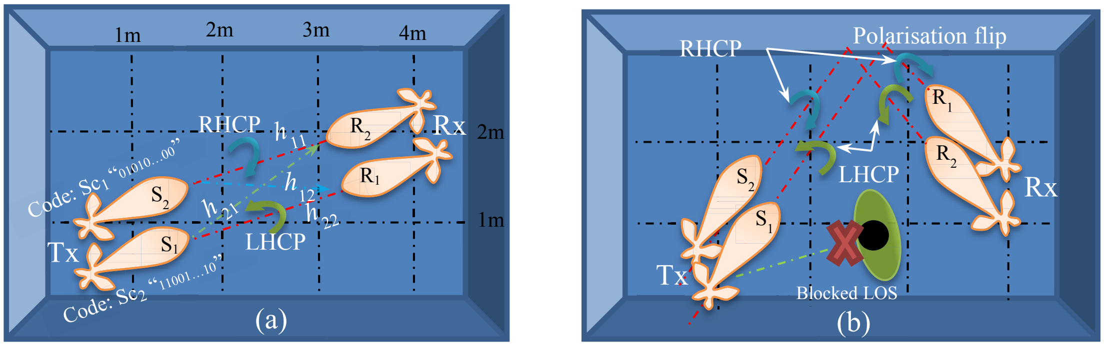

Fig. 1. Configuration of the proposed system in different simulation environment (LOS/NLOS).

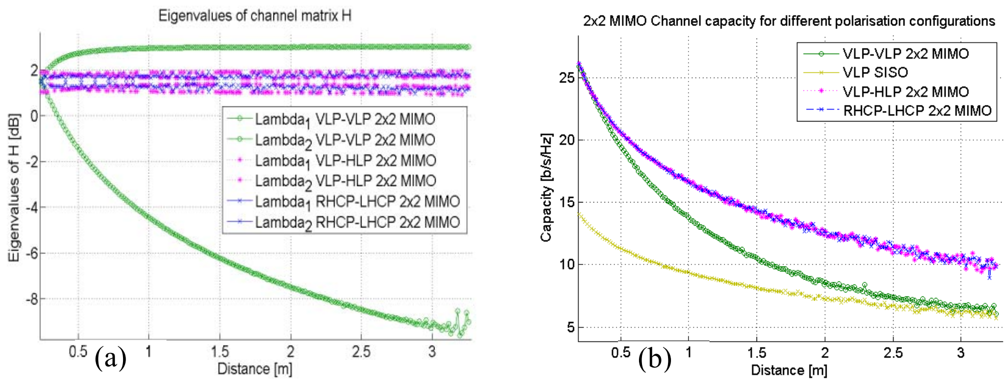

Fig. 2. Eigenvalues of **H** and channel capacity vs. distance using directional antennas (60°), for different 2x2MIMO polarisation configurations.

The 3D ray tracer provides the accurate space-time characteristics of the propagation channel, supports beamforming for steerable directional antennas, accounts for the polarization characteristics of the antennas and the propagating signals and supports the non-stationarity characteristics of the propagation channel arising from moving people (thus causing time-dependent channel variations).

The channel impulse response function generated by the 3D ray tracer, with polarisation support can be written using the following general structure [9]

$$\begin{cases} h(t,\omega_{AoD},\omega_{AoA}) = \sum_i \mathbf{H}^{(i)}\, A^{(i)}\left(t - T^{(i)}, \omega_{AoD} - \Omega_{AoD}^{(i)}, \omega_{AoA} - \Omega_{AoA}^{(i)}\right) \\ A^{(i)}(t,\omega_{AoD},\omega_{AoA}) = \sum_k \alpha^{(i,k)}\, \delta\left(t - \tau^{(i,k)}\right)\delta\left(\omega_{AoD} - \omega_{AoD}^{(i,k)}\right)\delta\left(\omega_{AoA} - \omega_{AoA}^{(i,k)}\right) \end{cases} \quad (1)$$

where: t, ω_{AoD}, ω_{AoA} are time and angles of departure and arrival respectively. $A^{(i)}$ is the channel impulse response for the i-th cluster. $\mathbf{H}^{(i)}$ is the 2x2 cluster polarization gain matrix for i-th cluster. $T^{(i)}$, $\Omega_{AoD}{}^{(i)}$, $\Omega_{AoA}{}^{(i)}$ are the time-angular coordinates of i-th cluster. $\alpha^{(i,k)}$ is the amplitude of the k-th ray of the i-th cluster. $\tau^{(i,k)}$, $\omega_{AoD}{}^{(i,k)}$, $\omega_{AoA}{}^{(i,k)}$ are relative time-angular coordinates of the k-th ray of the i-th cluster.

C. Channel Capacity Evaluation

Fig. 2-(a) shows λ_i (the eigenvalues of the channel matrix $\boldsymbol{H}$) versus distance. It can be seen that the difference in power between the eigenvalues of the proposed system is less than 2 dB. Thus, using 2x2 MIMO combined with orthogonal polarisation creates two independent modes that achieve results that tend towards the channel capacity as depicted in Fig. 2-(b). This justifies the equal power allocated to each transmit antenna, which can double the theoretical PHY throughput based on IEEE 802.11ad up to 13.4 Gbps.

Using the same polarisation, in this case vertical linear polarisation (VLP-VLP), leads to poor system performance as shown in Fig. 2-(b). The quick decrease in channel capacity is seen as a consequence of the high channel correlation caused by high path loss and directive antennas. Analysing the eigenvalues of the VLP-VLP configuration in Fig. 2-(a) shows fast eigenvalue divergence versus distance.

III. Beam Searching Algorithm

A. Directive beamforming exploiting orthogonal polarisation

The proposed beamforming procedure is represented schematically in Fig. 3. For the sake of simplicity, the transmitter and receiver antennas are restricted to steer their beams into 4 specified directions. In the figure, one LOS path and one NLOS path with attenuation α<1 are considered. Assuming that each end is equipped with two electrically steerable cross-polarised antennas, the beamforming proceeds as follows:

- Firstly, each transmit antenna is assumed to cover half of the coverage area. The same is applied at the receiver.
- The receiver estimates $\left(h_{11}^{(T_1)}, h_{12}^{(T_1)}, h_{21}^{(T_1)}, h_{22}^{(T_1)}\right)$ at time instance T_1 and then switches the coverage areas between the Rx1 and Rx2 antennas.
- The receiver re-estimates the coefficients $\left(h_{11}^{(T_2)}, h_{12}^{(T_2)}, h_{21}^{(T_2)}, h_{22}^{(T_2)}\right)$.
- Assuming that $h_{ij}^{(T_k)}$ is the largest coefficient, this means

that the best combination for the current stage is beam "i" at the transmitter with the specified polarisation (the transmitter keeps the polarisation unchanged during T_1 and T_2) and beam "j" at the receiver with the polarisation used at time T_k.

- Send "i" to the transmitter as a one bit feedback indicating which sector to choose for the next refinement stage.

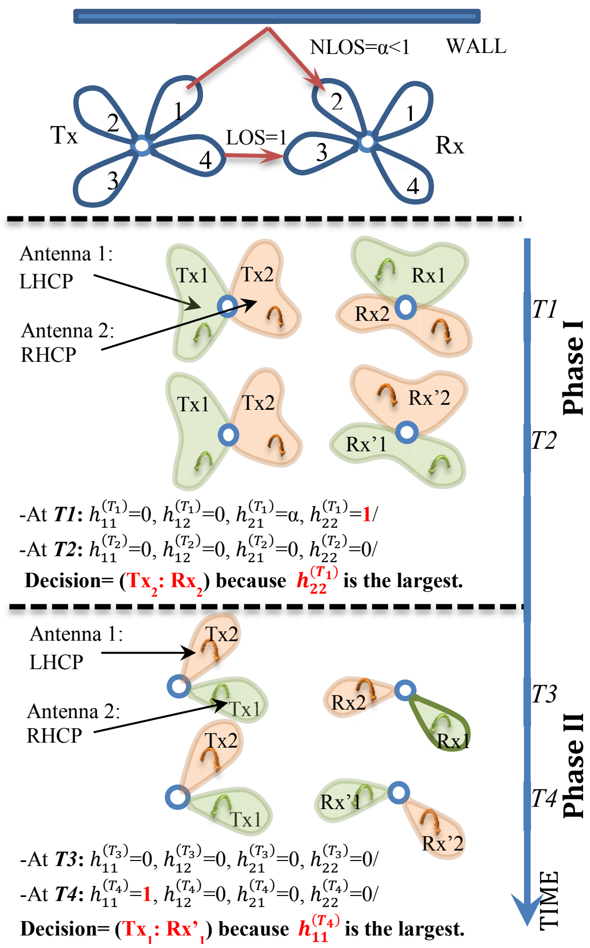

Fig. 3. Example of beamforming for 4 steerable beam directions.

The same methodology can be followed in the subsequent stages for beam refinement by splitting the chosen sectors into two narrower beams. This procedure is carried out until certain criteria are met. For example, reaching a certain width of the formed beams or achieving a minimum SNR at the receiver (or a minimum SINR).

B. Detection of LOS/NLOS Conditions

The propagation conditions can be determined by exploiting the response of the circular polarised signal to different cluster types. This can be performed by sending two orthogonal training sequences Sc_i using RHCP and LHCP at the transmitter simultaneously or sequentially as shown in Fig. 1. The propagation condition is resolved by applying a simple test. If each transmitted frame is detected by the same kind of polarised antenna i.e. $h_{ii}^{(T)} > h_{ji}^{(T)}$, then it is a LOS environment; otherwise, it is a NLOS scenario. This test is also valid for receivers with only one antenna. Depending on the type of the detected training sequence, the receiver can estimate whether it was received through a LOS or a NLOS cluster. Therefore, dynamic adaptive polarisation can be requested from the transmitter side which brings significant benefits to a SISO system as investigated in [5].

IV. Beam Searching Performance Analysis

The complexity of CSI estimation and the overhead cost of its feedback often make beam weight calculation from explicit CSI prohibitive. Thus codebook beamforming is often more appealing. Different beamforming techniques are analysed in this section and compared. A simple performance comparison can be done using Packet-by-Packet (PbP) BF training which consists of sending an individual packet per beam pair.

A. Existing beam switching procedures

Exhaustive search is a basic method to align the transmitter and receiver beams by exhaustively examining all beam pairs and selecting the strongest pair. This is achieved by sending a training packet using each pair of beams. Although the performance of such a scheme is shown to maximise the received power, the training period is excessively long. Let M_t and M_r be the number of antenna elements at the transmitter and receiver respectively. The number of beams is set to twice the number of antenna elements to provide a maximum fluctuation of 1 dB for all directions as shown in [11]. The number of training packets needed to complete the exhaustive search is then given by:

$$N_{exhaust} = N_t \,.\, N_r \,, \qquad (2)$$

where $N_t = 2.M_t$ and $N_r = 2.M_r$ are respectively the codebook size of the possible beams at the transmitter and receiver sides. It can be seen from (2) that the complexity order of such a training scheme is of the order of $O(N^2)$, (assuming $N_t = N_r$). However, by increasing the number of antenna elements, the BF set-up time becomes prohibitively large. For this reason, the IEEE802.15.3c standard [11] follows a different strategy by adopting a two-stage procedure. Sector beams with large beamwidth are used in the first phase. After this step each device knows the best sector pair. Following this stage a beam level search is performed within the selected sectors. Let $N_{beam}(t), N_{beam}(r)$ be respectively the number of supported beams at the transmitter and receiver and $N_{sec}(t), N_{sec}(r)$ be the number of sectors defining the low resolution stage (sector level) at the transmitter and receiver. The number of beams confined within a single sector is then defined as $N_{bps}(x) = N_{beam}(x)/N_{sec}(x)$, where $x \in \{r, t\}$. The total number of transmitted packets needed to complete the 802.15.3c beamforming procedure is calculated as in (3).

$$N_{15.3c} = N_{sec}(t)\,.\, N_{sec}(r) + N_{bps}(t).N_{bps}(r). \qquad (3)$$

Assuming the transmitter and receiver have the same antenna capabilities, it is clear that the optimum solution for $\begin{cases} N_{15.3c} = {N_{sec}}^2 + {N_{bps}}^2 \\ N_{bps} = N_{beam}/N_{sec} \end{cases}$, is achieved when $N_{15.3c} = {N_{sec}}^2 + (N_{beam}/N_{sec})^2$ is minimum, hence $N_{sec} = N_{bps} =$

$\sqrt{N_{beam}}$. This brings the complexity of the training procedure to the order of $O(N_{beam})$. By adopting a two stage procedure, the training time and the complexity order are reduced compared to the exhaustive search.

The beamforming procedure adopted in the 802.11ad standard [1] has three stages: Sector level sweep (SLS), multiple sector ID (MID) and beam-combining process (BC). In the SLS phase the transmitter sends a sector sweep (SS) frame in all beam directions while the receiver adopts a quasi-omni pattern. The SLS permits the transmitter to find the best transmit beam. The MID allows the beam at the receiver side to be refined by using a quasi-omni pattern at the transmitter and swapping through all the possible beams at the receiver. Due to the difficulty to produce quasi-omni patterns with high fidelity at 60 GHz [12] the chosen pair of beams for communication might not be the best one to use. Therefore, a joint trial among the best set of T_x and R_x beams is suggested to refine the chosen pair. A maximum number "$B=7$" of beam candidates for the BC procedure is suggested [1]. The total number of beam transmissions needed for the beamforming procedure in 802.11ad is given by

$$N_{11ad} = N_{quasi-omni}(r)\,.\,N_{beam}(t) + N_{quasi-omni}(t)\,.\,N_{beam}(r) + B^2. \quad (4)$$

The adopted beamforming technique in 802.11ad permits the reduction of the training time and improves the resolvability of the multipath since only high resolution beams are used during the training period.

B. Proposed beamforming technique

Assume that the number of possible beams N_{beam} is a power of 2, which means that $N_{beam} = 2^{N_b}$, where N_b is an integer. The total number of beam transmissions needed for the proposed beamforming procedure is given by (5).

$$N_{proposed} = 2.min\{N_b(t), N_b(r)\} + abs\big(N_b(t) - N_b(r)\big) = N_b(t) + N_b(r) \quad (5)$$

The complexity of the proposed technique is of the order of $O\big(log_2(N)\big)$ when $N_b(t) = N_b(r)$. This means that the complexity of the training procedure remains very low with increasing numbers of antenna elements. For example by doubling the number of the antenna elements the proposed training procedure needs just 4 more beam transmissions, whereas in the exhaustive search it multiplies the number of beam packets by a coefficient of 4.

C. Simulation results

Fig. 4 shows the evolution of the time needed to perform the beamforming procedure versus variation in the number of antenna elements. As can be seen the proposed scheme completes the beamforming in much less time slots than that needed for other schemes and manifests less sensitivity to the number of antenna elements. This is very crucial in a scenario where the environment is very dynamic. The beamforming procedure adopted in the 802.11ad standard shows less sensitivity to the increase in the number of antenna elements compared to the two-stage and exhaustive search techniques. The performance of the 802.15.3c BF is very sensitive to the choice of the number of sectors. The increase of the number of quasi-omni patterns in the 802.11ad BF slightly increases the training time. This can also be derived from (4).

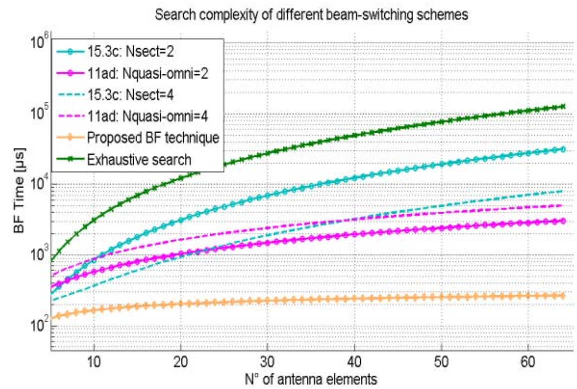

Fig. 4. Complexity order of different beamforming schemes (shows the time needed for each procedure using PbP beamforming).

D. Influence of device movement on system performance

Most application scenarios depicted in the 802.15.3c standard support relatively stationary channels where the BF procedure, once completed, remains valid for a long period. This is not true when devices move. The presence of humans makes the channel even more dynamic since 60 GHz signals are badly affected by human body shadowing. Linear translation or rotation of devices leads to beam misalignment. A handheld device moving at a maximum walking speed of 2 m/s at a distance of 2 m can cause a rotation of the beam of 6° in the azimuth plane over just 100ms. Different rotation speeds for different types of device manipulation are reported in [13] and shown in Table I. It can be seen that the effect of device rotation is more severe than device displacement. If a rotation speed of 50°/100ms and an antenna beamwidth of 30° is considered, a drop of 3 dB in the received power can be experienced in less than 60 ms. It is assumed here that once the received power drops below a certain level the BF procedure is automatically triggered to realign the beams.

TABLE I. ROTATIONAL MOVEMENT [13]

Activity	Rotation speed [per100ms]
Change tablet orientation (azimuth rotation)	6-11°
Turn tablet vertical to horizontal (elevation angle)	30-36 °
Game console rotation (solid angle)	72- 80 °

The time efficiency in Fig. 5 represents the ratio between the time spent transmitting data and the data transfer interval (DTI). This ratio can be linearly linked to the ratio between the total capacity of the system when devices are in movement to the total ideal capacity when the channel is absolutely stationary. The correct beam pair is assumed to be selected at the start of the simulation. The time efficiency is calculated for different beamforming techniques given various numbers of users in the environment for different rotation speeds. In the 802.15.3c and 802.11ad the devices complete the beamforming training during the Service Period Channel Access (SPCA) that was granted by the Piconet Coordinator (PNC) in a TDMA slot basis called Service Period (SP). Since TDMA enables more channel efficiency, it is preferred for the high performance Gigabit links. It is assumed here that the time allocated for Contention-Based Access Period (CBAP) is null. The number of antenna elements adopted in Fig. 5 is 16 at both sides, arranged in a rectangular 2D space 4x4 generating a codebook size of 4xM=64 as suggested in 802.15.3c standard. The number of quasi-omni patterns at the receiver is equal to 2 and the number of sectors in 802.15.3c procedure is set to 4. Similar parameters for all beamforming procedures were considered. Whilst these parameters may not be consistent with the individual standards, they facilitate a direct comparison.

TABLE II. SIMULATION PARAMETERS

Superframe time	30 ms
3dB Beamwidth	22.4°
Control PHy rate 802.11ad	27.5 Mbps
Control PHy rate 802.15.3c	50 Mbps
T_{STF}	3.636 μs
T_{CE}	0.655 μs
T_C	0.57 μs

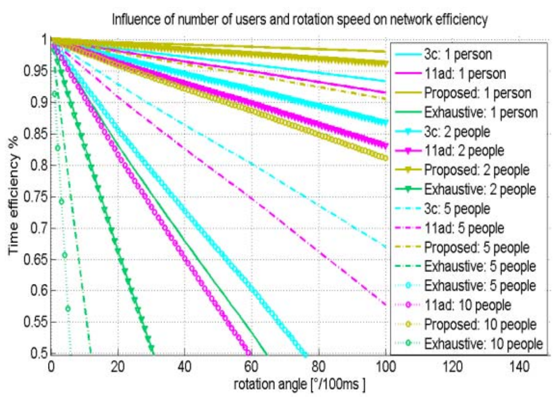

Fig. 5. Influence of the rotation speed and the number of links on the time efficiency of the system.

In reality, IEEE 802.11ad adopts an in-packet structure that allows the steering of beams into different directions within a training packet. Only one header and preamble is needed as they are shared by all the training sequence as shown in Fig 6. This considerably reduces the overheads and training time.

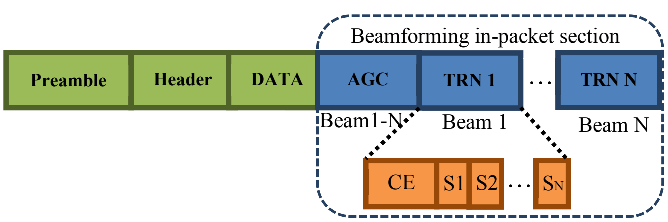

Fig. 6. In-packet structure in 802.11ad standard [14].

The following expression defines the training time needed for one packet incorporating packet beamforming [1].

$$Time_{In-packet} = T_{STF} + T_{CE} + T_{header} + T_{Data} + N_{TRN}.(256 \times 4 + 640 \times 4).T_C + N_{TRN}.T_{CE} \quad (6)$$

It includes 256×4 bits for AGC resetting, 640×4 bits for relative delay estimations and 1024 bits for CE sequences in a training packet. If we assume 32 possible beams and 2 quasi-omni patterns at both sides with C= 3: the beamforming procedure using the in-packet procedure need 550μs, which is almost half the time needed for PbP beamforming. Similarly, adopting the in-packet procedure will further reduce the beamforming time for all the beam searching procedures.

V. CONCLUSION

A 2x2 MIMO solution that exploits the special polarisation features at 60 GHz was presented. This scheme offered more than 12 Gbps of PHY layer throughput and was able to adaptively match the polarisation for LOS/NLOS condition changes and antenna tilting. Fast beamforming in LOS/NLOS condition was presented. The beam refinement was progressive, meaning that the receiver can stop at any stage if the SNR is satisfactory. The simulation results demonstrate that the proposed beam switching procedure outperforms existing schemes in terms of time of execution. Considerable improvement was shown in a dynamic environment where devices were subject to displacement, rotation and LOS obstruction.

REFERENCES

[1] *IEEE Standards 802.11.ad*, December 2012.

[2] Maltsev, A.; Maslennikov, R.; Sevastyanov, A.; Khoryaev, A.; Lomayev, A.; , "Experimental investigations of 60 GHz WLAN systems in office environment," *Selected Areas in Communications, IEEE Journal on* , vol.27, no.8, pp.1488-1499, October 2009

[3] Jacob, M.; Mbianke, C.; Kurner, T.; , "A dynamic 60 GHz radio channel model for system level simulations with MAC protocols for IEEE 802.11ad," *Consumer Electronics (ISCE), 2010 IEEE 14th International Symposium on* , pp.1-5, 7-10 June 2010

[4] IEEE doc. 802.11-09/0552r0. Experimental investigation of polarization impact on 60 GHz WLAN systems, A. Maltsev et al, May 11, 2009.

[5] Maltsev, A.; Perahia, E.; Maslennikov, R.; Sevastyanov, A.; Lomayev, A.; Khoryaev, A.; , "Impact of Polarization Characteristics on 60-GHz Indoor Radio Communication Systems," *Antennas and Wireless Propagation Letters, IEEE* , vol.9, pp.413-416, 2010

[6] Pan, H.K.; , "Dual-polarized Mm-wave phased array antenna for multi-Gb/s 60GHz communication," *IEEE International Symposium on Antennas and Propagation*, pp. 3279-3282, July 2011.

[7] Wollenschlager, F.; Stephan, R.; Lei Xia; Muller, J.; Muller, R.; Ariza, A.P.G.; Thoma, R.S.; Hein, M.A.; "A compact dual-polarized wideband patch antenna array for the unlicensed 60 GHz band," *Antennas and Propagation (EUCAP),* pp.1873-1877, April 2011.

[8] M. Park and H. K. Pan, "Effect of device mobility and phased array antennas on 60 GHz wireless networks," in *ACM workshop on mmWave communications: from circuits to networks (mmCom '10)*, 2010.

[9] *IEEE Standards 802.15.3c*, October 2009.

[10] IEEE 802.11-09/0334r8, "Channel Models for 60 GHz WLAN Systems," 2010-5-20.

[11] Li, B.; Zhou, Z.; Zou, W.; Sun, X.; Du, G., "On the Efficient Beam-Forming Training for 60GHz Wireless Personal Area Networks," *IEEE* Transactions on Wireless Communications, no.99, pp.1-12.

[12] K. Ramachandran, N. Prasad, K.Hosoya, K.Maruhashi, and S.Rangarajan. "Adaptive Beamforming for 60 GHz Radios: Challenges and Preliminary Solutions". In ACM mmCom Workshop, 2010.

[13] Tsang, Y.M.; Poon, A.S.Y., "Detecting Human Blockage and Device Movement in mmWave Communication System," Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE, pp.1-6, 5-9 Dec. 2011.

[14] Tsang, Y.M.; Poon, A.S.Y.; Addepalli, S., "Coding the Beams: Improving Beamforming Training in mmWave Communication System," *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE* , pp.1,6, 5-9 Dec. 2011