Abstract – In recent days, the unlicensed millimeter (mm) wave spectrum in the 60 GHz band is becoming a promising technology for multi-gigabit wireless communication. Compared to other lower frequency systems, the spectrum around 60 GHz holds several advantages including huge unlicensed bandwidth (upto 7 GHz), compact size of transceiver due to small wavelength (about 5 mm) and less interference owed by high atmospheric absorption. However, there are several challenges associated with this spectrum, such as reflection and scattering losses, high penetration loss and high path loss, which limits the range of coverage at 60 GHz. The 60 GHz links in indoor environment is also susceptible to line of sight (LOS) blockage due to its lack of ability to diffract around various objects. To overcome all these challenges, directional transmission is very vital. Thus, a technique known as beamforming utilizing multi-element antenna arrays is considered important for 60 GHz wireless communication. This paper focuses on providing a general understanding of beamforming and its techniques at 60 GHz and reviews the various issues associated with it.

Index Terms—60 GHz, beamforming, millimeter wave, multi-gigabit wireless communication.

I. INTRODUCTION

Due to expected congestion at lower radio frequencies, the 60 GHz band in the millimeter wave spectrum is becoming an attractive arena for upcoming multi-gigabit wireless communication systems, meeting requirements of most demanding applications. In addition to high data rates that can be achieved in this 60 GHz spectrum, energy propagation in this band has unique properties that provide many benefits such as high security, frequency re-use and excellent interference immunity. The 60 GHz frequency band is highly exploited mainly for the development of future Wireless Local Area Network (WLAN) and Wireless Personal Area Network (WPAN) systems, 60 GHz communication can be used in multiple deployment scenarios such as static-to-static, static-to-handheld and handheld-to-handheld [1]. The WiGig Alliance envisions that 60 GHz technology will be a platform for the existence of the widest ecosystem of interoperable systems, as it need not be adapted for future applications [2].

According to Friis’ transmission equation, operation at 60 GHz causes an additional propagation loss of around 22 dB when compared with the 5 GHz band upon considering the same gains of antennas, same transmitter (TXr) – receiver (RXr) separation and equal transmit powers [3]. Although the high path loss seems to be a disadvantage of 60 GHz, the effective interference levels for 60 GHz are less severe than those systems located in the congested lower radio frequency bands such as 2-2.5 GHz and 5-5.8 GHz, since it confines the 60 GHz operation to a limited area such as an indoor environment [4]. Due to small wavelength (about 5 mm), 60 GHz also favors the use of antenna arrays with large number of elements thus enabling the integration of multiple antennas into portable devices. The principle of diffraction states that beamwidth is inversely proportional to operating frequency. Thus, at 60 GHz, antennas have narrow pencil type beams. For point to point communication, highly focused antennas are required so that the transmitted energy is just directed to the intended receiver. At 60 GHz, the use of highly focused antennas with narrow beamwidth minimizes the possibility of interference thus maximizing performance [5].

Directional transmission is very vital for any deployment scenario involving 60 GHz radios in order to benefit the high bandwidth potential and to cope with the poor link budget confronted in this band due to high path loss and low output power of power amplifiers. Thus, a technique called beamforming is necessary to mitigate the link budget problem, wherein, the signals on various antennas are smartly combined so that
transmit and/or receive beams can be formed in the desired directions. In NLOS scenarios, beamforming can be used to electronically steer the transmit-receive beam-patterns towards the strongest reflection available [6]. In a TXr, beamforming techniques can be utilized for maximizing the Equivalent Isotropic Radiated Power (EIRP), while in a RXr, they can be used to increase the Signal to Interference plus Noise Ratio (SINR) of the antenna system. Beamforming can be considered as a spatial filtering technique where, transmission/reception is made possible in certain directions, meanwhile suppressing the transmission/reception to/from unwanted directions. This leads to interference reduction which is highly desirable at 60 GHz [7].

II. CONCEPTS OF BEAMFORMING

In beamforming, each transmitter/receiver signal is multiplied with complex weights that adjust the phase and magnitude of the signal to and from each antenna. This causes the output from the array of antennas to form a transmit/receive beam in the desired direction and minimizes the output in other directions. The block diagram of a basic beamformer is shown in Fig 1, where the signal from each antenna undergoes time/phase and amplitude weighting. Based on the beamforming architecture, the weighting can be done either in analog domain (Analog beamforming) or in digital domain (Digital beamforming) [6]. In analog beamforming, signals are weighted and combined in the analog domain prior to conversion to digital baseband. This requires the use of only one analog to digital convertor (ADC). In digital beamforming, each signal is converted to digital domain and then weighted before combining it. This requires as many numbers of ADCs as the number of signals.

A. Fixed Beamforming

Fixed beamforming does not perform amplitude weighting of the signals. It has the effectiveness of manual alignment and is the simplest beamforming technique [7]. Fixed beamforming is useful mainly in static-to-static deployment scenarios as long as the LOS is assured [1]. Some applications require the use of several fixed beams to cover an angular sector. We need to feed the array in order to produce multiple beams at different directions. This can be achieved using a feed network known as a beamformer. In a N x N beamformer, N input ports are connected to N antenna elements, whereas N output ports are connected to signal generators or receivers. The presence of a signal at one of the output ports will produce a phase shift between adjacent input ports and array elements, resulting in a radiation pattern with a main beam and nulls along specific directions. When different signals are fed to or applied at all output ports, corresponding radiation patterns will be produced, the superposition of which will result in multiple simultaneous beams along different angles. Even though all signals at the beamformer input ports are transported to all output ports, the signal from a source located along one of the main beams will only appear at the corresponding output port. The Butler matrix is the most commonly used beamforming network. This beamforming technique can be used for example in scenario such as HDMI cable replacement between a TV set and a DVD player.

B. Switched Beamforming

Switched beamforming follows a beam switching procedure. In this, interference is reduced to a certain extent but not suppressed and the system implementation cost is reasonable. If the complex weights that are to be multiplied with the TXr/RXr complexity. The power consumption of the ADC is directly proportional to sampling frequency, which is in the order of GHz for 60 GHz transceiver system. For 60 GHz, antenna size is very small. Thus the circuit complexity and power consumption will increase if we use more antenna elements along with ADCs for beamforming implementation [8]. Since only one ADC is required for analog beamforming compared with multiple ADCs required for digital beamforming, analog beamforming is usually the choice for 60 GHz wireless. This choice of analog beamforming over digital beamforming follows from the consideration that low complexity, low power and low cost implementation of systems is outlined as a key feature of 60 GHz radios. Beamforming techniques for 60 GHz based systems can be classified into 3 main groups as described below:

Fig 1: Basic beamformer block diagram
signal are selected from a library of weights that form beams in specific, predetermined directions, the process is called switched beamforming. Here, the TXr/RXr basically switches between the different beams based on the signal strength measurements. This technique can be used to switch the line of sight (LOS) link to a non-LOS (NLOS) link when the direct link is blocked.

Here, the switched antenna array assumes a structured codebook. A codebook is simply a collection of fixed, predefined beamforming vectors (or combining approaches). By configuring the beam selection, the switched antenna array which is equipped with a proper antenna training/tracking algorithm is able to automatically find the best path between the TXr and RXr. If the LOS is blocked, it will select a new beam pattern [9]. The cost function considered for beam-switching is the SNR at the beamformer output, averaged over the whole transmission bandwidth. Therefore, the transmit-receive beam-pattern pair that yields the maximum average SNR is selected among a pool of pre-defined beam-patterns [6]. But the performance of switched beamforming is limited by the inability to perform a continuous beam and null steering [7]. With switched beamforming based 60 GHz links, one can consider point to point or point to multipoint communications scenario (eg. data centers, mobile backhauls etc.) with respect to indoor scenario.

C. Adaptive Beamforming

Adaptive beamforming uses standard compliant complex signal processing beamforming algorithms in order to steer the main lobe towards desired direction and to suppress the undesired sources. This approach gives optimal performance but at the expense of higher implementation cost [7]. If the complex weights are computed and adaptively updated in real time, the process is called adaptive beamforming. In adaptive beamforming narrow beams are formed towards desired directions and nulls towards interfering sources, thus improving the SINR. In order to achieve the maximum SINR, very precise control over the complex weights applied to the signals at each element in the antenna array is required.

Based on the information required by the antenna system to perform adaptation, adaptive beamforming can be classified into 3 groups: Spatial reference, Temporal reference and Blind techniques.

Spatial reference techniques: They make use of the direction of arrival (DOA) of the desired and interfering signals in order to perform antenna adaptation. This technique requires the use of two algorithms, one to estimate the DOAs and other to estimate antenna weights. MUSIC algorithm and ESPRIT algorithm are two widely adopted DOA estimation algorithms [7].

Temporal reference techniques: They make use of a training sequence (a reference signal) which is known at both the TXr and RXr in order to perform antenna adaptation. The array output is subtracted from the reference sequence to generate an error sequence which is used to control the antenna weight vector. Unconstrained Least Mean Square (LMS) algorithm and Recursive Least Square (RLS) algorithm are the most commonly used temporal reference algorithms [7].

Blind techniques: They are based on a priori knowledge of some characteristics of the desired signal and do not require training sequences or any information regarding the antenna system. Most common algorithm using this technique is the Constant Modulus Algorithm (CMA) [7].

These beamforming techniques are in the order of increasing complexity, power consumption and cost and at the same time increasing flexibility or adaptability to changing environments [1]. The prime objective of beamforming is to align the beam with the incoming signal as closely as possible. In fixed beamforming, a set of fixed beams in particular directions is formed. In switched beamforming, the beam can be steered only to limited number of directions. But, in adaptive beamforming, the beam has a wide steering range and thus can be steered to the exact direction of the incoming signal. When compared to adaptive beamforming, switched beamforming has performance degradation. This results from the fact that the number of possible directions to which the beam can be steered is limited, which causes a mismatch between incoming signals and the beams [4]. But, depending on the application at 60 GHz, fixed, switched or adaptive beamforming can be used.

III. ISSUES OF BEAMFORMING

Despite of several advantages offered, there are several limitations for beamforming at 60GHz which must be taken into account and must be resolved [4].

A. Power margin

Power margin is the difference between available signal power and the minimum signal power needed to overcome system losses and still satisfy the minimum input requirements of the receiver for a given performance level. System power margin reflects the excess signal level, present at the input of the receiver that is available to compensate for (a) the effects of component aging in the transmitter, receiver, or physical transmission medium, and (b) deterioration
in propagation conditions. 60 GHz based communication is considered to provide multi-gigabit data rate for smaller distance and at this high speed data transfer, sufficient power margin should be provided to antenna systems to ensure reliable communication link.

B. Delay spread

Delay spread is a measure of the multipath richness of a communications channel. In general, it can be considered as the difference between the time of arrival (TOA) of the earliest significant multipath component (typically the LOS component) and the TOA of the latest multipath component. At 60GHz, a slight misalignment of TXr and RXr antenna could potentially lead to significant increase in delay spread [4]. Also, the high data rate of the order of Gbps offered by 60 GHz experiences significant dispersion. The delay spread typically ranges from 10-1000 ns in indoor channels [10]. Also, for WPAN application, shadowing effect such as blockage due to human body can attenuate LOS signal significantly. The above discussed two scenarios can increase the complexity of the system beyond practical limits of realization. A possible solution to this problem can be the use of adaptive beamforming algorithms that encompass dispersion estimation. Adaptation through dispersion estimation can provide high data rates with low power consumption, thus allowing improved performance [11].

C. Misalignment between incoming signal and receiver beam

The main goal of beamforming is to align the RXr beam with the incoming signal as closely as possible. In switched beamforming, the beam can be steered only to a limited number of directions, whereas in adaptive beamforming, the RXr beam can be steered to the exact direction of incoming signal. Therefore, in switched beamforming, misalignment can occur frequently, and in adaptive beamforming there might be slight beam pointing errors which occur due to inadequate knowledge about angle of arrival or inaccurate phase shifting between antenna elements [4]. Therefore, it is important to have a close look upon the effect of deviation of the incoming signal. In Fig 2, the power loss experienced due to the mismatch for the elevation dimension investigated in [4] is shown. It has been observed from the above figure that, at high deviation angles, the losses for smaller elevation angles are not as large as the losses encountered by larger elevation angles. Thus it has been demonstrated in [4] that the misalignment between the incoming signal and the receiver beam causes degradation in the beamforming performance in terms of gain losses. In [12], it is found that the optimal half power beamwidth (HPBW) is about twice the misalignment angle.

B. Angular spread of incoming signal

Since the refractive index varies with wavelength, it follows that the angle by which the signal is refracted will also vary with wavelength, causing an angular separation of the colors known as angular spread of signal. Therefore, in a condition that the receiving array is not able to follow the angular spread of incoming signal, the performance of beamforming may not be perfect even if the receiver beam of array is exactly matched with the main direction of arrival of incoming signal. Angular spread increases in obstructed NLOS indoor deployment environments than in less obstructed outdoor environments [13].

![Fig 2: Loss in power vs. deviation of the received signal from the focus of the beam in θ dimension [4].](image1)

![Fig 3: Distributed directivity vs. angular spread of the received signal [4].](image2)
This clearly points that angular spread is another challenge at 60 GHz, where communication within indoor scenario is prominent. In Fig 3, the distributed directivity values for various numbers of elements at uniform angular spreads up to 20° are presented [4]. The figure shows increasing distributed directivity with increase in angular spread. But the decreasing slope indicates that for higher angular spread the resulting gains will be lower compared to lower spread scenarios. Thus it can be noticed that gain is inversely proportional to angular spread which also affects the overall beamforming performance of array. Thus through the simulations done in [4], angular spread has been observed as a factor that degrades beamforming gain. 

Apart from the above mentioned limitations, beamforming at 60GHz can also have certain additional complexities: (1) Beamforming is performed based on a specified antenna structure; (2) the measuring signal’s angle of departure (AOD) or angle of arrival (AOA), or acquisition of the entire channel state information (CSI) matrices for weight vector calculation introduces large overhead due to complex calculations; (3) no complete MAC protocol is available to setup a reliable directional communication link [14].

IV. CONCLUSION

In this paper, an overview of the various beamforming techniques and related issues at 60 GHz has been presented. Each of the technique has its own advantages and disadvantages. Thus, based on the requirements of various applications at 60 GHz, a choice among the different beamforming techniques can be made. It is seen that fixed beamforming is a good choice for static-to-static application scenarios where probability of LOS blockage is less and for NLOS scenarios and mobile environments, adaptive beamforming is the best choice. Among the various issues related to beamforming, misalignment between incoming signal and receiver beam is an important factor to be considered as it has a more negative effect on beamforming performance in terms of gain losses.

V. REFERENCES


