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Beamforming in Wireless Communication Standards: A Survey

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Abstract

Background/Objectives: In this paper, we have analyzed the beamforming technology and surveyed the beamforming methods used over the years in various wireless applications and how it can be improved to be implemented in future technologies. **Methods/Statistical Analysis:** Beamforming plays an important role in pointing an antenna to the signal source and thereby reducing interference and improving signal quality. The importance of the technology and how each standard has benefited from it has been identified. We have then provided a review of the research going into this field on how the application of the technology can be employed in the future standards to provide a better user experience. **Findings:** At higher frequencies, more antennas can be packed into the same physical area. The implementation of hybrid beamforming technologies in large antenna arrays in these frequencies has yielded good performance. Advanced hybrid beamforming algorithm uses both analog and digital beamforming methods and not only offers highly directional beam to overcome propagation loss, but also advanced digital domain processing such as multi beam MIMO with lesser complexity. **Applications:** Use of millimeter wave band for future technologies can result in the adoption of various beamforming methods in a large scale in various wireless applications.

Keywords: Antenna Systems, Beamforming, Cellular Standards, Indoor Networks, Millimeter Waves

1. Introduction

The term Wireless Communication was introduced in the 20th century and wireless devices have developed over the years. In the present world, these devices have become an integral part of our lives and the importance of wireless communication cannot be undermined. Some of the applications for wireless communication include devices like cellular mobile phones, zigbee wireless technology, Wi-Fi, GPS etc.

In recent years, due to a large growth in the number of users added to the development of applications requiring high bit rates, an enormous increase in traffic has been experienced by wireless communication systems. As personal wireless devices increase, the problem of interference, increasing data traffic and capacity also increases as RF spectrum becomes more congested[1].

In such an environment, the development of interference mitigation methods and proper radio resource allocation schemes to guarantee the communication reliability and for supporting high data rate applications is very relevant. One method is the exploitation of the spatial domain of the communication channel by means of multiple antennas[2–4]. Multiple antenna systems play an important role in the improvement for enhancing the spectral efficiency of the wireless systems. With more antenna elements, it is possible to steer the transmission toward the intended receiver. There is an abundance of spectrum in the millimeter wave band and significant research efforts are going into these bands[5]. Fortunately, at higher frequencies, more antennas can be packed into the same physical area. Therefore, these higher frequency systems are expected to use large scale antenna arrays to overcome the poor propagation conditions at those bands[6].

For overcoming the problem of interference, the combination of multiple antenna arrays and beamforming methods help in suppressing the interfering signals and receiving the signals incoming from the desired ones. The basic principle of beamforming is the cancellation of

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interfering signal by constructing signals in such a way that at required angles we obtain constructive interference and at other angles, the interference is nullified by destructive interference[7].

Research on the role of digital beamforming in wireless communication has huge scope especially with the advent of millimeter wave technologies which is the frequency band from 30 GHz to 300 GHz[8,9]. This has motivated us to survey various beamforming methods emphasizing on the problems faced in wireless communication and future trends.

In this paper, we present an overview of beamforming methods and their importance in wireless communication standards history. We describe different types of beamforming and how beamforming was implemented in each standard. We also present the future trends in wireless communication and how beamforming can be used to improve the performance in keeping with the advancements.

2. Importance of Beamforming

The basic idea of beamforming is to focus energy towards a receiver. Traditionally access points were equipped with omni-directional antennas, named so because they send energy in all directions. Since they radiate waves in every direction, receiver antennas need not track every client but it comes with its own disadvantages. Alternatively, energy can be focused toward the particular receiver which is the principle of beamforming[10].

Beamforming is being used in radio waves as well as sound waves. To understand the concept of beamforming, let us consider the example of sound waves travelling towards a ship from a sonar projector. To obtain a single sharp pulse, the beamforming will send pulses at slight delays instead of all at the same time resulting in an effect of a single large pulse[11]. The same principle is used in antennas forming a phased array[12].

Other applications of beamforming apart from phased antenna radar are communication, sonar, optical imaging, astrophysical explorations, geophysical explorations and biomedical. Sonar systems which have plenty of military and commercial uses, utilize beamforming to analyze and evaluate possible targets in water. Optical beamforming is a technology which focuses LED light on a desire target. Adaptive beamforming is used to significantly improve the image quality in biomedical ultra sound by avoiding interfering signals, thus improving the image quality.

2.1 Beamforming in Wireless Communication

Beamforming can also be known as spatial selectivity where with the appropriate signal processing techniques, an array of antennas can be steered in such a way that interfering signals from a particular direction can be cancelled[13]. Beamforming works by combining elements in a phased array in such a way that signals at particular angles experience constructive interference (at the main lobe) while others experience destructive interference (at the nulls) as shown in Figure 1 and at the receiver by having gains in one direction and attenuation in others, and signal to noise ratio is significantly increased[14].

In the receiver beamformer, each signal is multiplied by a weight. Different weighing patterns can be used to obtain the required sensitivity patterns like Dolph-Chebyshev. The side lobes and nulls are created along with the main lobe. The position of the main lobe should be controlled along with the side lobe width and nulls to obtain the required pattern[10].

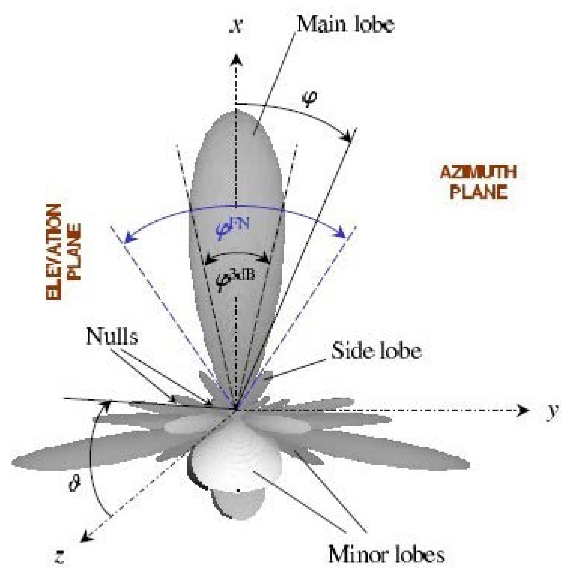

Figure 1. Example of a radiation pattern.

Beamforming can be broadly classified based on location as transmit beamformer or receiver beamforming. If the beamformer is placed between the signal source and the radiating elements, in order to direct the beam to a specific receiver, it is transmit beamforming. While in the receiver, it is performed between the antenna module and the antenna arrays so that the spatial sensitivity of the antenna module can be controlled. Another classification for beamforming can be done based on Signal Domain as Frequency Domain Beamforming and Space-Time Beamforming. Space-Time can further be classified as Analog Beamforming and Digital Beamforming and Analog can be either RF or baseband beamforming. Less common but equally important classification is based on weight vector application, which can be either adaptive beamforming or fixed weight beamforming. Adaptive beamforming has become an integral part of the modern smart antenna technology. Classifications can also be done based on channel estimation, signal bandwidth and received data[15].

Traditionally, in spite of having numerous advantages, beamforming was not widely applied since analog methods were expensive and sensitive to component tolerances and drifts. But after the advent of modern digital technology, which offers high speed A/D convertors and digital down convertors at cheaper rates, digital beamforming and hybrid beamforming are being widely employed[16].

3. Beamforming History in Wireless Communication Standards

Beamforming methods used in cellular phone standards and other wireless communication standards have advanced through the generations to achieve high density cells and higher throughputs. In traditional cellular communication systems, beamforming is implemented at the baseband[16].

3.1 Second Generation Cellular Standard

The 2nd generation cellular standards introduced the use of digital technology. Here, elementary beamforming methods were used to select a particular receiver antenna by the transmitter[17]. Some of the drawbacks of 2G technology like weaker digital signal at higher frequencies, angular decay curve and reduced range of sound which basically arise from the use of digital signal were overcome in 3rd generation technology.

3.2 Third Generation Cellular Standard

3rd Generation Partnership Project (3GPP) standardized Universal Mobile Telecommunication Systems (UMTS) with the aim of technical specifications and reports for a 3rd generation and beyond mobile system. Although elementary beamforming methods were an early technology, it was still supported by the 3rd Generation Partnership Project or 3GPP. The process of forming the beam in the desired direction and nulls in the direction of jammers was incorporated[18].

UMTS specifies three possible modes which are flexible beamforming and fixed beam patterns and none. None denoted that beamforming is optional and flexible beamforming denoted adaptive beamforming and grid of fixed beams denoted a set of predefined beams[17,19].

3.3 Fourth Generation – LTE/LTE-Advanced

The Long Term Evolution or LTE standard was developed as a new standard which is IP and packet based. The decade old UMTS networks did not have any more capacity to meets the high bandwidth and high speed demands made by the end user which resulted in the adoption of 4G[20]. LTE was built on technologies such as coordinated multipoint, advanced multiple-input multiple-output (MIMO), heterogeneous networks and carrier aggregation[21,22].

Operators seem hesitant to implement smart beamforming techniques into base stations, mainly due to cost and complexity of such designs. Fixed approach was the most adopted approach in adaptive signal processing due to its advantages like simplicity[23].

Still beamforming has the capability to enhance the modern cellular systems. Both switched beam and adaptive beam can be used. The switched beam beamforming systems have a switching network that can select the appropriate beam to be received at the mobile station (MS) while the adaptive beam system can form a beam for each user by using adaptive array processors[19].

3.4 Indoor Networks

After IEEE 802.11 was standardized in 1997, various Wireless LAN standards have been introduced. Indoor environments are known to have severe multipath effects that can cause significant fading of wireless signals and the key idea of using beamforming in indoor networks is to carefully choose the signal applied to each individual element of the antenna so that multipath effects can be avoided and SNR can be improved.

Beamforming is being deployed in various indoor network standards such as WiMAX, Wi-Fi and WPAN standards. Before 802.11n standard was developed, Access Points (AP) used antennas with fixed radiation patterns. These antennas were omni-directional and the radiation pattern could not be changed once used even though manufacturers could use external antennas with the highest range and narrowest beam width[24]. In the 802.11n, the absence of standardization made it hard for beamforming to work effectively among vendor products which was overcome to a great extent by the standardization of beamforming in the 5th generation Wi-Fi standard, 802.11ac.

To improve the reliability of the Wi-Fi signal, 802.11ac beamforming technology takes advantage of the MIMO system[25], in which the signals sent by multiple antennas is combined to produce a resultant beam. Any device with multiple antennas can perform beamforming to any other device at any time. But 802.11ac adds the opportunity for the receiver to help the beamforming transmitter to precisely steer its transmitted energy towards the receiver by a process called "channel sounding".

Channel sounding is performed as explained: a NDP (Null Data Packet) Announcement frame to the concerned receiver by the transmitter. When the receiver gets the NDP, it analyzes and calculates a feedback matrix towards the transmitter which is accepted and the steering matrix according to the feedback obtained is calculated. This steering matrix is then used to adjust the phase and amplitude of the signal, and therefore the transmitter can transmit data toward right directions. Thus it is ensured that, in the required directions, the signals get stronger and in the unwanted directions the signals get weaker and the energy is used in the most efficient way.

4. Future Trends

To obtain a peak data rate of gigabits per second, we require advanced antennas, flexible and user specific beamforming and a new mobility algorithm[26]. For this, spectrum at higher frequencies will be utilized and advanced antennas will be required to overcome the propagation loss and cost related problems that are common in these frequencies.

One of the effective solutions being discussed is the utilization of the millimeter wave spectrum from 30 GHz to 300 GHz. According to[27], the misconception regarding higher propagation loss at higher frequencies is refuted by experimenting with actual patch antennas at 3GHz and array antennas at 30 GHz proving that higher frequencies can indeed be used for cellular technologies. Advances in the low power CMOS RF circuits have paved way for placing large number of miniaturized antennas in small dimensions[28].

Use of millimeter wave bands can result in the adoption of beamforming methods on a large scale. The small wavelengths of mmWave frequencies make the use of a large number of antenna elements much easier. This way, highly directional beams corresponding to large array gains can be synthesized. An appropriate beamforming scheme is therefore necessary to focus the transmitted/received signal in a desired direction to overcome problems like path loss and propagation loss.

For implementing it, an advanced hybrid beamforming algorithm is described[6,29], which uses both analog and digital beamforming methods. This not only offers highly directional beam to overcome propagation loss, but also advanced digital domain processing such as multi beam MIMO with lesser complexity.

The use of large scale arrays in millimeter waves does pose a problem due to higher system bandwidths. In[30], two alternative cases of transmit and receive architecture are considered which is an all-RF architecture. Here, hybrid architecture is used where control of MIMO and beamforming is split between RF and baseband.

Even though, it is still unsure as to which frequency band will be utilized for 5G technology, we can be assured that beamforming is going to play a major role in the future.

In the case of indoor networks, IEEE 802.11ad standard, WiGig which operates at 60 GHz at multi-gigabit speeds is deemed the future of wireless networks at short distances. To overcome the signal decay seen in higher frequency transmissions, WiGig uses adaptive beamforming to a great extent. The 60 GHz signal cannot typically penetrate walls but can propagate through reflections and bouncing off walls, ceiling and floor using beamforming[31].

5. Conclusion

Over the past few years, telecommunication academia and industry has put in significant efforts on the research for providing better user experience by improving the spectral efficiency, aggregating more spectra and deploying more base stations. Various technologies have been developed and deployed for obtaining higher data rates. One of the most significant and widely used technologies is the beamforming technology. In this paper, we have presented the importance of beamforming in wireless standards and how they were implemented in various applications.

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