Millimeter-wave Techniques for 5G Mobile Communications Systems: Challenges, Framework and Way Forward

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Abstract

Millimeter-wave (mmw) transmission has drawn great attentions and is regarded as a key technique in next generation of wireless mobile communications systems (5G). However, the traditional mmw communication system has mainly been applied successfully in indoor scenarios, leaving its outdoor usage an open question. In this paper, how to use mmw frequency in 5G systems outside is considered for both access links and backhaul links. The challenges are analyzed from antenna gains, atmosphere and so on. Possible solutions and way forward are provided.

1. Introduction

According to the International Telecommunication Union (ITU), the conservative estimated traffic of wireless mobile communication in 2020 exhibits a 25 to 100-fold growth ratio compared to 2010. And the total spectrum requirements for international mobile telecommunication system (IMT) will reach up to about 1600 MHz in average [1]. In order to support the explosive increase in wireless data traffic, transmission rates up to Gbps are required. Driven by the rate and spectrum demand, the millimeter wave (mmw) communication technique has become one of the most attractive techniques in next generation of IMT (5G).

With the development of very large scale integration (VLSI), many countries have opened the band around 60GHz for public uses, such as IEEE 802.11ad and WirelessHD. However, due to the short wavelength and susceptibility to external environment, the mmw has been mainly applied in indoor short-distance scenarios, typically less than 100m. Studies and experiments have been done to exploit the feasibilities of mmw communication outside. It is shown to be able to provide stable coverage to a region with a radius of 200~300 meters in [2]. The coverage can also be extended if relay is introduced [3]. Up to now, it is still an open issue for applying mmw in outside 5G systems. In this paper, a heterogeneous network framework is considered, in which we discuss how to use the mmw frequency in access links and backhaul links. We try to sort out the key points of related research, challenges and possible solutions, which involve the network infrastructure, technologies and factors that will affect the mmw communication.

2. Access Links

In 5G systems, the access links have to meet both requirements in high data rate and user mobility, especially in the outdoor scenario. In view of this, many mmw communication systems (CS) employ highly directional antennas and one possible solution is the developed beamforming technique. With beamforming, the antenna beam can track the mobile user and the gain from multiple antennas can extend the coverage effectively. Though the transmission distance limits the application of mmw in current 2G/3G/4G systems, it is sufficient for the deployment of small cells in future 5G systems. Meanwhile, since the ability of mmw in penetrating solid substances is limited, denser access points or relays might need to be deployed to guarantee full coverage of a complex area.

2.1 Antenna Designs

For mmw CS, shorter wavelengths lead to more severe attenuation and path loss than microwave CS within the same communication range. To overcome the feature, a great number of works have been proposed to design the antennas at both the transmitter and receiver. Thanks to the short wavelengths, the size of antennas can be made very small. If antennas of the same size are deployed at both the transmitter and receiver, a gain of 31.5dBi can be achieved by 90GHz mmw CS over 2.4GHz microwave CS. It reveals that the attenuation and path loss encountered by the mmw transmission can be significantly compensated by employing antennas techniques.

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For the antenna manufacturing, along with the rapid development of high accuracy machinery processing and microelectronic techniques, the antenna performance has been improved obviously. At present, the antenna transmitted at V-band and E-band can achieve a gain of 45dBi. It is another advantage of mmw CS that narrow beam transmissions with high performance gains can be realized. It is shown that horn antenna as well as distributed lens antenna, or integrated multiple antenna arrays can be utilized simultaneously to generate narrow beam and provide high power concentration [4]. Measurement results show that for antennas operating at about 60GHz, three-quarter of the power is concentrated within a beam width of 10 degrees [5]. However, in order to guarantee the wanted antenna performance at the mmw band, high machining accuracy is required, e.g., up to 10^{-5}, which obviously improves the manufacturing cost.

Furthermore, in order to achieve full coverage of a large area, a great number of antennas are required to be deployed. Therefore, in order to promote the application of mmw CS, it is essential to design the cost-effective antennas techniques, which are worth exploring in the future.

2.2 Digital Beamforming

In order to support the user mobility, the antenna beam is supposed to provide certain tracking capability. With the development of signal processing techniques and VLSI, digital beamforming is able to create antenna beams pointing at the desired direction flexibly. By changing the weights of the digital array signals, it can effectively promote the multi-user communications. At the receiver side, adaptive algorithms for the array antennas can also be implemented to eliminate interference in particular directions. As shown in Table 1, compared to other multiple-input-multiple-output (MIMO) techniques, the mmw MIMO shows an obvious advantage in capacity due to more available spectrum resources [6].

Table 1. Rate comparison among multi-antenna techniques and mmw MIMO

	Massive MIMO	Coordinated multi-point transmission	Single-user MIMO	**mmv MIMO**
Signal bandwidth	50MHz	50MHz	50MHz	**500MHz**
User/cell	8	2	1	**1**
bps/Hz per user	5.47 bps/Hz	4.34 bps/Hz	4.95 bps/Hz	**8.00 bps/Hz**
Capacity/cell	1.10 Gbps	434 Mbps	248 Mbps	**4.00 Gbps**

In addition, for each antenna element, the digital beamforming can compensate the fluctuations in amplitude and phase. And the error incurs from the mutual coupling between antennas elements can be decreased by calibrations. With a joint design on adjustment and equalization techniques, the maximum side lobe level in the radiation pattern of the antenna array can be further reduced. Furthermore, spatial-division multiple access can be performed easily because of the plenty of antennas and narrow beams.

In mmw band, there are more available spectrum than current 2G/3G/4G systems, in which the spectrum are typically less than 3GHz and the bandwidth is 5-20MHz for one operator. However, it is more difficult for signal acquisition of the antenna elements due to the short wavelength in the mmw band. Meanwhile, for the antenna array, the wide band will cause higher noise power. Therefore, in addition to different delays or directions, advanced coding and modulation schemes should also be carefully considered in the designs of digital beamforming, which is worthy to be future studied.

3. Backhaul Links

The abovementioned transmissions of multiple users in access links put forward higher requirements to the backhaul links, which demand not only high transmission data rates but also long distances. With the help of antennas with good directivity, the E-band mmw CS modulated with 64QAM can achieve a data rate of 2.5Gbps in a distance of 1km [7]. Systems operating at 30GHz, with a longer wavelength than the E-band mmw, are more robust to the weather changes. In addition, the diffraction and penetration abilities of mmw will also influence the backhaul link significantly.

3.1 The Effect of Atmosphere

Firstly, the attenuations due to the atmospheric molecule absorption should be paid attention to. The exposition of the microwave spectroscopy has been shown in Fig.1, where oxygen, carbon dioxide and water in atmosphere are the main sources of the absorption of electromagnetic radiation. Absorption by oxygen and carbon dioxide reach peak values in certain spectrum and the water molecule in the gaseous state causes the most absorption. Fortunately, there are some atmospheric windows where the absorption of electromagnetic radiation is relatively weak such that the radiation power can pass through, e.g., 0.3~1.3um, 1.5~1.8um, 2.0~2.6um, 3.0~4.2um, 4.3~5.0um, 8~14um, and etc.

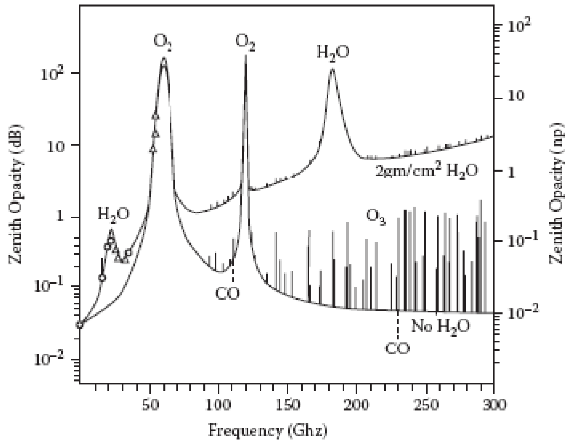

Fig.1. Atmospheric zenith opacity reported by Staelin (1966), Altshuler et al. (1968), and Carter et al. (1968).

Besides the atmospheric molecular absorption, the attenuation caused by different rainfall intensities should also be considered. In addition to absorption effect, the most important reason of rain attenuation is scattering, which relies on the diameter of particles, e.g., particles with diameter of $d_r = 3.3R^{-0.08}$ where R denotes the rain rate. Rayleigh scattering occurs if the diameter of particles is much smaller than the radio wavelength, which can be caused by fog, cloud or light rain (diameter from 0.01um to 800um). When the size of the particles is of the order of the wavelength, Mie scattering occurs, which can be caused by moderate to heavy rainfall (diameter from 3um to 3mm) [8]. Under the condition of heavy rainfall where the diameter could reach 3mm, the corresponding absorption and scattering of mmw will severely affect the transmission ability. For mmw CS working at 28GHz, where the wavelength is longer than 3mm, the rain attenuation is relatively small and acceptable. The attenuation under the condition of heavy rainfall reaches 7dB/km, which indicates only an attenuation of 1.4~1.5dB in 200m.

Besides, in heavy rainfall, the raindrop is not spherical and will cause more attenuation. For the non-spherical raindrops whose long axis is vertical, the attenuation suffered by vertical polarization waves is at least 10% greater than horizontal polarization waves.

3.2 The Penetration and Diffraction Abilities

In the backhaul link, the electromagnetic waves are usually obstructed by the ground obstacles. It depends on the penetration and diffraction abilities of the radiations for the signals to pass through the obstacles in the transmission path. In mmw band, effective communications generally require the pair of transmitter and receiver located in the line-of-sight (LOS) coverage. Therefore, the obstacles around the transmitter or receiver or near the LOS path between will significantly influence the performance. For example, measurement results show that when there is 1~3 trees between the transmitter and receiver, the attenuation caused by each tree can vary from 10-40dB, depending on the type of the trees, e.g., deciduous trees (low losses) or coniferous trees (high losses). And the gaps between trees leaves fluctuate with wind. This leads to unstable power receptions when the radio waves pass through the trees. Furthermore, the trees located 10~20m away from the transmitter or receiver may block the mmw signals.

The mmw radiations also have relatively weak diffraction abilities. As shown in [9], measurement results show that due to the short wave lengths, mmw cannot pass through an obstacle of thickness more than 10 cm (>160dB losses), which indicates that it is difficult for mmw to pass through buildings in outdoor environment. However, for typical indoor materials, low losses (<10dB) are incurred. Thus such degree of isolation of outdoor and indoor networks brings out a feasible solution for future 5G systems. Considering the limits that large buildings will seriously hinder the mmw transmission, it is necessary to increase the height of the antennas. In addition, it is also useful to overcome the shading effect by introducing overlap coverage between neighboring cells. Besides, deployments of intermediate relays can also help forward the signals but with the cost of additional equipment as well as complexity, which are also worth studying.

4. Conclusion

In this paper, a possible framework for the mmw heterogeneous network from the aspects of access links and backhaul links are discussed. As a feasible solution, the base station might be worked at the E-band equipped with the mmw antenna array, which is able to support backhaul links to an access point that is in a range of 1km. The access link equipped with multiple antennas that might work at 28GHz can cover an area with radius of 200 meters. The small size directive antennas and the steerable beams make the multi-antenna technique a key transmission technique to achieve high data-rate user access. Besides, in order to overcome the impact of atmosphere, rain, ground obstacle, and etc., the access points can also serve as relays. Taking into account the penetration ability of mmw, different access points should be deployed in the indoor and outdoor communication scenarios respectively.

Due to the page limits, some challenges are not mentioned such as the modulation scheme for mmw backhaul links. There is still plenty of work to do to promote the mmw CS in 5G. However, in view of its advantages, it is believed that joint designs on the mmw technique and corresponding transmission techniques will provide a feasible solution to high data rate wireless transmission for 5G and significantly alleviate the congestion in the spectrum below 6GHz.

5. Acknowledgments

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