International Journal of Engineering Applied Sciences and Technology, 2023
Vol. 8, Issue 05, ISSN No. 2455-2143, Pages 06-16
Published Online September 2023 in IJEAST (http://www.ijeast.com)

MILIMETER-WAVE MASSIVE MIMO: A PROMISING TECHNOLOGY FOR NEW AND EMERGING NETWORKS

Anioke Chidera Linda
Department of Electronic and Computer Engineering
University of Nigeria, Nsukka

Eleje Samson Ejiofor
Department of Electrical Electronic Engineering Technology
Federal Polytechnic of Oil and Gas, Bonny

Abstract: **This paper presents a review of the mm Wave technology and the massive MIMO technology first as individual technologies detailing their potentials and challenges. It also presents a review of the combined technologies, their channel models, various spectrum, interference and handover management schemes as a promising technology for new and emerging networks.**

Keywords: **MIMO, massive, mmWave, Channel, spectrum**

I. INTRODUCTION

The exponential increase in data traffic as well as the volume of users in emerging wireless networks and mobile communication systems has increased the need for high bit rate data services [1, 2]. Advancements in wireless technologies and antenna array configurations has increased the volume of ongoing researches in wireless channel modeling. A promising technology that will provide the required data rates for new and emerging wireless networks if harnessed properly is the mmWave massive MIMO. mmWave massive MIMO is a blend of the characteristics and potentials of the mmWave and massive MIMO technologies. For achievable capacity gains, mmWave massive MIMO is combined with small cell technology (pico and femtocells) that work at high frequency ranges (e.g. 60 GHz) within the macro cell area. Small cells that operate on the same frequency band can significantly increase the capacity of a mobile network to 100 folds. The extent of the increase depends on the number of small cells and the frequency reuse method employed.

A. mmWave technology

The demand for robust data rates and throughput with little or no congestion has led radio technology designers to shift attention to higher frequencies within the mmWave band (30 t0 300GHz).

The mmWave band, shown in figure 1, offers a huge range of frequencies for mobile communication applications. The huge bandwidth at 60 GHz band is among the main unlicensed bandwidths being allocated in history [3]. This huge bandwidth can be utilized to achieve improved capacity and flexibility which makes 60 GHz technology particularly attractive for gigabit wireless applications [3]. The design of most mmWave communication systems is suitable for short-range line-of-sight (LOS) indoor applications such as wireless personal area networking (WPAN) and wireless local area networking (WLAN). The reason being that the mmWave have narrow beam width that focuses its radiations in the direction of propagation. To this effect, the free space path-loss in non-line-of-sight (NLOS) outdoor environment, mmWave signals with acceptable strengths can be received within the range of 200 meters if smaller cell sizes are used. This property makes the use of mmWave technology feasible and attractive for future cellular networks with relatively small cell coverage.

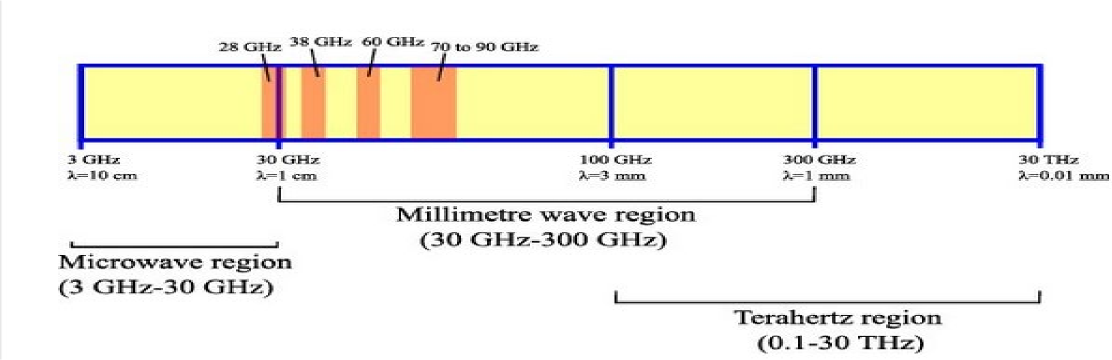

Fig.1.Wireless electromagnetic regions –the microwave region to the terahertz region [8].

B. Potentials/Challenges of mmWave technology

The third generation (3G) and fourth generation (4G) network standards were known to run in the microwave frequency band ranging from 3-30GHz. Scattering phenomenon is omitted when exploring transmissions at lower frequencies (e.g. 2.4 GHz, 3.1 - 10.6GHz) due to its wavelength (λ) of 12.5cm and 2.8cm at 2.4 GHz and 10.6GHz respectively. For scattering effect on the incident signal to count, its λ must be less in value than the surface roughness of the substance on which the signal falls [4]. In some materials whose surface roughness is in millimeters, the effect on incident signals are neglected. However, with the emergence of technologies such as the internet of things (IOT), fifth generation (5G), and other emerging networks and systems, the propagation uniqueness of the communication link continues to change significantly. These technologies have been developed to leverage the higher frequency wave bands such as the millimeter wave (mmWave) and the terahertz (THz) frequency bands. Unlike the microwave frequency bands, the high mmWave frequency bands (typically 30-300GHz) have very short wavelength (λ) in the order of millimeters. The value of λ, is negligible when compared to the characteristic vertical deviations on most incident surfaces on which the transmit signal falls. Therefore, the most pronounced limitations of mmWave propagation are (a) higher indoor path-loss due to higher carrier frequency, (b) outdoor path-loss and signal attenuation resulting from rain, foliage, and atmospheric absorption. Atmospheric attenuation resulting from oxygen absorption or heavy rain can be on the order of 10–20 dB/km (c) the effect of scattering on the propagating signal, (d) increased effect of signal blockage on incident surfaces (e) noise power effects caused by using larger bandwidths.

C. Massive MIMO technology

The technology that supports multiple antennas at both the transmitter and receiver units are referred to as multiple input multiple output (MIMO) technology. The massive MIMO (mMIMO) network is an extended MIMO technology that supports large number of antenna elements located at the base stations to serve relatively fewer user equipment (UE) simultaneously. This large number of antennas elements enables each BS to concentrate the radiated energy to serve a particular user in space or to intercept radiated energy more efficiently. Therefore, Massive MIMO offerimproved spectral efficiency and energy efficiency compared to conventional multiuser MIMO systems. As shown in figure 2, massive MIMO has the advantage of beam steering, which offers the possibility of serving many user equipment (UE) simultaneously in the same cell using the same frequency.

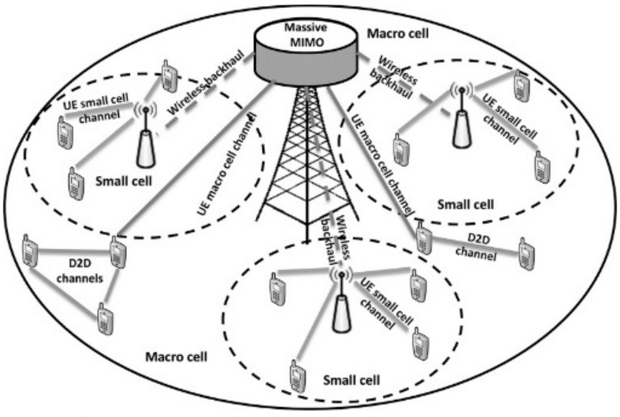

Fig.2.Massive MIMO technology in a heterogeneous network [9]

D. Potentials/Challenges of massive MIMO

The amount of bits of information that is transmitted and/or received through cellular communication links in Massive MIMO increases exponentially with the number of antenna, even under pilot contamination. The edge massive MIMO concept has over other concepts lies in its efficiency in power consumption [6]. Being energy efficient places Massive MIMO network above other promising technologies for next generation of cellular network .

standards. The key challenges associated with massive MIMO include the need to develop cost effective antennas, application of a plain duplexing scheme (TDD or FDD), reparation of hardware impairments, channel characterization, channel feedback, channel reciprocity, pilot contamination, pilot overhead in channel estimation e.t.c. Another challenge that faces massive MIMO is small fading effects and additive noise especially for a very large antenna array.

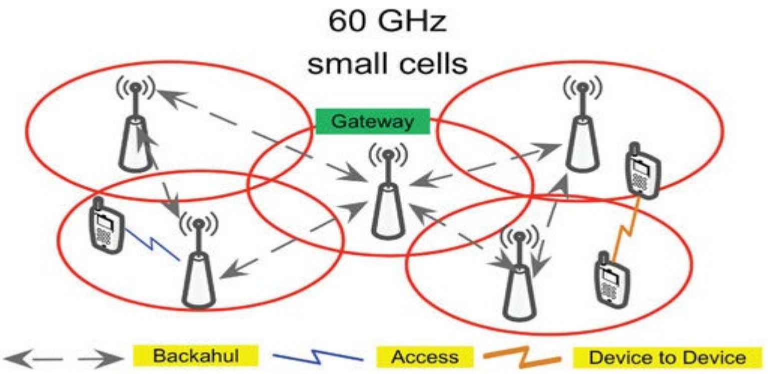

Fig. 3. mmWave small cells [10]

E. MmWavemasive MIMO

The smaller wavelengths of mmWave makes it practically feasible to pack a large number of antennas with reasonable form factors at both the transmitter and receiver to achieve highly directional communication and reduce propagation losses [11]. However, propagation losses are proportional to the square of the carrier frequency which means a decrease in the received power by the square of the wavelength [6, 7]. The increase in the number of antenna elements unto the same physical area increases the directional antenna gains by $\frac{1}{\lambda^2}$. This increase reduces the effect of the propagation loss resulting from mmWave frequencies while extending coverage at longer ranges. The reduction in channel coherence time at mmWave frequencies is offset by the lower mobility caused by small range and hence the higher channel coherence bandwidth due to operation in small cells, and the shorter wavelength associated with higher frequencies is appealing for massive MIMO transceiver designs since the physical dimensions of the antenna array and associated electronics are miniaturized. Therefore, systems that employ both Massive MIMO and mmWave technologies may be the key solution for future 5G mobile communication.

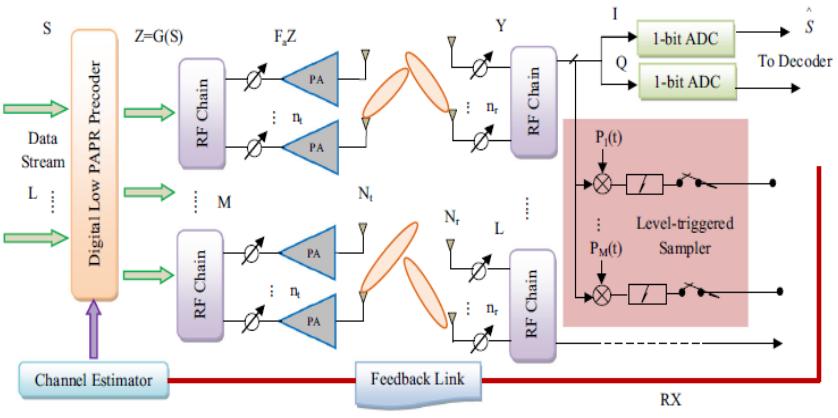

Fig. 4. System model of the mmWave massive MIMO [17]

F. **Potentials/Challenges of millimeter-wave massive MIMO**

The characteristic short wavelength of mmWave frequency band is promising for massive MIMO owing to the fact physical size of the antenna elements can be significantly reduced. Smaller cell sizes are suitable for short-range mmWave systems, whereas the large antenna gains offered by massive MIMO is key to overcoming the severe path loss of mmWave signals [12]. A major advantage of the massive MIMO concept lies in its possibility to offer improved energy efficiency. A user in a massive MIMO system with perfect channel state information (CSI) can theoretically realize the same uplink throughput as with a single-antenna BS using only 1/Ntofthe necessary transmits power [6]. A massive mmWave multi-antenna system would have a minimal form factor than designs executed at existing frequencies, and would benefit from the orders of magnitude increases in available signal bandwidth. The limitations of mmWave massive MIMO cut-cross communications theory and engineering. These challenges include information theoretic issues, inadequate 3D channel models, the demand for antennas and radio frequency transceiver design, multiple access technique, channel estimation issues, channel modulation and energy efficiency, interference and mobility management, health and safety issues [6, 12] and so on. Some of the issues around antennas and radio frequency (RF) transceiver design are the need for high-efficiency antennas, low mutual coupling and RF channel crosstalk, stable and coherent local oscillator distribution, sharing of transceiver resources, modular and easily scalable architectures, RF issues and antenna integration, as well as the choice of carrier frequency, signal bandwidth, antenna directivity, antenna geometry, array size etc. An RF factor that affects mmWavem MIMO systems is the beam forming/precoding technique. Different beam forming/precoding technologies in literature and their challenges will be presented.

II. CHANNEL MODELS FOR MMWAVE MMIMO SYSTEMS

Generally, the channel model of the mmWave massive MIMO systems is modeled after the popular Saleh-Valenzuela narrowband cluster channel model. This is based on scattering and large tightly-packed antenna elements that are characteristic to mmWave transceivers and massive MIMO systems. The large antenna array closely packed together, experiences high levels of antenna correlation. However, different antenna arrays have specific impact depending on the antenna beam steering vector. The mmWave massive MIMO channel matrix **H**may be expressed as

$$\mathbf{H} = \sqrt{\frac{\mathrm{N_t N_r}}{\mathrm{L}}} \sum_{\mathrm{l}=1}^{\mathrm{L}} \alpha_\mathrm{l}\, \mathbf{a_r}(\vartheta_\mathrm{l}^\mathrm{r}, \theta_\mathrm{l}^\mathrm{r}) \mathbf{a_t}(\vartheta_\mathrm{l}^\mathrm{t}, \theta_\mathrm{l}^\mathrm{t})^\mathbf{H}$$

Where L represents the number of channel paths, $\alpha_\mathrm{l}$denotes the complex gain of the lth path, $\mathbf{a_r}(\vartheta_\mathrm{l}^\mathrm{r}, \theta_\mathrm{l}^\mathrm{r})$and $\mathbf{a_t}(\vartheta_\mathrm{l}^\mathrm{t}, \theta_\mathrm{l}^\mathrm{t})$ represent the receive and transmit array steering vectors with $\vartheta_\mathrm{l}^\mathrm{r}(\vartheta_\mathrm{l}^\mathrm{t})$ and $\theta_\mathrm{l}^\mathrm{r}(\theta_\mathrm{l}^\mathrm{t})$ denoting the lth path azimuth and elevation angles of departure and arrival (AOD/AOA).The Uniform Linear Array (ULA) with N antenna elements has an array steering vector is represented as

$$\mathbf{a}_{\mathrm{ULA}}(\vartheta) = \frac{1}{\sqrt{\mathrm{N}}}\left[1, \mathrm{e}^{\mathrm{j}\frac{2\pi}{\lambda}\mathrm{d}\sin(\vartheta)}, \dots, \mathrm{e}^{\mathrm{j(N-1)}\frac{2\pi}{\lambda}\mathrm{d}\sin(\vartheta)}\right]^\mathrm{T}$$

The Uniform Square Planar Array (USPA) was used in [18] to model$\sqrt{\mathrm{N}} \times \sqrt{\mathrm{N}}$ antenna elements. The array response vector of the lth path is given as

$$\mathbf{a}_{\mathrm{USPA}}(\vartheta, \theta) = \frac{1}{\sqrt{\mathrm{N}}}\begin{bmatrix} 1, \dots, \mathrm{e}^{\mathrm{j}\frac{2\pi}{\lambda}\mathrm{d}(\mathrm{p}\sin\vartheta\sin\theta + \mathrm{q}\cos\ \ \theta)}, \dots, \\ \mathrm{e}^{\mathrm{j}(\sqrt{\mathrm{N}}-1)\frac{2\pi}{\lambda}\mathrm{d}\sin\vartheta\sin\theta + (\sqrt{\mathrm{N}}-1)\cos\theta} \end{bmatrix}^\mathrm{T}$$

where d represents the antenna spacing and λ denotes the wavelength. The parameters p and q are defined as the channel indices in the 2-dimensional plane and defined analytically as $0 \leq \mathrm{p}, \mathrm{q} < \sqrt{\mathrm{N}}$.

The channel matrix for the ray tracing technique was used to model mmWave massive MIMO in [17]. The model also considers L propagation paths within which exist rays and clusters.

III. UNIQUE ADVANTAGES OF THE MMWAVE MASSIVE MIMO SYSTEMS

MmWave massive MIMO technology offers several unique advantages. Here are some of its peculiar advantages:

i. Large Bandwidth**:** mmWave frequencies provide access to large bandwidths, enabling high data rates and increased capacity [19, 21-23]. The availability of abundant spectrum allows for the allocation of wider channels, which is particularly beneficial for Massive MIMO systems. With a larger bandwidth, more data can be transmitted simultaneously, leading to improved spectral efficiency and higher throughput.

ii. Spatial Multiplexing: The use of mmWave frequencies enhances spatial multiplexing capabilities, as the smaller wavelengths enable closely spaced antenna arrays [20, 23]. This results in higher spatial resolution, allowing for increased capacity and better performance. A mmWave massive MIMO system utilizing a distributed antenna architecture can achieve significantly higher multiplexing gain compared to a system with a co-located antenna architecture [23, 24].

iii. Higher Antenna Directivity: Compact massive antenna arrays can be utilized in mmWave communication systems to improved antenna directivity [28] and beam forming capabilities. Massive MIMO systems leverage this enhanced directivity to create highly focused beams, thereby compensating for the increased path loss at mmWave frequencies [26, 27]. The ability to direct beams towards specific users increases the signal strength and improves overall coverage [32, 38].

iv. Reduced Interference: The use of mmWave frequencies inherently mitigates interference as a result of the smaller wavelength as well as narrower beams [27]. The highly directional beams in Massive MIMO systems combined with the high path loss at mmWave frequencies result in reduced interference from other cells or nearby base stations operating on the same frequency [26]. This enables better signal quality and increased system capacity. However, the likelihood of encountering destructive interferences is heightened in the millimeter wave bands [29] but with SIC [30], the interference from other users can be taken care of.

v. Enhanced Frequency Reuse: Spectrum scarcity is mitigated by proper allocation [37] and effective utilization of the available spectrum through frequency reuse [36]. In 3D spectrum reuse, the frequency of reuse increases with frequency of the spectrum [31]. Due to the narrow beams and reduced interference, mmWave massive MIMO systems can achieve efficient frequency reuse [39]. By directing beams towards specific users, the same frequency resources can be reused in neighboring cells without significant interference. Inherent inter-cell interferences due to frequency reuse are mitigated through schemes such as fractional frequency reuse (FFR) [33], and Dynamic Fractional Frequency Reuse (DFFR) method [34, 35]. Spectrum reuse with interference reduction schemes enables higher capacity [33, 40] and denser deployments [32], making mmWave an attractive technology for urban environments with high user density.

IV. SPECTRUM MANAGEMENT IN MMWAVE MASSIVE MIMO SYSTEMS

As a result of spectrum scarcity, frequency planning significantly improve the utilization of the available spectrum [43]. However, reusing frequency in neighboring cells creates interferences among users [32, 23]. Some key spectrum management techniques in mmWave massive MIMO are:

i. Spatial Frequency Reuse (SFR): SFR is a frequency reuse technique that exploits the spatial dimension by dividing the coverage area into multiple sectors or zones. Each sector or zone is assigned a different set of frequencies, enabling frequency reuse in a coordinated manner. In [44], spatial reuse is applied where the same frequency resource is used for both backhaul networks and access links with no cross link interference [44]. Spatial reuse helps to circumvent fibre-based backhauling on the bases of cost [45] flexibility and easy execution [46]. SFR optimizes the use of available spectrum resources while minimizing interference between neighboring sectors or zones.

ii. Fractional Frequency Reuse (FFR): FFR is a frequency reuse technique that divides the available frequency spectrum into multiple sub-bands. Diverse frequency reuse factors are applied to different regions of the cell, allowing for differentiated reuse patterns. FFR allocates a larger portion of the spectrum to the cell center, where interference is relatively low, and a smaller portion to the cell edge, where interference is higher. FFR optimizes the balance between interference mitigation and spectrum efficiency in mmWave Massive MIMO systems [55]. For efficient utilization of the spectrum, a unity reuse factor which make the entire bandwidth available for all the cells is necessary but with increased interference. However, a significant trade off in spectral efficiency is inevitable when a higher reuse factor is applied [42] which significantly mitigates inter-cell interference. FFR-based techniques primarily focus on addressing the challenges faced by users situated at the cell border, as they experience the greatest impact from co-channel interference.

iii. Cognitive radio (CR): Cognitive radio is a wireless communication standard that allows secondary users (unlicensed or opportunistic users) to dynamically access underutilized frequency bands without causing damaging interference to primary users (licensed users) by intelligent sensing [61]. The primary goal of cognitive radio is to address the concern of spectrum shortage and inefficiency and enable the coexistence of multiple users in a shared spectrum environment [59].

V. INTERFERENCE MANAGEMENT IN MMWAVE MASSIVE MIMO SYSTEM

MmWave frequencies are susceptible to elevated path loss and more severe attenuation as a result obstacles and atmospheric conditions. To overcome these challenges, Massive MIMO systems rely on dense deployment of small cells, which can cause interference concerns. Spectrum management becomes crucial in mitigating interference and ensuring efficient coexistence of neighboring cells. Receivers in interference zone experience high BER which degrades throughput and increases the latency because of frequent retransmissions [44]. Some techniques employed to manage interference in mmWave Massive MIMO systems are:

i. Block Diagonalization: Block diagonalization is a precoding scheme that provides an efficient way to manage interference in multi-user MIMO systems. By exploiting the knowledge of the channel state information and designing appropriate precoding matrices, it allows for simultaneous transmission to multiple users while mitigating inter-user interference [48-50]. This technique helps improve system capacity

[50], enhance user experience, and enable efficient resource utilization in multi-user MIMO scenarios.

ii. Hybrid beam forming: Hybrid beam forming is a technique used in millimeter-wave (mmWave) communication systems to achieve efficient beam forming with a reduced number of radio frequency (RF) chains [51]. It combines the benefits of analog and digital beam forming to achieve high gain and interference mitigation in mmWave environments [52, 80].
iii. Interference Alignment: Interference alignment (IA) is a technique that aims to align interference signals from multiple transmitters onto a subspace that is orthogonal to the desired signal subspace [57]. This technique allows multiple users to share the same frequency resources without causing significant interference to each other and significantly improve the data rate and the overall coverage [56]. However, IA is computationally intensive and requires perfect CSI [54] but achieves best degree of Freedom (DoF) [58]. A blind IA scheme proposed in [53] successfully controlled inter- and intra-cell interference using suitable message scheduling and appropriate antenna selection and achieved near-full DoF in the absence of CSI.
iv. Power Control: Power control techniques are used to adjust the transmit power of each user to mitigate interference [49]. By carefully controlling the transmit power levels either by fixed or adaptive control, interference can be managed and minimized, leading to improved system performance and reduced interference [62].
v. Interference Avoidance: Interference avoidance techniques aim to minimize interference by carefully selecting the operating frequencies, avoiding frequency bands with high interference levels. Interference avoidance techniques in mmWave MIMO systems are crucial for maximizing spectral efficiency, improving system capacity, and ensuring reliable communication. The scheme proposed in [60] leverage beam forming and TDMA to improve the throughput through interference avoidance.

VI. PATH LOSS COMPENSATION SCHEMES IN MMWAVE MASSIVE MIMO SYSTEMS

Path loss is an inherent phenomenon that limits the performance of mm-wave communication systems [65]. The signal strength decreases as it propagates through the transmission medium [66, 67] and degrades the system capacity [50]. While it is not possible to completely eliminate path loss, there are several techniques that can help mitigate its effects in mmWave massive MIMO systems:

i. Beam forming: Beam forming is a key technique used in mmWave systems to improve the signal strength and overcome path loss by using multiple antennas and steering the transmitted or received beams towards the intended direction [64]. Beam forming can focus the energy in a specific direction, increasing the signal power at the desired location but imposes a peculiar challenge of initial access [67].
ii. Massive MIMO: Massive MIMO systems employ a large number of antennas at the base station, allowing for spatial multiplexing and beam forming. The use of multiple antennas helps to combat path loss by increasing the signal power through spatial diversity and beam forming [63].
iii. Small Cell Deployment: Deploying small cells in a dense network architecture improves the signal strength and provide high data rates [71] by decreasing the distance between the transmitting and receiving devices. Denser the small-cell network, the better the throughput [70]. The main motivation of the mm-wave small-cells is to improve coverage for both LOS and NLOS scenarios [69]. This reduces the path loss effects and allows for more efficient communication in mmWave systems.
iv. Relay Nodes: Introducing relay nodes or intermediate points between the transmitter and receiver can help overcome path loss [72]. These nodes receive the signal and retransmit it to the destination. It effectively extends the range and improves the system capacity [73].
v. Adaptive Transmission Power: Adjusting the transmission power based on the channel conditions and distance can help compensate for path loss [74] and maintain energy efficient transmission [75]. Adaptive power control algorithms can optimize the power levels to maintain a desired signal-to-noise ratio (SNR) and compensate for the attenuation experienced in the propagation environment.
vi. Reconfigurable Intelligent Surfaces (RIS): RIS offers a promising approach to improve transmission environment in wireless communication systems by leveraging its reflection, manipulation capabilities, adaptability, and integration with beam forming. Through intelligent signal redirection, amplification, and focusing, RIS can mitigate the effects of path loss, enhance signal quality, and improve overall system performance [76].

VII. HANDOVER SCHEMES IN MMWAVE MIMO SYSTEMS

Handover (HO) is a key mobility management scheme that makes transferring an ongoing communication session from one base station (cell) to another as the user moves between cell boundaries or coverage areas possible. To provide better coverage in mmWave MIMO systems, base stations are densely deployed leading to frequent intercellular contacts [80]. Hence, increased HO with its attendant high signaling overheads [77] is unavoidable to ensure seamless connectivity and uninterrupted service during the transitions. Moreover, Ping-pong HO (PPHO) is highly probable which leads to additional overhead and inefficiency in energy consumption [80]. However, a reliable link with a reduced signaling overhead is maintained if the trajectory could be accurately predicted [78]. A handover decision-making scheme based on the Markov decision process (MDP) is proposed in [79]. The scheme avoids excessive vertical handovers by leveraging action elimination procedures to reduce latency and complexity. Unwanted HO initiations results in unstable network performances. Integration of jump Markov linear system (JMLS) and deep reinforcement learning (DRL) is applied in [81] to avoid the execution of undesirable HO. The scheme is updated at an interval using DRL and meta training procedures. Meta training is a strategy that leverages existing training data with similar characteristics to inform new decision-making processes. At full update, the reliance on acquiring entirely new training datasets for making decision in a new location is minimized [81]. A data-driven HO estimation scheme using recurrent deep learning (RDL) design in [83] achieved improved user experience, low latency, minimal signaling overhead, and reduced resource wastage. Fixed mobility management pattern(FMP) used in [82] reduced the frequency of HO and signaling overhead at increased latency. An Enhanced Handover scheme leveraging mobility prediction yielded a drastic increase in throughput with minimal retransmissions in both heterogeneous and homogenous network [84]. Also a predictive approach that integrates Vector Auto regression (VAR) and gated recurrent unit (GRU) is used in [85] achieved a lower signaling overhead and high accuracy in prediction.

VIII. CONCLUSION

The holistic review for the mmWave massive MIMO shows that it offers increase in data rates, throughput and energy efficiency for new and emerging technologies. Techniques employed to manage interference and spectrum as well as path loss compensation schemes have been discussed within the paper.

IX. REFERENCES

[1]. Goldsmith, A., Jafar, S. A., et al. (2003). Capacity Limits of MIMO Channels. IEEE Journal On Selected Areas in Communications, (pp. 128-140).

[2]. Arogyaswami J. Paulraj, Dhananjay A. Gore, et al. (2004). An Overview of MIMO Communications—A Key to Gigabit Wireless. Proceedings of the IEEE, 92(2).

[3]. Su Khiong Yong and Chia-Chin Chong. (2007). An overview of multi-gigabit wireless through millimeter-wave technology: potentials and technical challenges. EURASIP Journal on Wireless Communications and Networking.

[4]. Anioke Chidera Linda, NnamaniObinnaChristantus, Ani Ikechukwu Cosmas. (2020). "Investigating Indoor Scattering at mmWave Frequencies." International Journal of Scientific & Technology Research.

[5]. Zhouyue Pi, Farooq Khan. A millimeter-wave massive MIMO system for next generation mobile broadband. Samsung R&D America.

[6]. A. Lee Swindlehurst, Ender Ayanoglu, PayamHeydari, and Filippo Capolino. (2014). "Millimeter-Wave Massive MIMO: The Next Wireless Revolution?" IEEE Communications Magazine, September.

[7]. Fatimah Al-Ogaili and Raed M. Shubair. Millimeter-Wave Mobile Communications for 5G: Challenges and Opportunities. Conference paper.

[8]. Nicholas P. Lawrence, Brian W.-H. Ng, Hedley J. Hansen, Derek Abbott. (2017). "5G Terrestrial Networks: Mobility and Coverage - Solution in Three Dimensions." IEEE Access.

[9]. Daniel C. Araújo, TarasMaksymyuk, André L.F. de Almeida, Tarcisio Maciel, João C.M. Mota, Minho Jo. (2016). "Massive MIMO: Survey and Future Research Topics." IET Communications.

[10]. Chuhan Gao, Yong Li, Haohao Fu, Yong Niu, DepengJin, Sheng Chen, Han Zhu. (2017). "Evaluating the Impact of User Behavior on D2D Communications in Millimeter-Wave Small Cells." IEEE Transactions On Vehicular Technology.

[11]. Zeng, Y., & Zhang, R. (2015). Millimeter Wave MIMO with Lens Antenna Array: A New Path Division Multiplexing Paradigm. arXiv:1507.01699v1 [cs.IT].

[12]. Mumtaz, S., Rodriguez, J., & Dai, L. (Year). mmWave massive MIMO. sciencedirect.

[13]. El Ayach, O., Rajagopal, S., Abu-Surra, S., Pi, Z., & Heath, R. W. (2014). Spatially Sparse Precoding in Millimeter Wave MIMO Systems, IEEE Transactions on Wireless Communications.

[14]. Dai, L., Wang, B., Peng, M., & Chen, S. (2019). Hybrid Precoding-Based Millimeter-Wave Massive MIMO-NOMA with Simultaneous Wireless Information and Power Transfer, IEEE Journal on Selected Areas in Communications.

[15]. Lin, T., Cong, J., Zhu, Y., Zhang, J., & Ben Letaief, K. (2019). Hybrid Beamforming for Millimeter Wave Systems using the MMSE Criterion, IEEE Transactions on Communications.

[16]. Rao, L., Pant, M., Malviya, L., Parmar, A., &Charhate, S. V. (2020). 5G beamforming

techniques for the coverage of intended directions in modern wireless communication: in-depth review, International Journal of Microwave and Wireless Technologies

[17]. Reddy, G. N., Ravikumar, C. V., & Rajesh, A. (2022). Literature review and research direction towards channel estimation and hybrid pre-coding in mmWave massive MIMO communication systems, Journal of Reliable Intelligent Environments.,

[18]. Yu, X., Shen, J. C., Zhang, J., &Letaief, K. B. (2016). Alternating Minimization Algorithms for Hybrid Precoding in Millimeter Wave MIMO Systems, IEEE Journal of Selected Topics in Signal Processing.

[19]. Busari, S. A., Huq, K. M. S., Mumtaz, S., Dai, L., & Rodriguez, J. (2018). Millimeter-Wave Massive MIMO Communication for Future Wireless Systems: A Survey, IEEE Communications Surveys and Tutorials.

[20]. Yue, D., Nguyen, H. H., & Xu, S. (2018). Multiplexing Analysis of Millimeter-Wave Massive MIMO Systems, ArXiv abs/1801.02987. 2018.

[21]. Al-Samman, A.M., Rahman, T.A., Hindia, M.N., Daho, A., & Hanafi, E. (2018). Path Loss Model for Outdoor Parking Environments at 28 GHz and 38 GHz for 5G Wireless Networks. Symmetry. https://doi.org/10.3390/sym10120672

[22]. Tolulope T. Oladimeji, Pradeep Kumar, & Nicholas O. Oyie. (2022). Propagation path loss prediction modeling in enclosed environments for 5G networks: A review. Heliyon.

[23]. Dianwu Yue, Ha H. Nguyen, &Shuai Xu. (2019). Multiplexing Gain of Millimeter-Wave Massive MIMO Systems with Distributed Antenna Arrays. 2019 IOP Conf. Ser.: Earth Environ. Sci., 234(012101).

[24]. Yue, Dianwu, Shuai Xu, & Ha H. Nguyen. (2019). Diversity gain of millimeter-wave massive MIMO systems with distributed antenna arrays. EURASIP Journal on Wireless Communications and Networking.

[25]. Kei Sakaguchi, Takumi Yoneda, Masashi Iwabuchi, & Tomoki Murakami. (2021). Mmwave Massive Analog Relay Mimo. ITU Journal on Future and Evolving Technologies, 2(6)

[26]. I. Ahmed et al. (2018). A Survey on Hybrid Beamforming Techniques in 5G: Architecture and System Model Perspectives. IEEE Communications Surveys & Tutorials, 20(4), 3060-3097. DOI: 10.1109/COMST.2018.2843719

[27]. Kebede, Tewelgn, Wondie, Yihenew, &Steinbrunn, Johannes. (2020). Massive MIMO, mmWave and mmWave-Massive MIMO Communications: Performance Assessment with Beamforming Techniques. 10.21203/rs.3.rs-69959/v1.

[28]. Brilhante, D.d.S., Manjarres, J.C., Moreira, R., de Oliveira Veiga, L., de Rezende, J.F., Müller, F., Klautau, A., Leonel Mendes, L., & P. de Figueiredo, F.A. (2023). A Literature Survey on AI-Aided Beamforming and Beam Management for 5G and 6G Systems. Sensors, 23, 4359. https://doi.org/10.3390/s23094359

[29]. R. Hidayat, Rushendra, & E. Agustina. (2017). Digital beamforming of smart antenna in millimeter-wave communication. In 2017 International Conference on Broadband Communication, Wireless Sensors and Powering (BCWSP) (pp. 1-5).

[30]. D. Zhang, Z. Zhou, C. Xu, Y. Zhang, J. Rodriguez, & T. Sato. (2017). Capacity Analysis of NOMA with mmWave Massive MIMO Systems. IEEE Journal on Selected Areas in Communications,(pp.1606-1618). DOI:10.1109/JSAC.2017.2699059

[31]. Saha, RonyKumer. (2021). Spectrum Allocation and Reuse in 5G New Radio on Licensed and Unlicensed Millimeter-Wave Bands in Indoor Environments. Mobile Information Systems,(pp.5538820:1-5538820:21).

[32]. Wang, J., Weitzen, J., Bayat, O., Sevindik, V., & Li, M. (2019). Interference coordination for millimeter wave communications in 5G networks for performance optimization. EURASIP Journal on Wireless Communications and Networking. https://doi.org/10.1186/S13638-019-1368-6

[33]. Saquib, N., Hossain, E., & Kim, D. I. (2013). Fractional frequency reuse for interference management in LTE-advanced hetnets. IEEE Wireless Communications, (pp. 113-122). doi:

[34]. Hamza, Abdelbaset S., Khalifa, Shady S., Hamza, Haitham S., &Elsayed, Khaled. (2013). A Survey on Inter-Cell Interference Coordination Techniques in OFDMA-Based Cellular Networks. CSE Journal Articles, 116. http://digitalcommons.unl.edu/csearticles/116

[35]. Sastry, A. S., &Akhila, S. (2017). Resource Allocation using Dynamic Fractional Frequency Reuse: A Technique to Reduce Inter-Cell Interference at the Cells Edges. International Journal of Wireless Networks and Broadband Technologies,

[36]. Saha, R. K. (2020). 3D Spatial Reuse of Multi-Millimeter-Wave Spectra by Ultra-Dense In-Building Small Cells for Spectral and Energy Efficiencies of Future 6G MobileNetworks.Energies. https://doi.org/10.3390/en13071748

[37]. Saha, R. K. (2020). A New Paradigm for Spectrum Allocation in Millimeter-Wave Systems. ICSNC 2020: The Fifteenth International Conference on Systems and Networks Communications.

[38]. Mabrouki, S., Dayoub, I., Li, Q., &Berbineau, M. (2022). Codebook Designs for Millimeter-Wave Communication Systems in Both Low and High-Mobility: Achievements and Challenges. IEEE Access, (pp. 25786-25810).

[39]. Mehmood, K., Niaz, M. T., & Kim, H. S. (2018). Dynamic Fractional Frequency Reuse Diversity Design for Inter-Cell Interference Mitigation in Non-Orthogonal Multiple Access (NOMA) Multicellular Networks. Wireless Communications and Mobile Computing. doi: 10.1155/2018/1231047.

[40]. Seema, & Ashok. (2019). Analysis of Frequency Reuse Techniques in LTE Network. International Journal of Engineering Research & Technology (IJERT),

[41]. Thakre, K., Shrivastava, M., &Agwekar, A. (2019). Study and Analysis of Frequency Reuse for MU Massive MIMO Systems. International Journal of Engineering Research & Technology (IJERT),

[42]. do Rego, I. D., & de Sousa, V. A., Jr. (2021). Solution for Interference in Hotspot Scenarios Applying Q-Learning on FFR-Based ICIC Techniques. Sensors, 21, 7899. https://doi.org/10.3390/s21237899

[43]. Busari, S. A., Huq, K. M. S., Mumtaz, S., Dai, L., & Rodriguez, J. (2018). Millimeter-Wave Massive MIMO Communication for Future Wireless Systems: A Survey. IEEE Communications Surveys & Tutorials, 20(2), doi: 10.1109/COMST.2017.2787460.

[44]. Silard, M., Fabian, P., Papadopoulos, G. Z., & Savelli, P. (2022). Frequency Reuse in IABbased 5G Networks using Graph Coloring Methods. GIIS 2022: Global Information Infrastructure and Networking Symposium, Sep 2022, Argostóli, Greece. hal-03844951.

[45]. Li, Y., Luo, J., Stirling-Gallacher, R. A., &Caire, G. (2019). Integrated Access and Backhaul Optimization for Millimeter Wave Heterogeneous Networks. ArXiv, abs/1901.04959.

[46]. Feng, M., & Mao, S. (2016). Harvest the potential of massive MIMO with multi-layer techniques. IEEE Network, 30(5), (pp. 40-45).

[47]. Moayyed, M. T., Restuccia, F., &Basagni, S. (2020). Comparative Performance Evaluation of mmWave 5G NR and LTE in a Campus Scenario. 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada, (pp. 1-5).

[48]. Du, J., Wang, Z., Zhang, Y., Guan, Y., &Jin, L. (2021). Multi-user hybrid precoding for mmWave massive MIMO systems with sub-connected Structure. Wireless Com Network (2021), 2021:157. https://doi.org/10.1186/s13638-021-02031-0.

[49]. Fikry M. S., Shaaban, S., Esmail, N., &Abdelkarim, M. (2020). Power Allocation in 5G mmWave Networks with Massive MIMO and Block Diagonalization. Journal of Physics: Conference Series, 1447, 012026. doi:10.1088/1742-6596/1447/1/012026.

[50]. Patil, D. A. (2017). Block Diagonalization Based Beamforming. Degree Project In Electrical Engineering, Second Cycle, 30 Credits, Stockholm, Sweden.

[51]. Abdul HaqNalband, MrinalSarvagya, and Mohammed Riyaz Ahmed. (2021). Optimization of Precoder and Combiner in mmWave Hybrid Beamforming Systems for Multi-user Downlink Scenario. Journal of Applied Science and Engineering, (pp. 257-265.

[52]. Song Wang, Jingqi Huang, and Xinyu Zhang. (2020). Demystifying Millimeter-Wave V2X: Towards Robust and Efficient Directional Connectivity Under High Mobility. In Proceedings of The 26th Annual International Conference on Mobile Computing and Networking, London, United Kingdom(MobiCom’20)https://doi.org/10.1145/3372224.3419208

[53]. V. Kalokidou, A. Doufexi, and M. Beach. (2018). Blind Interference Alignment in Multi-Cell mmWave Access and Fronthaul. In 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), Chicago, IL, USA (pp. 1-5).

[54]. X. Chen and C. Yuen. (2014). Performance Analysis and Optimization for Interference Alignment Over MIMO Interference Channels with Limited Feedback. IEEE Transactions on Signal Processing, (pp.1785-1795).

[55]. R. Ullah, N. Fisal, H. Safdar, W. Maqbool, Z. Khalid, and A. S. Khan. (2013). Voronoi cell geometry based dynamic Fractional Frequency Reuse for OFDMA cellular networks. In 2013 IEEE International Conference on Signal and Image Processing Applications, Melaka, Malaysia (pp. 435-440).

[56]. J. Song, L. T. Tu, and M. Di Renzo. (2016). On the feasibility of interference alignment in ultradense millimeter-wave cellular networks. In Proceedings of the 2016 50th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, USA. doi: 10.1109/ACSSC.2016.7869557.

[57]. V. R. Cadambe and S. A. Jafar. (2008). Interference Alignment and Spatial Degrees of Freedom for the K User Interference Channel. In 2008 IEEE International Conference on Communications, Beijing, China (pp. 971-975

[58]. S. A. Jafar and S. Shamai. (2008). Degrees of Freedom Region of the MIMO X Channel. IEEE Transactions on Information Theory, (pp. 151-170).

[59]. M. Farooq-i-Azam, Q. Ni, M. Dong, H. Pervaiz, C. Zarakovitis, and F. Alsolami. (2022). Interference Avoidance in Cognitive Radio Networks Using Cooperative Localization. IEEE Systems Journal, (pp. 5120-5130).

[60]. K. S. Mohamed, M. Y. Alias, and M. Roslee. (2019). Interference Avoidance Using TDMA-Beamforming in Location Aware Small Cell Systems. Applied Sciences. doi: 10.3390/app9234979.

[61]. Abdulkadir, Y., Simpson, O., & Sun, Y. (2019). Interference Alignment for Cognitive Radio Communications and Networks: A Survey. Journal of Sensor and Actuator Networks, doi: 10.3390/jsan8040050.

[62]. Nugraha, T. A., Pamungkas, M. P., &Chamim, A. N. (2018). Title of the Article. Journal of Telecommunications and Information Technology, (pp. 31-36).

[63]. Jung, J. S., Lee, W. S., Lee, Y. R., Kim, J., & Song, H. K. (2021). Improved Hybrid Beamforming for mmWave Multi-User Massive MIMO. Computers, Materials & Continua, (pp. 345-359).

[64]. Abdullah, Q., Salh, A., Mohd Shah, N. S., Abdullah, N., Audah, L., Hamzah, S. A., ... Nordin, S. (2020). A Brief Survey and Investigation Of Hybrid Beamforming For Millimeter Waves In 5G Massive MIMO Systems. Solid State Technology, (pp. 1699).

[65]. [65] Hamdan, N. K. A., &Engiz, B. K. (2021). A Brief Review of Path Loss Models for mmWave Channels. European Journal of Science and Technology, Special Issue 29, (pp. 264-272).

[66]. Oladimeji, T. T., Kumar, P., &Elmezughi, M. K. (2023). Performance analysis of improved path loss models for millimeter-wave wireless network channels at 28 GHz and 38 GHz.Available: https://doi.org/10.1371/journal.pone.0283005.

[67]. Barati, C. N., Dutta, S., Rangan, S., et al. (2020). Energy and Latency of Beamforming Architectures for Initial Access in mmWave Wireless Networks. J Indian InstSci, (pp. 281-302). [Online].

[68]. Saraereh, O. A., & Ali, A. (2022). Beamforming Performance Analysis of Millimeter-Wave 5G Wireless Networks. Computers, Materials & Continua. doi: 10.32604/cmc.2022.021724.

[69]. Weiler, R. J., Keusgen, W., Peter, M., Filippini, I., Sciancalepore, V., &Haustein, T. (2015). Millimeter-Wave Small-Cell Deployment Scenarios as an Enabler for 5G Applications and Use Cases. IEEE Transactions on Wireless Communications, (pp. 1471-1486).

[70]. Athanasiadou, G. E., Fytampanis, P., Zarbouti, D. A., Tsoulos, G. V., Gkonis, P. K., &Kaklamani, D. I. (2020). Radio Network Planning towards 5G mmWave Standalone Small-Cell Architectures. Electronics 2020, 9, 339. doi: 10.3390/electronics9020339.

[71]. Gao C, Li Y, Fu H, Niu Y, Jin D, Chen S, Zhu H. (2017). Evaluating the Impact of User Behavior on D2D Communications in Millimeter-Wave Small Cells. IEEE Transactions on Vehicular Technology, (pp.6362-6377).

[72]. Alkhawatrah M. (2022). Buffer-Aided Cooperative Millimeter Waves for IoT Networks. Journal of Electrical and Computer Engineering, 2022,doi: 10.1155/2022/7474679.

[73]. Biswas S, Vuppala S, Xue J, Ratnarajah T. (2016). On the Performance of Relay Aided Millimeter Wave Networks. IEEE Journal of Selected Topics in Signal Processing, (pp. 576-588).

[74]. Saad S, Ismail M, Nordin R, Ahmed A. (2016). A fractional path-loss compensation based power control technique for interference mitigation in LTE-A femtocell networks. Physical Communication, (pp.1-9).

[75]. Kaushik S, Agrawal M, Mondal HK, Gade SH, Deb S. (2017). Path loss-aware adaptive transmission power control scheme for energy-efficient wireless NoC. 2017 IEEE 60th International Midwest Symposium on Circuits and Systems (MWSCAS), (pp. 132-135).

[76]. Yildirim I, Koc A, Basar E, Le–Ngoc T. (2022). RIS-Aided Angular-Based Hybrid Beamforming Design in mmWave Massive MIMO Systems. GLOBECOM 2022 - 2022 IEEE Global Communications Conference, (pp. 5267-5272).

[77]. Khosravi S, Ghadikolaei HS, Petrova M. Learning-based Handover in Mobile Millimeter-wave Networks. IEEE Transactions on Cognitive Communications and Networking, (pp. 663-674).

[78]. Mohamed A, Onireti O, Hoseinitabatabaei SA, Imran M, Imran A, Tafazolli R. (2015). Mobility prediction for handover management in cellular networks with control/data separation. 2015 IEEE International Conference on Communications (ICC), (pp. 3939-3944).

[79]. Zang S, Bao W, Yeoh PL, Vucetic B, Li Y. (2019). Managing Vertical Handovers in Millimeter Wave

Heterogeneous Networks. IEEE Transactions on Communications, (pp. 1629-1644).

[80]. Alotaibi S. (2022). Key Challenges of Mobility Management and Handover Process in 5G HetNets. IJCSNS International Journal of Computer Science and Network Security,: https://doi.org/10.22937/IJCSNS.2022.22.4.18.

[81]. Chiputa M, Zhang M, Ali GGMN, Chong PHJ, Sabit H, Kumar A, Li H. (2022). Enhancing Handover for 5G mmWave Mobile Networks Using Jump Markov Linear System and Deep Reinforcement Learning. Sensors,: https://doi.org/10.3390/s22030746.

[82]. Ojesanmi OA, Vincent OR, Kassim MA, Osinuga O. (2022). A Mobility Aware Handover Scheme for 4G LTE System. Nigerian Journal of Technology (NIJOTECH), (pp. 980-989).

[83]. Ozturk M, Gogate M, Onireti O, Adeel A, Hussain A, Imran M. (2019). A novel deep learning driven low-cost mobility prediction approach for 5G cellular networks: The case of the Control/Data Separation Architecture (CDSA). Neurocomputing, 358, (pp. 479–489).

[84]. Yap K-L, Chong Y-W, Liu W. (2020). Enhanced handover mechanism using mobility prediction in wireless networks. PLoS ONE, e0227982. doi: 10.1371/journal.pone.0227982.

[85]. Bahra N, Pierre SA. (2021). Hybrid User Mobility Prediction Approach for Handover Management in Mobile Networks. Telecom, 2, (pp. 199-212).