Towards green communication in 5G systems: Survey on beamforming concept

Khalid S. Mohamed | Mohamad Y. Alias | Mardeni Roslee | Yusuf M. Raji

1 Centre for Wireless Technology (CWT), Faculty of Engineering, Multimedia University, Persiaran Multimedia, Malaysia
2 Fibre Optic Research Centre (FORC), Faculty of Engineering, Multimedia University, Persiaran Multimedia, Malaysia

Correspondence
Khalid S. Mohamed, Centre for Wireless Technology (CWT), Faculty of Engineering, Multimedia University, Persiaran Multimedia, Cyberjaya 63100, Malaysia. Email: khalidkaradh@hotmail.com

Abstract
Connectivity in recent wireless communication is accessible anywhere because of the large footprints of both cellular and WiFi networks. Yet, the broadcasting in wireless technology increases the susceptibility of signals to contemporary challenges such as interference, fading, and distortion. In addition, the energy of signals is lost because of Doppler effects and scattering caused by the obstacles in the channel. The use of smaller base stations, exploitation of higher frequencies and millimetre waves, and the expansion towards massive multiple-input multiple-output makes beamforming one of the most important key technologies in fifth generation (5G) systems. Besides the energy efficiency enhancements because of the narrower beamwidths, it reduces the broadcasting probability by adaptively steering the signals towards the targeted receivers while reducing the reception for nearby receiver, that is less interference. It also increases the energy efficiency of the signals because of the narrow beamwidth. In this work, the 5G technology challenges, two of the most known channel models, applications is briefly received. The fundamentals of beamforming technology are also described and provide the necessary information to understand the technology.

1 INTRODUCTION

Extensive deployment of fifth generation (5G) communication started to take place in few countries around the world [1]. Therefore, extensive studies on channel modelling and signal measurements with respect to the physics fundamentals are needed to properly design the architecture whereby such signals are precisely transmitted and received [2].

The motivation of using such technology is that it promises higher data rates and enhanced network performance relative to the existing ones. This is typically achieved by exploiting wider ranges of bandwidth in higher frequency bands, for example 30 Gigahertz (GHz) [3]. For instance, millimetre wave (mmWave) communication provides up to 10 Terabits data rates and spectral efficiency (SE) of approximately 100 bps/Hz over a bandwidth of about 270 Megabits per second (Mbps) (30–300 GHz frequency band) [4, 5]. Figure 1 shows the Federal Communication Commission (FCC) initiative of bandwidth allocation in 5G. Clearly, the existing long-term evolution (LTE) system will no longer be able to embrace the network demands such as data rates and spectrum needed neither solve for the challenges such as the excessive interference [6].

Given that, investigations on the performance of the system with respect to the operating frequency and bandwidth such as the Terahertz (THz) bandwidths are already ongoing because of the high capacity figures it provide. On the other hand, higher frequencies are extremely fragile especially in wider distances which enforces the fact that higher frequencies are best for indoor communications [7, 8]. This has encouraged researchers to investigate the possibility of designing transmitters that are able to radiate stronger signals without increasing the power, examples of such techniques are beamforming, and multiple-input multiple-output (MIMO). These techniques enable high signal gains and may extend the reach of the signals but it also increases antenna sizes, and the complexity of antenna designs at both transmitters and receivers. This is evidenced by the study in [9] which concluded that performance degradation is proportional to antenna size. The study has also highlighted some of the technical challenges that researchers should realise before approaching the technology. While massive MIMO and cell-free
technologies are deemed to be some of the exciting innovations for the 5G communication paradigm, beamforming extends the use of such technologies by exploiting the broad range of antenna elements to provide high security, enhanced energy efficiency (EE), good communication reliability, and low signal processing complexity. Cell-free technology is one of the areas that could adopt the beamforming technology to enhance the directivity and connectivity in wireless networks whereby a user is connected to several distributed antennas instead of the conventional systems to insure maximum sum rate reception. [10, 11].

Subsequently, interference is considered the most destructive factor to wireless communication systems [12]. Therefore, the availability of proper channel models of the conventional LTE communication system such as Rayleigh [13], Okumura-Hata [14] etc. has made it easy for researchers to investigate and propose innovative ways to overcome the interference issue. Nevertheless, the existence of limited channel representation that precisely model 5G channels may have limited the availability of realistic simulation models. In that regard, two famous channel models were developed to visualise and understand the signal behaviour, namely: the third generation partnership project (3GPP) [15] and New York university simulation (NYUSIM) [16].

On the other hand, electromagnetic radiations are generally categorised into non-ionising radiations such as infra-red, microwave, radio frequency etc., and ionising radiations such as X-rays. The non-ionising radiations define the ones that have insufficient energy to break the atoms and turn them into ions, that is it does not cause any damages to the human body. Whereas the ionising radiations at high doses increase the risks of cancer, birth and DNA defects etc. [17]. However, concerns of thermal heating caused by the electromagnetic radiations were raised. Therefore, the FCC limits the maximum exposure to radio frequency energy measured by the specific absorption ratio (SAR) to 1.6 watts per kilogram for mobile phones. The FCC approval indicates that the device will never exceed the maximum exposure levels, but it does not describe the consumers exposure during normal use [18].

Given that, consumers may accidentally overheat a specific part of their body, for example head, torso, legs etc. while using their phones, for example talking for long durations on the phone. Therefore, manufacturers advise to keep phone conversations short, use of plug-in earpieces, and that a minimum distance of 5–20 mm to be maintained between the consumer’s body and his/her phone. These recommendations make us wonder about the extent of the maximum exposure that human tissues can tolerate especially when considering cellular base stations that are deployed on top of houses and at the middle of residential areas. And while many people are happy with the pays of telecommunication companies for deploying cellular base stations on top of their houses, some are worried about the threats posed by these especially if the number of base stations is to be increased, for example in 5G communication systems. Despite the claims of the harmfulness of the electromagnetic signals, it can be said that through directional transmission, consumers’ concerns will be put to rest. Not only this, but quality of service will also be improved. Therefore, the motivation of this paper is to address the efforts of some researchers on beamforming methods which contribute to minimising the radiations in all directions and enhance the network performance. The contributions are summarised as follows:

1. Enhanced understanding of interference in 5G communication and beamforming methods that achieves less interference (i.e. green communication).
2. Summarised, yet efficient presentation on the important 5G channel modelling models.
3. The evaluations of different interference mitigation techniques provide clearer understanding of the effectiveness of beamforming techniques.
4. The presentation of different works on this issue promotes the work to be a reference for beamforming in future 5G systems.

The remainder of this paper is divided as follows: Section 2 describes the 5G systems and addresses the concerns in relation to it, the channel models are addressed in Section 3. Section 4 discusses the interference aspect in 5G systems and provides some of the research contributions that link beamforming and interference mitigation in 5G communication system. Beamforming fundamentals and how it can be implemented are presented in Section 5, and Section 6 summarises the paper.

2 | 5G COMMUNICATION SYSTEM

The motivation behind the development of 5G system (i.e. the rapid unprecedented growth of the network, and the increasing network demands) has triggered the researchers to approach the limitations of the fourth generation (4G) communication systems to underlay the new 5G system specifications and services. This network growth can be illustrated in Figure 2 in which the network supports numerous kinds of communications (e.g. agricultural monitoring services [19, 20], medical services [21] etc.). In such environments, the amount of information exchanged is impressively large which requires advanced technologies to cater for such. The relation between the frequency and the data rate is a major concern whereas low frequencies will not be able to support such demands and high frequencies cannot support wider coverages. Various studies concluded that the traffic is expected to grow to 24.3 Exabytes per month by 2019 on top of the requirements of emerging new services such as cloud computing, smart homes, drone systems, multimedia streaming, point-to-point communication etc. which has now been exceeded already. Therefore, 5G communication system is the revolution of wireless communication in which impressive applications and exceptional data rates and performance are supported. This necessitates fundamental changes in communication infrastructure and innovative realisation of the expected performance. Some of the 5G applications, services, and major challenges are described in the subsequent subsections.

2.1 | Internet of things

Due to the rapid changes and implementation of new technologies and the trendy nature of the term, internet of things (IoT) is one of the most misused and misunderstood term in modern day technology [22]. Many years have passed since the appearance of the term and its emergence as one of the major research topics in information and communications technology (ICT) [23]. While many have considered IoT to be only radio frequency identification (RFID) devices, others thought they were just sensor networks, others considered it as a form of machine-to-machine type of communication. The consideration of IoT as mere sensor networks or RFID devices stems from the fact that these two technologies were the main enablers of IoT [24]. The discordant definition of IoT by different scientific literature due to their niche segment and application also failed to offer much clarity on the term. Another reason for this ambiguity is the huge overlap between IoT and other research areas and the generational evolution of IoT itself.

However, IoT as defined by the international telecommunications union (ITU) is a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies [25]. This network of interconnected things promises to deliver
new services within and across industries. The "things" in IOT refers to objects in the physical world (physical things) or of the information world (virtual world) that are able to be identified and integrated into communication networks as illustrated in Figure 3. It could be a person with a heart rate monitor, a home with smart electric meter, an automobile with sensors and actuators to enable autonomous features, and so on. Referring to the definition given by ITU in [25], IOT can be loosely regarded as the seamless internet-like connection of billions of IOT devices (physical things) designed to perform non-complex tasks. These devices (physical things) which are usually equipped with sensors, actuators, processors and communication modules to perform a specific meaningful task are usually constrained by their limited capabilities in terms of computational power and storage resources. Although these limited capabilities may seem as a disadvantage at first, they are actually a desirable feature of IOT devices (physical things). IOT devices (physical things) are often required to be extremely power efficient, as they often work on batteries and are required to work for many years in the field under a single charge. Depending on their design and application, these devices will continuously gather, transmit, receive, manipulate, and act on data in real time over a particular time period without the need for human intervention. Such a continuous exchange of data has been envisaged to put a lot of pressure on the current network. The prediction that billions of IOT devices will be connected in the near future (an average of six to seven devices per person) has led to question as to how to connect all these devices with the current wireless infrastructure. The current infrastructure lacks the capacity to cater for all these with a minimal amount of lag. This, among many other reasons has led to the emergence of the 5G wireless network technology. 5G standards are designed to support IOT with promising features and tackle the challenges peculiar to the current 4G LTE standards. These features include [26]:

- **More connected devices**: the number of connected devices is expected to increase to at least 10 times more than the current figures.
- **Higher data rates**: similarly, least of 10 times higher data rates.
- **Less energy consumption**: comparatively lower energy consumption.
- **Ultra low latency**: extremely low latency of <1 ms.
- **Users per area volume**: the number of users per area is also expected to expand 1000 times higher.

The potential use cases for IOT may include [27]:

- **Smart home**: recent technologies enable automating of house appliances such as television, doors, thermostat, surveillance systems etc. and allow full control of the house from a remote location.
- **Smart cities**: this describes urban areas that utilises IOT sensor networks and technologies to collect, analyse, and process data such as air quality, temperature, and humidity.
- **Smart metering**: this is achieved through electronic devices that are able to record energy consumption and relay it to suppliers for billing and monitoring purposes.
- **Smart agriculture**: IOT also enables using modern technology to enhance not only the quality but the quantity of agricultural products through soil and data monitoring and managing, respectively.
- **Smart transportation**: in conjunction with the smart cities applications and sensors, this is expected to allow intelligent transportation in which no traffic congestion occurs.
- **eHealth services**: accessing and monitoring patients health records, conditions, diseases diagnosis, and remote surgery.
- **Environmental monitoring**: this helps in reducing the pollution, energy consumption, global warming etc.
- **Industrial control**: machineries in factories and industrial firms is reliable.
- **Smart wearables**: such as fitness and sports to monitor the physical performance during trainings.
- **Automotive driving or internet of vehicles**: self-driving and thinking vehicles to enable trip duration and road optimisation.

### 2.2 Requirements

There are seven key elements recognised by Samsung to enable 5G communication, these are: Gigabits data rate in both peak hours and cell edges, higher spectral efficiency, exceptional mobility, cost efficiency, continuous connectivity, and low latency [28]. In comparison to conventional communication systems, a 5G system is expected to deliver minimum data rates of 10 Gbps regardless of users locations. The network infrastructure is also expected to be much heavier than in LTE. Therefore, it is supposed to be acceptable price-wise. Nevertheless, it should be able to support cloud computing and storage.
The definition of clusters:

- of 0.5–100 GHz known as the mmWave [16, 30, 31]. The most model form 6 to 100 GHz while the former describes the model namely: the NYUSIM and the 3GPP . The latter describes the Mainly, two channel models are described in this section, about 10 bps/Hz. Hence, it adopts the usage of MIMO systems, also be capable of supporting a minimum spectral efficiency of for the system to be able to support high data rates, it should sensing for vehicles for instance is possible [29]. Furthermore, services, provide a latency of less than 5 ms in which pre-crash also be capable of supporting a minimum spectral efficiency of about 10 bps/Hz. Hence, it adopts the usage of MIMO systems, and advanced coding and modulation schemes. 5G systems are also expected to provide mobility on demand services for speeds up to 300–500 km/h.

3 1 CHANNEL MODELLING

Mainly, two channel models are described in this section, namely: the NYUSIM and the 3GPP. The latter describes the model form 6 to 100 GHz while the former describes the model of 0.5–100 GHz known as the mmWave [16, 30, 31]. The most evident differences are described below:

- **Line of sight model:**
  1. **3GPP**: described in Table 1.
  2. **NYUSIM**: it is similar to 3GPP model but with squared equations whereby the values are obtained based on ray-tracing approach.

- **Large scale pathloss**: The received signal $P^L$ in wireless communication systems is calculated simply by $P^L (dBm) + G(dB) + P^L$ whereby $P^T$ is the transmitter power, $G$ is the gain arguments, and $P^L$ is the large scale pathloss. Therefore, obtaining the pathloss gives a better realisation of the received power in 5G communication systems. Both 3GPP and NYUSIM adopt two different types of pathloss models, namely: close-in free space reference distance, and alpha–beta–gamma model whereby both models support different frequencies. However, NYUSIM includes the same mathematical formulas of both but with fewer parameters and provide simpler analysis and increases accuracy. The two pathloss models are provided below [1].

  1. **Close-in free space model**:

$$P^L = 32.4 + 10\log_{10}(d_{3D}) + 20\log_{10}(f_c) + \chi_\sigma$$  \hspace{1cm} (1)

whereby $d_{3D}$ is the 3D distance between the transmitter and receiver, $f_c$ is the carrier frequency in GHz, $\sigma$ is the pathloss exponent, $\chi$ is the zero-mean Gaussian random variable with a standard deviation $\sigma$.

  2. **Alpha–beta–gamma model**:

$$P^L = 10\alpha\log_{10}(D_{3D}) + \beta + 10\Gamma\log_{10}(f_c) + \chi_\sigma$$  \hspace{1cm} (2)

| Scenario          | LOS probability                              |
|-------------------|----------------------------------------------|
| RMa               | $R_{LOS} = \begin{cases} 1, & d_{2D} \leq 10m \\ \exp\left(-\frac{d_{2D}-10}{1000}\right), & 10m < d_{2D} \end{cases}$ |
| UMI - Street canyon | Outdoor users: $R_{LOS} = \begin{cases} 1, & d_{2D} \leq 18 \\ \frac{18}{d_{2D}} + \exp\left(-\frac{d_{2D}}{36}\right), & 18 < d \end{cases}$ |
| Indoor users: use $d_{2D-out}$ in the formula above instead of $d_{2D}$ |
| UMa               | Outdoor users: $R_{LOS} = \begin{cases} 1, & d_{2D} \leq 18m \\ \frac{18}{d_{2D}} + \exp\left(-\frac{d_{2D}}{36}\right), & 18 < d \end{cases}$ |
| Indoor users: use $d_{2D-out}$ in the formula above instead of $d_{2D}$ |
| Indoor - mixed office | $R_{LOS} = \begin{cases} 1, & d_{2D} \leq 1.2m \\ \exp\left(-\frac{d_{2D}}{4.7}\right), & 1.2m < d_{2D} < 6.5m \\ \exp\left(-\frac{d_{2D}}{32.6}\right), & 6.5m \leq d_{2D} \end{cases}$ |
| Indoor - open office | $R_{LOS}^{\text{open-office}} = \begin{cases} 1, & d_{2D} \leq 5m \\ \exp\left(-\frac{d_{2D}}{70.8}\right), & 5m < d_{2D} < 49m \\ \exp\left(-\frac{d_{2D}}{211.7}\right), & 49m < d_{2D} \end{cases}$ |

**TABLE 1** Line of sight probability in 3GPP model [15]
whereby $\alpha$ and $\Gamma$ are the pathloss dependency coefficients, and $\beta$ is the pathloss optimised offset.

It is noteworthy to mention that the described models are designed for omnidirectional transmissions. This is because joining multiple directional antenna gains does not contribute in calculating directional pathloss [16, 35, 36].

4 | INTERFERENCE IN 5G

All signals in its basic form experience fading and undergo huge losses in the channel. To illustrate this, we look at Figure 4 in which the wave propagation is described. In Figure 4a, the base station has an omnidirectional antenna in which signals are propagating in all directions equally. In that sense, the user equipments are supposed to receive equal signal powers. However, it is not achievable due to the unequal distance at which the users are located.

On the other hand, user equipments receive much more improved signal powers when beams are not radiated equally in all directions which is done using different types of antennas. The terminology of forming the beams to a specific direction is familiarly known as beamforming (Figure 4b). The function used in beamforming determines the shape and the direction at which the beam is directed, that is number of antenna elements, their arrangement, the separation of elements, and the phase of each signal fed into each antenna element.

In that regard, the work presented in [37] proposed a hybrid beamforming approach that is able to utilise the channel state information and come up with a beamsteering map codebook. The approach attempts to mitigate the interference between the sub bands caused by the carrier offsets of the orthogonal frequency division multiplexing (OFDM). Although the design seem to be complex, a digital beamformer with regulated channel inversion was used to lower the complexity.

In [38], a 5G-IOT smart virtual antenna array is designed to eliminate the interference by precisely directing the generalised frequency division multiplexing (GFDM) beams towards the targeted angles. Although the interference is mitigated, the performance raises few concerns due to the availability of limited higher frequencies channel models. On the other hand, the authors of [39] analysed the end-fire arrangement arrays to combat interference in MIMO infrastructure in 12.9 GHz frequency band. OFDM techniques were also used to suppress the interference of in-band null duplex channels. However, both reports did not discuss the performance in terms of bit error rates and throughput ratios.

The smart antenna is another approach in which the antenna is able to construct a different beam for each user at the simultaneously. The antenna can hop to any beam at any given time [40]. With the aid of smart antennas, other techniques can be used to suppress the interference [41] such as zero-forcing (ZF) of [42, 43], or time division multiple access (TDMA) techniques in [44].

In [45], a combined beam antenna that operates in 28 GHz frequency band is proposed. The design relies on combining two different radiating elements to obtain a wider beam that has a high gain. On the azimuth plane, wider beams are obtained by microstrip patches while the higher gain is achieved using a wave-guide aperture in the elevation plane. Besides the reduced antenna size, the antenna can also constructively reduce interference by optimising the radiation of the two radiating parts.

In [46], an uplink interference computation algorithm was designed for 70 and 80 GHz frequency bands to mitigate the interference by sectoring the cell zones and exclude certain zones from the transmission via switching off certain beams. Moreover, the spatial power control method helps in elevating the coverage area affects resulting from the beam on/off method. This also supports the fact that no coordination between the current and the 5G systems is needed.

In [47], the interference in 2.6 GHz frequency band is mitigated using beamforming whereby an array antenna consisting of 4 antenna elements that gives a $40^\circ$ beamwidth was used. The proposed scheme relies on estimating the locations of the users by obtaining the angles of the users in relation to their respective femtocells. Subsequently, the users are re-associated to the femtocell that gives the highest interference plus noise ratio (SINR). Although the spectral efficiency and throughput were considerably enhanced, the interference occurrence probability can inflate in dense deployment environments. The same authors in [48] improved the performance by utilising TDMA to time the transmissions instead of re-associating the users which improved the throughput even further and mitigated the outage probability to less than 5%.
It is understood that the amount of interference produced by an antenna that has a specific beamwidth, can be related to the distance between the antenna and the mobile station. Hence, it can be said that altering the radiation pattern of an antenna can significantly reduce the interference to the surrounding environment [49]. More works that utilised beamforming can be found in [50].

Technically, the transmitted or received beams can be represented in two ways, namely, Cartesian and polar. Although both represent the same thing, different information can be extracted from the two representation. For instance, the beamwidth information can be obtained from the Cartesian representation, and the angle at which the beam is directed can be obtained from the polar representation. It can now be understood that beamforming techniques can be exploited to achieve the following:

- **Enhanced signal quality**: narrower beamwidths have stronger directivity and longer coverage.
- **Less interference contribution**: users do receive some amount of neighbouring base stations signals due to the omnidirectional propagation of signals. However, if the beamwidths are narrowed down, the beams are said to be directed towards the desired users only, that is less interference.
- **Improved network capacity**: when beams are more directional, antenna gain is higher in which it increases the signal to SINR, and spectral efficiency. Thus, higher capacity.
- **Increased frequency reuse**: it also gives room for reusing the frequency in other beams whereby one beam does not interfere with other beams.
- **Mitigation of multipath effects**: the directivity of beams enhances the transmission which helps in mitigating the multipath effects.

Beamforming can also be categorised into analogue and digital beamforming whereby the latter defines the beamforming that is implemented by circuits and not the antennas. Therefore, static and dynamic beamforming can be categorised as analogue beamforming, while the transmit beamforming is considered digital. Analogue beamforming can be implemented using linear, circular, and planner array setups [51–53]. This can be implemented in both transmitter and receiver to obtain spatial selectivity. Figure 5 illustrates beamforming in the transmitter (Figure 5a) and receiver (Figure 5b) parts.
The work of [54] combined both low-dimensional digital and large-dimensional analogue processing to achieve hybrid beamforming in massive MIMO systems. The work also caters analysis on the required channel state information to achieve better SINR rates.

The authors of [55] also designed a hybrid beamformer for large scale antenna arrays that is comprised of an analogue phase shifter RF beamformer and a low-dimensional digital beamformer. Heuristic hybrid beamforming algorithm is also used a nearly full-digital beamforming. This achieves an improved performance in terms of spectral efficiency and sum rate.

In [56], the existence of 5G, mmWave, and non-orthogonal multiple access (NOMA) techniques is investigated. The characterisation of the performance of the proposed NOMA-mmWave scheme is done using stochastic geometry in a way that enables a high directivity transmission for the mmWave and achieve smaller communication overhead, enhanced sum rate, and less outage probability.

In [57], beamforming is used to enhance the communication in areas that utilise intelligent reflective surfaces (IRSs) point-to-point multiple-input single-output (MISO). The total received power is maximised by optimising the transmit beamforming at the transmitters. In return, users receive the direct signals after it reflects on the IRS. Beamforming in IRS-based applications is proven to be very effective as IRSs includes the channel in the optimisation process and the beamforming enhances the directivity of the transmitted signals.

Additional works that utilised beamforming to enhance the overall performance are briefly discussed in Table 2.

5 | FUNDAMENTALS OF BEAMFORMING

Here, we define the basics of the beamforming technology in which the familiar annotations and terminologies are described.

- **Weight vector**: for an antenna \( i \in S \) that has \( \mathcal{K} \) elements where \( \mathcal{K} = [1, 2, \ldots, |\mathcal{K}|, \mathcal{K}] \), each \( k \) antenna element is composed of certain components that define its radiation characteristics of this antenna, such components are referred to as weight vector \( \mathcal{V}_{k} \). Some refer to them as real and complex components and some refer to them as phase and amplitude components and are described below:

\[
\mathcal{V}_{k} = a_{k}e^{i\phi_{k}}
\]

whereby \( a_{k} \) and \( \phi_{k} \) are the amplitude and phase of \( k \) element, respectively. The strength of the main and side lobes of the radiation pattern is controlled by the amplitude while the phase controls the angles at which the beam is directed.

- **Steering vector**: to understand this, consider that multiple transmitted signals \( I = [1, 2, \ldots, |I|, I] \) arrive at a receiver in which each signal has a different weight vector. The vector of a received signal \( i \) (i.e. the array factor that describes the angle of arrival of that specific signal) is known as the steering vector \( a(\theta) \). Simply, if the main beam is directed by \( (\phi, \theta) \) whereas there is no interference in the channel, the antenna provides the maximum SINR levels.

  - **Null steering**: signals may often get attenuated by some interference either intentionally or unintentionally. Thus, null steering occurs simply when it is necessary to attenuate specific signals at specific angles. This can improve the systems’ performance substantially whereby interference is cancelled to obtain the best SINR levels.

  - **Grating lobes**: refers to the main lobes that are formed because of large element spacing.

5.1 | Beamforming types

The types are described below:

1. **Scanning**: this is familiarly used in radar applications whereby the beams scan the aperture back and forth searching for targets by increasing the weight vector of each element.

2. **Phased array**: the beams direction is changed by varying the phase of the weighting vector while the amplitude remains constant. In mobile communication, the direction of arrival (DoA) is utilised to identify the targets.

3. **Switched beamforming**: this denotes the existence of finite number of static beams in which high sensitivity occurs at the targets directions. Each of the beams is allowed the entire bandwidth and has different SINR level but the one with the best SINR is chosen to serve several users at different time slots.

4. **Sected beamforming**: the cell sectors are subdivided into narrower beams whereby one or more users are served using these beams. Unlike the switched beamforming, the bandwidth is divided among the sectors and further the beams. Although this may reduce the inter-beam interference but it increases the handoff probability.

5. **Adaptive beamforming**: this defines the use of spatial filtering that is used when desired signals use the same channel with interference signals. This is used because in such cases temporal filtering cannot be used to separate interference from the desired signals.

   (a) **Temporal reference**: it utilises a training sequence and compare it with the weights of the spatial signals in time domain.

   (b) **Spatial reference**: here, no training sequence is used. The desired signals are steered using the DOA information.

   (c) **Blind**: the weights of the signals are obtained with neither temporal nor spatial reference.

5.2 | Power and radiation in beamforming systems

The power in wireless communication systems is the one radiated by the antenna fields (electric and magnetic) towards the
| Paper | Main objective |
|-------|---------------|
| [58]  | Enhancing the min–max fairness and maximising the per user sum rate in both centralised and decentralised deployments |
| [59]  | Maximising the user SINR |
| [60]  | Enhancing the network capacity and user sum rate |
| [61]  | Enhancing the spectral efficiency |
| [62]  | Maximising the users' sum rate by optimising the uplink power optimisation |
| [63]  | Enhancing the spectral efficiency |
| [64]  | Uplink and downlink power allocation and fairness enhancement |
| [65]  | Energy efficiency enhancements in cell-free systems |
| [66]  | Positioning accuracy calculation in three-dimensional space with direction of arrival (DOA) measurement |
| [67]  | Smart ultra wideband circular antenna array at both transmitter and receiver to minimise BER in UWB communication system |
| [68]  | Proposal of deep learning framework for the optimisation of downlink beamforming |
| [69]  | Beamforming design to reduce the computational complexity compared to traditional weighted minimum mean-squared error (WM-MSE) algorithm |
| [70]  | Maximising the sum rate with lower computational complexity |
| [71]  | Control the sparse antenna array via adaptive beamforming |
| [72]  | Maximising the sum rate in cooperative and secure transmission in relay beamforming networks |
| [73]  | Compensate the propagation loss and enhance beamforming gains using hybrid analogue and digital beamforming |
| [74]  | Flexible spatial processing in mmWaves using digital beamforming |

| Techniques and characteristics |
|-------------------------------|
| Proposed a fully centralised beamforming method that uses the deep deterministic policy gradient algorithm (DDPG) with continuous space |
| Proposal of an optimum beamforming method for downlink transmissions in cell-free massive multiple-input multiple-output (MIMO) systems |
| Discussion of a fully decentralised design framework for cooperative beamforming by transforming the maximisation problem to an optimisation problem. The beamforming algorithm is updated using an alternating direction method of multipliers (ADMM) |
| Evaluation of the performance under different precoders utilisation (e.g., full pilot zero-forcing (fpZF), maximum ratio transmission (MRT), and modified regularised zero-forcing (mRZF)) by deriving the closed-form sum rate expressions. The design considers imperfect successive interference cancellation, Rayleigh channel conditions, and the intra-cluster pilot contamination effects as well as the interference |
| Compressing and expanding the signal to interference ratio by employing fractional power control |
| Proposal of heuristic threshold-based-beamforming (TBF) protocol which selects the access point that provides the best energy efficiency based in a threshold level that is determined using the eigenmodes of the strongest channel |
| Mathematical model based on Cramer–Rao lower bound (CRLB) concentration ellipsoid |
| Regulation of antenna feed length of transmitter and receiver array elements using genetic algorithm (GA) and self-adaptive dynamic differential evolution (SADDE) to minimize BER |
| Convolutional neural network (CNN) to construct three beamforming neural networks (BNN) to optimise signal-to-interference-plus-noise ratio (SINR) balancing, power minimisation, and sum rate maximisation |
| Unsupervised Deep neural network (DNN) in the downlink MIMO scenario to maximise sum-rate under power constraint of the total transmit power while accelerating the DNN computation using pruning techniques |
| Using deep learning based fast beamforming, virtual equivalent uplink channel is used to derive a heuristic solution structure for the downlink beamforming. The MMSE receiver categorises the problem into virtual uplink beamforming and power allocation designs. This will later enable designing a beamforming prediction network to optimise the power allocation and maximise the sum rate |
| Design or constrained normalised least-mean-square adaptive beamforming. The sparsity of the antenna is controlled by forcing the quantities of the antenna to select the suitable parameters for the adaptive beamforming |
| Designing the beamforming vectors for cognitive receivers, the beamforming matrix for the primary transmitters and a matrix for the artificial noise. A monotonic optimisation algorithm is also proposed to obtain optimal solution for the sum rate optimisation problem. |
| Optimising the hybrid transmitted and received beamforming vectors using alternating minimisation techniques. An eigenvalue decomposition based hybrid beamforming is also proposed to reduce the computational complexity |
| Using additive quantisation model to assess the effects of coarse quantisation at receivers and increase the quantiser resolution. |
receiving antenna. Considering a theoretical isotropic source, the power radiated can be viewed in a spherical shape and represented by perpendicular tangent far-fields with respect to the distance. The cross product of the electric $E$ and magnetic $H$ fields results in the Poynting vector $\mathbf{P}$ measured by Watts per meter square as follows:

$$ \mathbf{P}_i = \sum_{k \in \mathcal{K}} E_{ik} \times H_{ik} $$

(4)

The usefulness of the Poynting vector lies behind measuring the density of power at a distant receiver (located in $r$ distance). Mathematically, the power radiated by an isotropic source is calculated through the surface integral of the power density by Equation (5) where the power is neither a function of $\theta_i$ nor $\phi_i$.

$$ \mathbf{P}_i \in \{S\} \setminus s = \int_0^{2\pi} \int_0^{\pi} W(r_{\theta_i}) r_{\theta_i}^2 \sin^2 \theta_i d\theta_i d\phi_i $$

(5)

The radiation intensity $U_i$ on the other hand refers to the normalised power density inversely proportional to $r_{\theta_i}^2 \mathcal{V} \in \{S\} \setminus s$ in which it helps in determining the power levels at a distance. The power is then obtained by the following:

$$ \mathbf{P}_i \in \{S\} \setminus s = \int_{-\pi}^{\pi} U_i(\theta_i, \phi_i) d\Omega \ W_i $$

(6)

5.3 | Antenna beamwidth and directivity

The antenna beamwidth determines the angle that lies between the two points of the main lobe, that is strongest lobe. These points are referred to as the 3 dB or half power points. The beamwidth of antenna gives an idea of how wide the antenna radiation is but it does not indicate the direction of which the beam is directed. The antenna directivity can be determined by the following:

$$ D_i = \frac{\sum_{i \in \mathcal{I}} 4\pi U_i^{\max}}{\int_0^{2\pi} \int_0^{\pi} \sin \theta_i d\theta_i d\phi_i} $$

(7)

This weighs the constant power maximum directivity of antenna (i.e., the power density ratio to an isotropic antenna). It is meaningful to mention that the directivity does not describe the transmission line and conduction losses. Therefore, the metric that describes the radiation of an antenna that has an efficiency of $\eta$ including these losses is known as the gain $G = \eta D_i(\theta_i, \phi_i)$.

Subsequently, the intensity of radiation describes the antenna pattern in $\mathcal{X}, \mathcal{Y},$ and $\mathcal{Z}$ directions. Figure 6 allows us to understand the effects of power variations on the antenna surface beam pattern.

5.4 | Implementation of beamforming

In relation to previous sections, beamforming can be implemented by dynamically adjusting the phase shifts of the signals whereby the beams are directed towards the users in real-time fashion. In that sense, the technique is referred to as beamsteering.

Technically, this can be implemented by various configurations of antenna elements, that is arrays depending in the requirements of the design. Examples of such are listed below:

- **Linear**: elements are distributed along a linear plane separated by inter-element spacing $l_i$.
- **Circular**: elements are to be placed in a circular plane of radius $r_c$.

1 Named after John Henry Poynting (1852–1914).
- Planer: elements are placed over different planes, for example horizontal and vertical. In fact, circular array can be considered as a planer array.

The configuration of the array is important in determining the radiation characteristics such as directivity, side lobes, strength etc. which can be understood from the antenna radiation pattern as highlighted earlier. The radiation pattern is familiarly known as the array factor. To further understand this, we assume a linear array that consists of $\mathcal{K}$ elements spaced by $l = \frac{\lambda}{2}$, each element is having a complex weight of $Y_k$. Subsequently, the summation of the complex weights of all the elements that produces the beam directed towards $\theta_{\xi \in \{1\} \cup \xi}$ is known as the array factor obtained by the following:

$$P(\theta_{\xi \in \{1\} \cup \xi}) = \sum_{k \in \mathcal{K}} Y_k e^{j \frac{2\pi}{\lambda} k / \sin \theta_\chi + \kappa}$$

where $\beta = -\frac{2\pi}{\lambda} / \sin \theta_\chi$ is the beamforming vector. The phase lead $/ \sin \theta_\chi$ helps in calculating the angle of arrival and departure later on.

In relation to this, the angle of arrival and AoD are the angles that defines the arrival and departure of the beams with respect to a specific plane, respectively. In 5G, the angle of arrival and departure are very important in determining and estimating the channel conditions. Therefore, each of the previous models adopts its own method in calculating the angles.

Beamforming techniques are of great importance to 5G communication because of the high directivity that it provide which enhances both antenna gain and signal quality. It can also be understood that interference can easily be eliminated if the locations of the targeted users, devices, etc. are known which can be estimated by utilising the signals angles of arrival. However, interference elimination in switched, scanning, and sectored beamforming types is considerably difficult because of the complexity of identifying the interference when interferers are moving. On the other hand, it can easily be nullled out by the adaptive beamforming because the beamwidth is relatively narrower.

6 | CONCLUSION

In summary, system capacity and signal quality can be improved by reducing the interference and minimising the fading effects that signals experience, respectively. Besides the complex algorithms that contribute to interference cancellation aspects, smart antenna technologies can also be utilised to obtain quality of service improvements. Technically, this is done by placing identical or distinct antenna elements next to each other to steer and direct the beams towards the desired users, targets etc. while nulling out the interference in other directions. On the other hand, the fading and high penetration loss limitations of high frequency signals in 5G communication systems can be minimised by smart antenna technologies. In this paper, we described the fundamentals of beamforming technology and different literatures on beamforming designs. We also described the motivations behind moving towards 5G along with its applications and requirements. Moreover, it is believed that by using beamforming technology, power distribution per unit area can be enhanced in which the beams are directed adaptively. The antenna directivity in beamforming applications can also enhance antenna gains at the desired directions and can minimise the probability of exposure to power. Future researches are directed towards achieving energy efficiency, enhancing the precision of localisation acquisition, channel optimisation, and allowing a degree of intelligence in network management.

ORCID
Khalid S. Mohamed https://orcid.org/0000-0001-5835-4299
Mardeni Roslee https://orcid.org/0000-0001-8250-4031
Yunuf M. Raja https://orcid.org/0000-0002-6838-2952

REFERENCES
1. Rappaport, T.S., et al.: Investigation and comparison of 3GPP and NYUSIM channel models for 5G wireless communications. In: 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), IEEE, pp. 1–5 (2017)
2. Rappaport, T.S., et al.: 5G channel model with improved accuracy and efficiency in mmwave bands. IEEE 5G Tech. Focus 1(1), 1–6 (2017)
3. Akylidiz, I.F., et al.: Teranets: Ultra-broadband communication networks in the terahertz band. IEEE Wir. Commun. 21(4), 130–135 (2014)
4. Faisal, A., et al.: Ultra-massive MIMO systems at terahertz bands: Prospects and challenges. arXiv:190211090 (2019)
5. Rangan, S., et al.: Millimeter wave cellular wireless networks: Potentials and challenges. arXiv:14012560 (2014)
6. Mohamed, A.M.R.M.K.: Review on femto-cell networks interference management techniques. Int. J. Eng. Technol. 10(4), 1248–1262 (2018)
7. Lin, C., Li, G.Y.: Terahertz communications: An array-of-subarrays solution. IEEE Commun. Mag. 54(12), 124–131 (2016)
8. Federici, J., Moeller, L.: Review of terahertz and subterahertz wireless communications. J. Appl. Phys. 107(11), 6 (2010)
9. Lin, C., Li, G.Y.: Indoor terahertz communications: How many antenna arrays are needed? IEEE Trans. Wir. Commun. 14(6), 3097–3107 (2015)
10. Zhang, X., et al.: Secure communications over cell-free massive mimo networks with hardwork impairments. IEEE Syst. J. 14(2), 1909–1920 (2019)
11. Zhang, X., et al.: Secure communication in multigroup multicast cell-free massive mimo networks with active spoofing attack. Electron. Lett. 55(2), 96–98 (2018)
12. Mohamed, K.S., et al.: Investigation and improvement of maximum likelihood channel estimator in OFDM systems. In: 2017 International Conference on Platform Technology and Service (PlatCon) IEEE, pp. 1–4 (2017)
13. Sklar, B.: Rayleigh fading channels in mobile digital communication systems. I. Characterization. IEEE Commun. Mag. 35(7), 90–100 (1997)
14. Nadir, Z., et al.: Pathloss determination using okumura-hata model and spline interpolation for missing data for oman. In: Proceedings of the World Congress on Engineering, vol. 1, pp. 2–4. London (2008)
15. 3GPP: Study on channel model for frequency spectrum above 6 GHz, 3rd generation partnership project (3GPP), TR 38.900 v14.2.0, https://www.etsi.org/deliver/etsi trä 138901 138999 /138900/14.02.00_00_60 /tr 138900v140200pdf (2016). Access date 1 June 2020
16. Rappaport, T.S., et al.: Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design. IEEE Trans. Commun. 63(9), 3029–3056 (2015)
17. Khetrimayum, R.S.: Mobile phones: Bad for your health? IEEE Potentials 27(2), 18–20 (2008)
18. Commission, F.C.: Specific absorption rate (SAR) for cell phones: What it means for you. Available from: https://www.fcc.gov/consumers/guides/specific-absorption-rate-sar-cell-phones-what-it-means-you?fbclid=IwAR1G2npnVmu4lFLqFnhvYKel2qIPAZ3WeApY3jGyEvITw3W HFnutMxc (2017). Access date 1 June 2020
19. Bayraktar, M.E.: A smart insect pest detection technique with qualified underground wireless sensor nodes for precision agriculture. IEEE Sens. J. 19(22), 10892–10897 (2019)
20. Bayraktar, M.E.: Enhancing sensor network sustainability with fuzzy logic-based node placement approach for agricultural monitoring. Comput. Electron. Agr. 174, 105461 (2020)
21. Bayraktar, M.E.: Priority based health data monitoring with iot 802.11 af technology in wireless medical sensor networks. Med. Biol. Eng. Comput. 57(12), 2757–2769 (2019)
22. Mahmood, Z.: Fog computing: Concepts, frameworks and technologies. Springer International Publishing, New York (2018). https://doi.org/10.1007/978-3-319-49804-4_2. Access date 1 June 2020
23. Atzori, L., et al.: Understanding the Internet of Things: Definition, potential, and societal role of a fast evolving paradigm. Ad Hoc Networks (2017)
24. Golbon-Haghighi, Mohammad-Hossein: Beamforming in Wireless Networks Towards 5G Wireless Networks: A Physical Layer Perspective. 163–192 (BoD–Books on Demand, 2016). https://www.intechopen.com/books/towards-5g-wireless-networks-a-physical-layer-perspective/beamforming-in-wireless-networks
25. ITU Telecommunication Standardization Sector (ITU-T): Recommendation ITU-T Y.2060: Overview of the Internet of things. Series Y: Global information infrastructure, internet protocol aspects and next-generation networks - Frameworks and functional architecture models, p. 22. (2012). https://www.itu.int/rec/T-REC-Y.2060-201206-I/en. Access date 1 June 2020
26. Golbon-Haghighi, Mohammad-Hossein: Beamforming in Wireless Networks Towards 5G Wireless Networks: A Physical Layer Perspective. 163–192 (BoD–Books on Demand, 2016). https://www.intechopen.com/books/towards-5g-wireless-networks-a-physical-layer-perspective/beamforming-in-wireless-networks
27. Sisimi, E., et al.: Industrial internet of things: Challenges, opportunities, and directions. IEEE Trans. Industr. Inform. 14(11), 4724–4734 (2018)
28. Benn, H.: Vision and key features for 5th generation (5G) cellular. Samsung R&D Institute, UK (2014)
29. Intelligence, G.: Understanding 5G: Perspectives on future technological advancements in mobile. White paper, pp. 1–26 (2014)
30. Rappaport, T.S., et al.: Millimeter wave mobile communications for 5G cellular: It will work! IEEE Access 1, 335–349 (2013)
31. MacCartney, G.R., Rappaport, T.S.: Rural macrocell path loss models for 5G millimeter wave communications. IEEE J. Sel. Areas Commun. 35(7), 1663–1677 (2017)
32. Czink, N., et al.: A framework for automatic clustering of parametric MIMO channel data including path powers. In: IEEE Vehicular Technology Conference IEEE, pp. 1–5 (2006)
33. Fleury, B.H., et al.: Channel parameter estimation in mobile radio environments using the sage algorithm. IEEE J. Sel. Areas Commun. 17(3), 434–450 (1999)
34. Samimi, M.K., Rappaport, T.S.: 3-D millimeter-wave statistical channel model for 5G wireless system design. IEEE Trans. Microw. Theory Tech. 64(7), 2207–2225 (2016)
35. Sun, S., et al.: Synthesizing omnidirectional antenna patterns, received power and path loss from directional antennas for 5G millimeter-wave communications. In: 2015 IEEE Global Communications Conference (GLOBECOM) IEEE, pp. 1–7 (2015)
36. MacCartney, G.R., et al.: Omnidirectional path loss models in New York city at 28 GHz and 73 GHz. In: 2014 IEEE 25th Annual International Symposium on Personal, Indoor, and Mobile Radio Communication (PIMRC) IEEE, pp. 227–231 (2014)
37. Yuan, H., et al.: Hybrid beamforming for MIMO-OFDM terahertz wireless systems over frequency selective channels. In: 2018 IEEE Global Communications Conference (GLOBECOM) IEEE, pp. 1–6 (2018)
38. Datta, J., Lin, H.P.: Interference Avoidance using Spatial Modulation based Location Aware Beamforming in Cognitive Radio IOT Systems. Advances in Science, Technology and Engineering Systems Journal 3(2), 49–57 (2018). https://doi.org/10.25046/aj030206
39. Honma, N., et al.: Enabling full-duplex MIMO communication exploiting array antenna arrangement. In: 2018 International Symposium on Antennas and Propagation (ISAP) IEEE, pp. 1–2 (2018)
40. Misra, G., et al.: Smart antenna for wireless cellular communication—A technological analysis on architecture, working mechanism, drawbacks and future scope. In: 2018 2nd International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC), pp. 37–41 (2018)
41. Patcharamaneepakorn, P., et al.: On the equivalence between SLNR and Mmse precoding schemes with single-antenna receivers. IEEE Commun. Lett. 16(7), 1034–1037 (2012)
42. Peek, C.B., et al.: A vector-perturbation technique for near-capacity multi-antenna multiuser communication part i: Channel inversion and regularization. IEEE Trans. Commun. 53(1), 195–202 (2005)
43. Wiesel, A., et al.: Zero-forcing precoding and generalized inverses. IEEE Trans. Signal Process. 56(9), 4409–4418 (2008)
44. Khang, Y.Y., et al.: Finite-alphabet beamformed noma for multiuser MISO broadcast visible light communications. In: 2018 IEEE 10th Sensor Array and Multichannel Signal Processing Workshop (SAM) IEEE, pp. 563–567 (2018)
45. Park, J.S., et al.: A tilted combined beam antenna for 5G communications using a 28-GHz band. IEEE Antennas Wirel. Propag. Lett. 15, 1685–1688 (2016)
46. Hatrab, G., et al.: Uplink interference mitigation techniques for coexistence of 5G millimeter wave users with incumbents at 70 and 80 GHz. IEEE Trans. Wirel. Commun. 18(1), 324–339 (2018)
47. Mohamed, K.S., et al.: Interference management using beamforming techniques for line-of-sight femtocell networks. IEICE Trans. Commun. E103.B(8) 881–887 (2020)
48. Mohamed, K.S., et al.: Interference avoidance using TDMA beamforming in location aware small cell systems. Appl. Sci. 9(23), 4979 (2019)
49. Munecu, G., et al.: Mm-wave beam steering antenna with reduced hardware complexity using lens antenna subarrays. IEEE Antennas Wirel. Propag. Lett. 17(9), 1603–1607 (2018)
50. Kim, S., Choi, J.: Beam steering antenna with reconfigurable parasitic elements for FPV drone applications. Microw. Opt. Technol. Lett. 60(9), 2173–2177 (2018)
51. Mahmoud, K.R., et al.: A comparison between circular and hexagonal array geometries for smart antenna systems using particle swarm optimization algorithm. Prog. Electromagn. Res. 72, 75–90 (2007)
52. Dalli, A., et al.: Comparison of circular sector and rectangular patch antenna arrays in c-band. J. Electromag. Anal. Appl. 4(11), 457 (2012)
53. Khodier, M.M., AL-Aqeel, M.: Linear and circular array optimization: A study using particle swarm intelligence. Prog. Electromagn. Res. 15, 347–373 (2009)
54. Molisch, A.F., et al.: Hybrid beamforming for massive MIMO: A survey. IEEE Commun. Mag. 55(9), 134–141 (2017)
55. Sohrabi, F., Yu, W.: Hybrid digital and analog beamforming design for large-scale antenna arrays. IEEE J. Sel. Topics Signal Process. 10(3), 501–513 (2016)
56. Ding, Z., et al.: Random beamforming in millimeter-wave noma networks. IEEE Access 5, 7667–7681 (2017)
57. Wu, Q., Zhang, R.: Intelligent reflecting surface enhanced wireless network: Joint active and passive beamforming design. In: 2018 IEEE Global Communications Conference (GLOBECOM) IEEE, pp. 1–8 (2018)
58. Fredj, F., et al.: Distributed uplink beamforming in cell-free networks using deep reinforcement learning. arXiv:200615138 (2020)
59. Zhou, A., et al.: Max-min optimal beamforming for cell-free massive MIMO. arXiv:200605598 (2020)
60. Huang, S., et al.: Decentralized beamforming design for intelligent reflecting surface-enhanced cell-free networks. arXiv:200612238 (2020)
61. Shaka, L.L., Ali, F.H.: Joint access point selection and interference cancellation for cell-free massive MIMO. arXiv:200705631 (2020)
62. Huang, H., et al.: Fast beamforming design via deep learning. IEEE Trans. Veh. Technol. 69(1), 1065–1069 (2020)
63. Rezaei, F., et al.: Rate analysis of cell-free massive MIMO-NOMA with three linear precoders. IEEE Trans. Commun. 68(6), 3480–3494 (2020)
64. Nikbakht, R., et al.: Uplink fractional power control and downlink power allocation for cell-free networks. IEEE Wirel. Commun. Lett. 9(6), 774–777 (2020)
65. Khodkar, Z., Abouei, J.: Energy efficiency enhancement of cell-free massive multiple-input multiple-output network employing threshold-based beamforming. Trans Emerg. Telecommun. Technol. 31(7), e4007 (2020)
66. Lazarev, V., et al.: Positioning for location-aware beamforming in 5G ultra-dense networks. In: 2019 IEEE International Conference on Electrical Engineering and Photonics (EEExPolytech), pp. 136–139 (2019)
67. Chiu, C.C., et al.: Beamforming techniques at both transmitter and receiver for indoor wireless communication. J. App. Sci. Eng. 21, 407-412 (2018)
68. Xia, W., et al.: A deep learning framework for optimization of MISO downlink beamforming. IEEE Trans. Commun. 68, 1866–1880 (2019)
69. Huang, H., et al.: Unsupervised learning-based fast beamforming design for downlink MIMO. IEEE Access 7, 7599–7605 (2019)
70. Huang, H., et al.: Fast beamforming design via deep learning. IEEE Trans. Veh. Technol. 69(1), 1065–1069 (2019)
71. Shi, W., et al.: Controllable sparse antenna array for adaptive beamforming. IEEE Access 7, 6412–6423 (2019)
72. Li, Q., Yang, L.: Beamforming for cooperative secure transmission in cognitive two-way relay networks. IEEE Trans. Inf. Forensics Secur. 15, 130–143 (2019)
73. Lin, T., et al.: Hybrid beamforming for millimeter wave systems using the MMSE criterion. IEEE Trans. Commun. 67(5), 3693–3708 (2019)
74. Dutta, S., et al.: A case for digital beamforming at mmWave. IEEE Trans. Wirel. Commun. 19(2), 756–770 (2019)
75. Gross, F: Smart Antennas for Wireless Communications with MATLAB. McGraw Hill, New York (2005)

How to cite this article: Mohamed KS, Alias MY, Roslee M, Raji YM. Towards green communication in 5G systems: Survey on beamforming concept. IET Commun. 2021;15:142–154. https://doi.org/10.1049/cmu2.12066