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Development Challenges of Millimeter-Wave 5G Beamformers

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Abstract

Beamforming is the central concept that can make millimetre-wave (mmWave) a viable solution by solving challenges of link-budget, cost, power, form factor, complexity, regulatory constraint and so on. Before deployment of mmWave beamforming solution for 5G, and possibly beyond, several fundamental questions need to be answered. Some of them include hardware constraints, performance matrices, realistic propagation channel models including impairments due to obstacles such as body, blockages due to casings, phase noise, a model for Spatial-temporal variations in channels, and advanced MIMO techniques for multi-carrier and multi-user communications. The site constraints and massive non-line-of-sight transmission within the urban environment are severely questioning the conventional terrestrial low power node deployments that used to work well at low operational frequencies (sub-6 GHz). In addition to this, in beamforming technology using massive antenna arrays, the coordination of the users and beams at the transmitter and receiver end within a large network are very challenging. In this study, we comprehensively investigate some of the most prominent and best practice solutions that attempted to answer these challenging questions.

Keywords

Millimetre-wave, beamforming, antenna, array, lens, hybrid, radio, 5G.

INTRODUCTION:

The fifth generation of communication technology (5G) is a reality now. In some of the major cities in the world, the first stage of 5G has already been deployed. We can now easily get our hands on a “5G supported” smartphone. Is that all? Or there is something more than 5G can offer our societies. The answer is, we have just scratched the surface of the real potential of the 5G technology. By the year 2021, we expect to see a practical deployment of just over 20% of what was promised before the 5G launch phase. So far, the sub-6 GHz part of 5G is marketed, which, on one hand, is better with respect to performance compared to the Long-Term Evolution (LTE) and LTE Advanced (LTE-A), however, is limited in terms of achievable data rates expected by the 5G technology. We are yet to see the deployment of infrastructure providing multiple gigabits per second per user, and this is possible by the millimetre wave (mmWave) 5G.

It is now well established that the multiple-input multiple-output (MIMO) system is an integral part of the 5G infrastructure and this has already been accepted by major telecom operators. Current frequency spectrum for wireless communication is already congested due to massive deployment of the wireless radiators using technologies supported by the earlier generations (3G, 4G etc). Moving high in the frequency spectrum is the next logical step since we are limited in terms of available bandwidth at sub-6 GHz. However, this migration is not straight forward. The free space path loss and hardware impairments at mmWave frequencies are much higher compared to lower frequencies. Consider in a standard line-of-sight scenario of a wireless link, suppose path loss value of an RF signal at the carrier frequency of 2 GHz is ~80 dB. The path loss of the same link will be ~114 dB at a carrier frequency of 100 GHz, considering all other channel parameters constant. Another way of looking at it, a signal of the same power that can reach ~300 meters at 2 GHz can only reach ~6 meters at 100 GHz. One of the best ways of mitigating this path loss is to use one of the standard concepts of radio engineering called *beamforming*. This is not a new concept and is being used since the early development of the radio. A *beamformer* (a system that performs beamforming) directly adds a gain factor into the radiated power of antenna(s) in a defined direction, which can compensate the path loss. To put it in a perspective, suppose a beamforming gain factor of 10 dBi added to radiated power can now decrease the free space path loss by a factor of 10 dB, which will directly translate to signal being transmitted at a greater distance compared to an isotropic radiator.

Beamforming is most commonly achieved by increasing the number of antennas radiating equal power. The magnitude of radiated signal *constructively* adds up in some directions and *destructively* cancel each other out in other directions. By carefully placing antenna elements such that the radiated wave adds constructively in the required direction, we can achieve higher gain values. Such a placement of multiple antennas is also called as antenna arrays and the gain achieved is called *array gain* or *beamformer gain*. If the phase of radiating antennas in an array is controlled in such a way that the constructive interference between radiated waves is tilted along azimuth or elevation, we can realize a repositioning of the beam. This concept is also referred to as *beam tilt* or *beam scan*. Standard terminology of such an array is *phased array*.

Forming an antenna array is a straight forward process and a vast literature on designing and synthesis is available. As we move higher in the frequency spectrum, the array formation and phase controlling become complicated due to two major reasons. First, the technology available at low frequencies is well mature and it is easy to find radio frequency electronics and techniques to accurately develop arrays for beamforming as per the gain and scanning

requirements. This becomes harder, as we move higher in the frequency. The second reason, the amount of array gain required to compensate free space path loss becomes higher with the increase in frequency, and consequently, the number of antennas increases with it. This increases the associated electronics with each antenna elements making the overall array cost too high compared to its lower frequency counterpart. Nevertheless, beamforming is inevitable for most applications in high frequencies, so a lot of research effort has been pushed forward into this field of communication (Mondal *et al.*, 2018; Hegde and Srinivas, 2019; Kim *et al.*, 2019; Zhang *et al.*, 2019).

In this chapter, we explored research fronts that are critical for the future of mmWave 5G and beyond communication systems. It is important to mention that we primarily focus our investigation on cellular systems operating at frequencies higher than already deployed sub-6 GHz system. In doing so, we consider all frequency bands starting from ~20 GHz and above. Since frequency bands like 26 GHz, 28 GHz, 30 GHz, 38 GHz and 60 GHz captivated noteworthy amount of attention by the telecom industry, standardization bodies and research institute around the world, we will keep our focus around these bands too.

In this chapter, two classes of beamforming systems are discussed. First is the beamformer on a fixed transmitter/receiver and second is on a mobile transmitter/receiver. The reason for this classification is the application scenarios since the engineering specification and requirements of beamformer changes entirely, when we consider it a part of either a fixed or a mobile transmitter/receiver. All the future mmWave communication access points including base stations (BS), hot spots, indoor fixed wireless nodes etc lay under the umbrella of *fixed beamformers* while all movable communication systems including handsets, automobiles, unmanned aerial vehicles etc will be considered *mobile beamformers*.

1. FIXED BEAMFORMERS:

Generally, an array of antennas elements with a phase shifter network is mounted at the RF-front end of fixed radio transmitters/receivers. Any planar antenna array configuration is applicable at the fixed beamforming systems. The selection of the kind of antenna used as an array *unit cell* is often done depending upon the application. Sometimes polarization diversity is considered while circularly polarized antennas are preferred for best *diversity gain* in addition to the array gain. Standard phased array (like in (Hill and Kelly, 2019)) is amongst the most commonly used as a feed network in antenna array beamformers. Other techniques include the butler matrix (like in (Ikram *et al.*, 2018)) and substrate integrated waveguide-based feed network (like in (Lian *et al.*, 2018)).

Beamforming performance is normally tested in an *anechoic environment* with setups like (Fan *et al.*, 2018) and (Fridén, Razavi and Stjernman, 2018) before mounting to the system. High gain radiating apertures like 16 elements stacked patched structure shown in (Khalily *et al.*, 2018) is an example of a fixed beamformer. The array operates from 24.35 GHz to 31.23 GHz and realized gain is 18.7 dBi. One example shows a 32-element antenna array exhibiting polarization control while providing gain of ~8 dBi for 28 and 38 GHz operation. A switch beam system based on positive-intrinsic-negative (p-i-n) diodes for 28 GHz operation is shown in (Yashchyshyn *et al.*, 2017). This system provides multiple beam states to a maximum of 45°. A similar fixed antenna beamformer for the operation of 28, 38 and 48 GHz is shown in (Mahmoud and Montaser, 2018) depicting antenna gain of 7.82, 8.39 and 7.73 dBi. In an octagonal prism configuration, the antenna array depicts the radiation efficiency of 82%. Another frequency selection surface structure is shown to aid in beam tilt, operating from 28 to 31 GHz (Mantash, Kesavan and Denidni, 2017). Due to no limitation on size constraints, a scaled version of similar *intelligent* surfaces can easily be realized to work as mmWave fixed beamformer.

In a standard two-dimensional fixed beamformer that focuses only on the beam tilting or scanning in azimuth or elevation, a significant amount of diversity impact is ignored. This beamforming approach is generally used by uniform linear array (ULA) in which phase shift to achieve beamforming can only happen in 1-D. Utilizing azimuth as well as elevation plane with multiple antenna systems is often referred to as “full dimensional” MIMO. This way offers an extra degree of freedom while realizing MIMO and massive MIMO antenna arrays. The most important benefit is the elimination of inter-cell interference. It has been shown that the spectral efficiency achieved by a uniform rectangular array (URA) is less compared to that of ULA at MIMO front-end if the number of antennas is considered equal (M Ali Babar Abbasi *et al.*, 2019). The main reason behind this is that in the case of URA, the number of non-uniformly distributed users can be served using a higher resolution. A new concept of structuring a non-uniform full-dimension MIMO (Liu and Wang, 2019) resolves this issue to some extent, but there is still room for improvement.

A ceiling-mounted fixed beamformer based on tapered slot antennas for the operation of 27 to 29.8 GHz is shown to achieve gain on 9 dBi with strong pattern integrity (Karthikeya, Abegaonkar and Koul, 2019). With this gain specification, the path loss is computed and re-calibration of beam to 45° with a higher gain of 12 dBi is shown. The antenna uses the classical concepts of dielectric loading with *metamaterial* unit cell operating exactly at the frequency band of the tapered slot antenna. In this work, the relationship of antenna efficiency with the aperture efficiency is interestingly evaluated to be 73%. A stacking topology is shown to help the pattern diversity of the antenna. Another pattern diversity example for fixed antenna array can be found in (Sadananda, Abegaonkar and Koul, 2019) where shared aperture antenna is used to ensure beam integrity at 27 to 30 GHz frequency band. Measured mutual coupling is found to be below -18 dB at 28 GHz while the gain values are confined within 7 to 8 dBi range. A dual-polarized zero-index metamaterial is used to ensure multiple-beam equalization, such that the end-fire gain of orthogonal ports ranges from 9.2 to 9.6 dBi. Antenna with electromagnetic bandgap (EBG) backing is also a good candidate for fixed beamformers. An example is shown in (Mantash and Denidni, 2019) operating from 26 to 32 GHz. Here, a Yagi-Uda antenna principle is shown to use EBG principle when two parallel T-junctions are used to form parallel antenna feeding resulting in circular polarization. Antenna shows gain of 11.9 dBi.

Photonic beamforming is another concept that is gradually leading research focus for mmWave 5G transceivers. The general concept is the feeding of antenna elements with fast switching optical fibre. In (Morant *et al.*, 2019), such configuration is performed when operating wavelength modifies the coupling coefficient of optical ring resonators implemented on Si₃N₄. With this, multi-beam operation of realized at 17.6 and 26 GHz radio. A 128 Quadrature amplitude modulation signal is shown to be transmitting at the mmWave operation frequency band with the beamformer. The transmitter provides up to 16.8 Gigabits per second per-user data rate with beam steering from 11.3° to 23° is shown. Similar wavelength-division multiplexing elements for controlling the signals corresponding multiple beams in a multiantenna system is shown in (Tsokos, Mylonas, Groumas, Gounaridis, *et al.*, 2018). Here a microwave signal of 15 GHz is used as a carrier frequency with high-order modulation formation. This system is expected to work in a similar fashion at the mmWave band. A recent example also uses Mach-Zehnder interferometer and phase shifters into the beamformer to realize multiple beams (Tsokos, Mylonas, Groumas, Katopodis, *et al.*, 2018). This work uses amplitude modulated optical signal and successfully translated optical phase shifts into an equitant phase shifted at 28.5 GHz. The same method is applicable for even higher frequencies in mmWave spectrum.

Classical lens topologies like Rotman, Luneburg and constant dielectric are increasingly gaining attention in recent years. Two and three-dimensional *electromagnetic*-based lens beamformers have shown to sometimes outperform standard planar antenna array

(Muhammad Ali Babar Abbasi *et al.*, 2019) (Li *et al.*, 2019) (Rahimian *et al.*, 2019) (Mujammami, Afifi and Sebak, 2019). A printed 3D Luneburg lens with simplified geometry shows a gain value as high as 21.2 dBi with a radiation efficiency of 75%. The feeding, in this case, is a magnetoelectric dipole antenna with the wideband performance of 40% covering entire Ka-band. Multibeam operation is shown to have a feed mutual coupling as low as -17 dB (confirmed by experiments). Scan range of this beamformer is $\pm 61^\circ$. The feeding mechanism of similar lens types can be waveguide fed based horn antennas (Muhammad Ali Babar Abbasi *et al.*, 2019), or groove gap waveguides (Rajo-Iglesias, Ferrando-Rocher and Zaman, 2018) (Tamayo-Dominguez, Fernandez-Gonzalez and Castaner, 2018). A unique leaky-wave antenna operating from 21.9 to 23.9 GHz shows metallic strip grating structure can also be used for lens feed (Comite *et al.*, 2018). A slightly different single-polarization Fresnel zone plate lens antenna operating from 57 to 64 GHz is presented in (Kodnoeih *et al.*, 2018). Due to the functionality of trans-reflector and twist-reflector in the structure, a maximum achievable gain is shown to go as high as 32.7 dBi.

Unlike the aforementioned electromagnetic lens beamformers, Rotman and Fourier's lens falls within the class of transmission line-based lens beamformers that introduces an analogue phase shift into a mmWave signal entering the antenna array. The functionality of these lenses is analogous to that of a Butler matrix (Ikram *et al.*, 2018). A conformal Rotman lens is used for beamforming in (Rahimian *et al.*, 2019) where passive beam switching happens at 28 GHz. The bandwidth of such systems is normally high due to wideband of Rotman lenses, same is the case in this work where bandwidth is shown to be from 18 to 38 GHz. Another Rotman lens-based beamforming solution shows bandwidth from 26 to 40 GHz (Mujammami, Afifi and Sebak, 2019), where the beam scanning capacity is from -39.5° to $+39.5^\circ$. Another such example is in (Ershadi *et al.*, 2018) where a Rotman lens capable of hosting 7 beams operates from 25 to 31 GHz.

Let's now see some recent beamforming technologies at even higher frequencies. Two identical parallel fed slot antennas are shown in (Manzillo *et al.*, 2018) with a beam selection mechanism operating at 57 to 66 GHz. The development technology for this is low-temperature cofired ceramic which ensures a high accuracy beam scanning of 11 beams from -39° to $+39^\circ$. A method of measuring and modelling the channel based in synthetic beamwidth for indoor fixed transceiver for 60 GHz is given in (Sun *et al.*, 2018).

1.1. WHAT IS HYBRID BEAMFORMING?

Previously discussed beamformers, are also referred to as analogue beamformer especially in communication literature. A stand-alone antenna beamformer needs a fully connected processing unit to host the system level processing of MIMO and/or massive MIMO. This gives rise to *hybrid beamforming* which enjoys the benefits of both *analogue* as well as *digital* beamforming.

In hybrid beamforming any kind of analogue beamforming hardware is usable, but it is a common practice to first formulate an optimization problem with traceable form in the digital domain. In doing so, a weighted minimum mean squared error is generally used. This formulation is then solved by schemes like interference aware beam selection e.g. (Guo *et al.*, 2018). Best possible design of hybrid beamforming structure is generally evaluated based on the number of a receiver (denoted as N) and the number of active antenna elements per receiver (denoted as M). Optimal spectral efficiency and the energy efficiency of $M \times N$ matrix is then determined. This allows finding the so-called "Green point" which is defined as the highest point at the spectral efficiency versus the energy efficiency curve. This way, a thorough understanding of the number of antenna element per array for the number of receivers can be identified. It has been shown that an accurate trade-off between energy and efficiency for a given system can be identified (Han *et al.*, 2015). Note that this approach sometimes requires

reference signal for accurate channel estimation compared to only relying on the analogue beamforming approach. Sometimes, channel estimation is used based on models on coverage expressions derived through stochastic geometry. This is well mature for sub-6 GHz band but classical approaches are pretty much questionable for mmWave 5G scenarios (Rebato *et al.*, 2019). Realistic channel models in conjugation with real beam patterns are required for accurate channel estimations. One way of doing this is by using reference signal transmission from the fixed beamformer like the one shown in (Weng *et al.*, 2018). An experimental prototype of hybrid beamformer at 28 GHz realizing high data rate to the downlink is shown in (Raghavan *et al.*, 2018). It is shown that the direction nature of mmWave can be leveraged to utilize beam switching and handovers at the BS end. This can eventually help in overcoming the path losses in non-line-of-sight beam links. Another practically viable hybrid beamformer transceiver (e.g. (Zhang *et al.*, 2019)) show operation at 28 GHz with high beamforming accuracy and high-precision phase shifter network. An 8 element MIMO beamforming receiver array with autonomous frontend beamforming and digital baseband beamforming is evaluated in (Huang *et al.*, 2019).

1.2. IMPORTANCE OF BEAMFORMER'S BEAMWIDTH:

To understand the importance of beamwidth in a mmWave communication at the fixed beamformer end, this section reviews the following sequence of events:

A fixed beamformer at a BS end produces multiple beams generally in all possible beam directions. These beams are sharp enough to be able to mitigate the path loss at giving mmWave communication band. As per the theory of massive MIMO, a beam training procedure starts in which fixed beamformer transmit the information which is received by a mobile terminal (also referred to as user equipment (UE) in literature). The mobile terminal provides feedback with the information of the index of beam which provides the best reception among all other candidate beams. Fixed beamformer pairs this beam for data transmission to the mobile terminal.

This process reduces spectral efficiency since it requires several training overheads. On the other hand, if we use wider beams at the fixed beamformer, the amount of training sequence overheads will reduce, and spectral efficacy will increase. There is always a trade-off between these two approaches. It requires very careful engineering specific for different cell size, area of coverage as well as mmWave frequency band. A good report on this, based upon experimental data in an urban environment at 28 GHz and 38 GHz, is shown in (Lee *et al.*, 2018). First the beamwidth impact on users in mmWave 5G is evaluated and the propagation loss is quantified as a result of decreasing beamwidth. In addition, the impact of beam miss alignment is shown to add a large power loss. Note that in addition to sharp beams, baseband signal bandwidth of the order of ~1 GHz is desirable to meet theoretical mmWave system capacity (Ariyaratna *et al.*, 2018).

Another point to consider here is that the beam width and sharpness also depends upon the area of coverage. For example, consider a typical full-dimensional massive MIMO BS covering a street using fixed beam optimized beamwidth. Most likely, more users will be situated at the ground compared to high rise building and the busiest set of beams will be the one covering the ground area. In contrast, the high-rise beam covering the indoor users will be less utilized. Such wastage of spectral resources is costly at mmWave. Non-uniform full-dimension MIMO (Liu and Wang, 2019) helps here as well where the ground area is covered by sharper beams and wider beams are responsible for the high-rise users (see Figure. 1). This way the spectral resources can be utilized in a better way. Generally, a number of sharp beams projected by BS requires a higher beam training overhead in a massive MIMO system. To further reduced this, prior information of utilization frequency and sometimes out-of-band information is also considered which will be discussed later in the text.

Figure. 1. Non-uniform full dimensional massive MIMO fixed beamformer serving mobile terminals.

It is sometimes preferable to have a beamforming system where several users are served using the same beam. A form of non-orthogonal multiple access systems is required for this to happen (Rupasinghe *et al.*, 2018). It is proved in (Sun *et al.*, 2018) that the number of multipath components, as well as delay spread, is reduced when directive beams with narrower beamwidths are used. Another benefit shown experimentally is the reduction of path loss with a figure as high as 20 dB using narrow beamwidth, posing a significant benefit to the mmWave link budget. Another important point to mention, narrower beamwidth does not always require a higher number of antenna elements in an array. Thanks to antenna array synthesis techniques like compressive sensing (Abbasi, Fusco and Zelenchuk, 2018; Abbasi and Fusco, 2019) where narrower beamwidth is achievable using sparsely distributed a lesser number of antenna elements compared to fully populated high antenna number array.

1.3. IMPORTANCE OF THE MMWAVE CHANNEL INFORMATION:

Channel knowledge is vital for MIMO operation in a hybrid beamforming system. This is simple to do when a standard MIMO operation is considered in which digital baseband processing has direct access to signal at each antenna element. For beamformers with a higher number of antenna elements (massive MIMO), this is too expensive to implement, so hybrid architecture with two-way channel estimation techniques is preferred. Other techniques like power iterative adaptation are also useful (Abdo *et al.*, 2018). Due to sparse nature of mmWave channels (Tsai and Wu, 2018), a small number of measurements are enough for channel recovery. Still signalling and storing the configuration of codebooks is a burden on the system.

When the mmWave channel like in Figure. 2 is known to the beamformer, the information of scatterers, obstacles and blockers can be processed dynamically. By virtually suppressing blockers, the desired signal will be higher, improving signal-to-noise ratio values. In addition to this, suppression of inter-cell interference can be done using two-level beamforming coordination which is realizable by partitioning the network into small manageable clusters. In the small clusters, the standard user selection algorithms can be used to establish multi-user MIMO links (Wang *et al.*, 2019). This helps in maximizing the utility function and minimizing the signal-to-interference-plus-noise ratio within a specific cluster. On a higher processing level at the fixed beamformer, inter-cluster interference information can be recorded and shared in such a way that the user is allocated dynamically to the best-suited cluster. Low complexity signal transmission to multiple users using beam channel set selection and by

clustering the users is another example of low complexity scheme (Sheu, Sheen and Guo, 2018).

Figure. 2. A typical mmWave channel with obstacles where line-of-sight and non-line-of-sight connections are established between fixed and mobile beamformers.

Unlike standard closed-loop hybrid beamformer channel estimation techniques, an open-loop method shown in (Zhang *et al.*, 2018) ensures low-complexity processing. This is done by utilizing a low-rank subspace decomposition approach in which sub-optimal but stationary solution of the estimation problem is achieved. This way also made the mmWave system robust to low signal-to-noise ratio values compared to open-loop techniques. A fully connected beamformer does not rely on decomposition but weights every antenna element independently before handing over data stream to the processing unit. This RF weighting is generally done using the programmable amplifier at the receiver end before the I/Q based down conversion. An example of such a system operating from 25 to 30 GHz is shown in (Mondal *et al.*, 2018) implemented in 64-nm CMOS. Note that for such a hybrid beamforming system, interferences cancellation between consecutive streams and codebook search of beam acquisition needs to be highly reliable.

1.4. LOCALIZATION OF USERS IN MMWAVE CHANNEL:

User location in a known mmWave channel helps to enhance the productivity of fixed beamforming system. localization protocols like the one presenting (Garcia *et al.*, 2018) uses in-band aiding, but pose a burden on the system. One technique of localization scheme avoiding in-band burden is using GPS location data. This simplifies the problem by eliminating non-coverage beams and using the beams that are most likely to cover the location, hence reducing the size of candidate beams. On top of this, such a beam training scheme finds the best coverage beam link faster and reduces the beam training overheads. This method can be further explored by (Liu and Wang, 2019). Another example (Ruble and Güvenç, 2018) shows a two-step approach. In the first step network with radio-environment mapping is used to identify the position of scatterers and blockages. It is shown that even with the accurate information of scatterers, localization of user is very difficult because the likelihood functions will have a large number of local optima. The approach further added second step of using a filter-based estimator to accurately identify the user position.

Aforementioned schemes work best for channels where obstacles are sparse. For more complex channels e.g. multiple streets and junctions where hindrance between fixed beamformer and users is more likely, high-density BS deployment is inevitable. This seemingly

simple task has issues of its own and additional training overheads are required for such systems to work. One method introduces a scalable high-density deployment system specific for mmWave communications in (Fiandrino *et al.*, 2019). This study also utilized the location information of users to enable adaptive capabilities like finding secondary propagation paths for a given beam link, timely reacting to changes within channel link temporary blockage. Again, out-of-band frequency applications such as GPS is used in this case as well. The downside is that this approach converts a very high speed mmWave massive MIMO into comparatively low speed yet more reliable network.

It has also been reported that sensor information like that of an accelerometer and gyroscope (Fiandrino *et al.*, 2019) is also usable for localization. In other words, any sensor information that is available to the physical or MAC layer of the communication stack is useful. Localization algorithms are to be run by the mmWave device, their initiation, as well as runtime phase, needs to be as short as possible. By carefully looking at the aforementioned investigations, we can conclude that the out-of-band applications aiding in localization of mmWave communication systems can provide three major advantages.

- It reduces the network overheads for tasks including, handovers, beam link training, device tracking and load balancing.
- It supports almost all the location-aided services without adding extra load on mmWave beamformer hardware.
- The process is user-driven and scales very well when the number of users increases.

1.5. BEAM SELECTION AND MANAGEMENT IN FIXED BEAMFORMERS:

Beam selection and management are extremely important since it controls the core functions of successful mmWave wireless network, such as beam tracking, initial user access and user handover. A small misalignment between fixed beamformer and user (due to mobility etc.) can result in high signal loss. A dynamic, reactive and robust beam management tool is as important as single antenna array beam performance (Giordani *et al.*, 2019). Note that beam management is purely dependent upon the current channel state, which is detectable using channel estimation schemes and reference signal transmission schemes (e.g. (Weng *et al.*, 2018), (Chiang *et al.*, 2018) and other examples in section 1.4). System load is also reduced by using automatic link adaptation schemes (Yan, Fang and Fang, 2018).

A novel approach in (Hegde and Srinivas, 2019) shows beam selection that considers the beams at fixed beamformer end as one partner and user as another partner. After considering the preferences of both partners the proposed algorithm finds the best match. The approach in (Xue *et al.*, 2018) added blockage control strategies for beam selection as well as multiuser power allocation for corresponding beams. Theoretically, this approach can improve the rate performance however practical implementation is challenging. A beam angle tracking strategy shown in (D. Zhu *et al.*, 2018) use an array calibration error and beam pair design to assist beam management. Another approach (Yeh *et al.*, 2018) shows novel architecture for beam selection that is claimed to be scalable. A sub-version of the scheme is implemented and tested on 40-nm CMOS technology with 16 beams and 8 simultaneous users. Other variations of time-to-space division multiplexing (like (Bonjour, Welschen and Leuthold, 2018)) are also found to enable multiple beam steering serving multiple users. The most prominent benefit is that it requires simpler hardware compared to counterparts which need complex antenna feeding and relaying. In the beam selection problems, it is a common practice to find a balance between power loss probability and minimization of misalignment probability. In many cases, IEEE 802.11ad is considered baseline.

Beam training methods are resource hungry and based on this a low-complexity low hardware extensive approach is shown in (X. Zhao *et al.*, 2018). Here, a large number of users is shown to be serviceable using a single RF chain connected to 64 antenna elements. This method in

conjugation with the reference signal shown in (Weng *et al.*, 2018) can assist in channel state information, initial access and beam alignments. The approach shown in (Chiang *et al.*, 2018) uses pilot signals required for channel estimations to identify channel state. This does not even require the information on MIMO channel. For a small number of RF chains, algorithm shown in (Pal, Srinivas and Chaitanya, 2018) is expected to work well with the evaluated channel state. Along similar lines, the impact of different parameters like number of users, antennas and number of antenna per user on beamforming resolution and hardware impairments is evaluated in (Guo, Makki and Svensson, 2018).

An interesting investigation in (M. Cheng *et al.*, 2018) considers the beam alignment as a discrete random variable and numerically estimated the probability density function based on the variation in beam alignment. It is shown that in channels where beam alignment is expected to have small imperfections, increasing the number of antenna elements in BS array will be enough to mitigate the misalignment implications. Similar conclusions are drawn in (Va *et al.*, 2017). Note that the channel state is expected to change relatively slow compared to the coherence time, but this is sometimes not possible. New schemes like (Alkhateeb *et al.*, 2018) try to mitigate this bottleneck and are applicable for urban environments with high mobility, like highways and motorways etc.

2. MOBILE BEAMFORMERS:

The requirements of a spherical coverage of mmWave mobile beamformers placed on mobile terminals are defined in the latest release of Third-Generation Partnership Project (3GPP) which is identified based on cumulative distribution function over the isotropic radiated power. Unlike sub-6 GHz mobile terminal, where a few antennas were enough to provide coverage in an isotropic spherical fashion. This changes at mmWave frequencies since the isotropic radiated power is not enough to reach the fixed beamformers placed at the access points or BS ends. This is compensated by adding beamforming capabilities into the mobile terminals and also by leveraging MIMO operations (see Figure. 3). It has been shown that as the directivity of the antenna arrays at the mobile terminal are increased, the number of capturable multipath in a mmWave channel becomes lesser (Lee *et al.*, 2018). So, there is a trade-off between free space penetration of the mmWave and multipath resolution.

Figure. 3. Antenna or antenna array placement to achieve beamforming, energy focusing, and spatial diversity illustration in mmWave mobile beamformers.

Beamforming at mobile terminals is generally made, to some extent, reconfigurable in the literature to yield the benefits of best multipath. This is normally used for best beam selection for reliable signal reception. Multiple stream MIMO modes normally use multiple frequency bands for different data streams. In the majority of the times, such multi-band operation is done using Cartesian-combining-based complex RF-domain weighting schemes. One such example is (Mondal and Paramesh, 2019) in which image-rejection heterodyne beamforming is presented that leverages the reconfigurability scheme. Two frequency bands used in this

work are 28 and 37 GHz. The technology used in receiver side is 65 nm CMOS. Conversion gain of receiver is 5.7 dB at 28 GHz and 8.5 dB at 37 GHz. Another example of reconfiguring beam switching network can be found in (Basavarajappa *et al.*, 2019). A 16-element antenna array with bandwidth of 1.5 GHz in conjugation with a phasing network is experimentally validated. 5 beam states are shown when splitting beam is considered the building block of the scheme. Work in (Shakib *et al.*, 2019) presents 5G handset phased array using 40-nm CMOS technology. Test circuit performance is compared with the hardware after thorough investigation on the block-level specifications. The fabricated front-end prototype on 1P6M bulk CMOS is used to show communication over carrier-aggregated 64-QAM OFDM scheme. Bands used are 27 to 30 GHz while the work concluded a noise figure of 5.5 to 6 dB and third-order intercept point of -8.5 to -6 dB.

Fully digital beamforming in mobile terminals is sometimes used to calibrate the signals of all the RF-chains. Generally, in-band signal, that is not used for communication, is used for correction in errors of phase and amplitudes. Implementation of such a system on a software-defined radio, using slot antennas and low noise amplifier is shown in (Kim *et al.*, 2019). The system first uses 8 RF-chains and 8 elements antenna array to achieve phase shifter resolution up to 0.72° . After calibration, amplitude and phase errors are bounded to 0.5 dB and 0.9° respectively. It is important to mention that in communication society for massive MIMO systems, it is widely believed that digital beamforming is the best way forward for sub GHz frequency bands. This conclusion is not yet settled for mmWave spectrum and efforts like (Yang *et al.*, 2018) are trying to explore this further. Here, 28 GHz carrier frequency is used to demonstrate 64 channel MIMO system with digital beamforming. A valuable comparison at 60 GHz between hybrid and digital beamforming schemes can be found in (Roth *et al.*, 2018).

Avoiding unwanted phase shifters due to constant mobility is also possible using innovative beamforming techniques like frequency modulated frequency diverse array in which small frequency increment is added at the antenna input. In doing so, angle range and time-dependent signal form beams without requiring any phase shifter (Nusenu, 2019).

To avoid mmWave leakage from the directions where the hand is located, it is sometimes referred to confine the energy using EM structures like dielectric slabs, co-planar waveguides and plasmonic structures (Zhang, Sun and Chen, 2019). Although these methods are helpful for directing the propagating wave energy in an efficient manner, due to features like slow-wave propagations and spoof surface plasmon polarization, sometimes the signal integrity became questionable. A novel method of converting the bounded Spoof Surface modes to radiation modes in (Zhang, Fan and Chen, 2018). The mechanism of how the wave is confined within the EM structure is compared with that of a horn antenna. Such a structure can show gain as high as 15 dB and good radiation efficiency of over 90%. A good read on mobile beamforming approaches for applications beyond 5G is (Ghosh and Sen, 2019).

A good comparison of carrier frequencies is done in (Raghavan *et al.*, 2018). A comparison between 2.9 GHz, 29 GHz and 61 GHz is done for multiple practical scenarios including indoor office, shopping centre and outdoor. Key features of such scenarios and impact of them on different frequencies are studied, for example the impact of blockage and propagation loss of electromagnetic energy through materials, walls and building etc. This helps in understanding the mmWave systems starting from impact of environment/channel on the mmWave communication link.

2.1. ARE THERE SYSTEM LEVEL IMPLICATIONS OF MOBILE BEAMFORMERS?

Adding beamforming in mobile terminals provoke several practical issues with respect to form factor. For reliable end-to-end connectivity between fixed and mobile beamformer, we

normally try to define link budget based on the mobile beamforming capabilities. It became imperative not to rely on single beam location but to analyse all beam states of a mobile terminal as accurately as possible to engineer a good communication performance on average. Adding beamformers in mobile terminals possess three major challenges:

Additional antenna module requires additional antenna component cost and associated RF electronics.

It is well understood in RF engineering that for frequency bands in the mmWave spectrum, the performance of traditional RF components like diodes, microelectromechanical system switches, ferrites and ferrites films etc degrades severely. Sometimes they are not even usable at mmWave frequency band. If we push forward their functional limitations to a maximum, fabrication cost will grow massively adding burden on the commercial sector. In response to this challenge liquid crystal based tuning solutions are considered in recent years that owns properties like moderate loss, low dispersion, consistent and low dielectric constant and low cost. One of the best features of liquid crystal based tuning systems at mmWave is the response time which makes them comparatively promising (Zografopoulos, Ferraro and Beccherelli, 2019).

A beam selection and management overheads increase processing load in mobile beamformers in every coherence time.

Densely crowded environments require dynamic reassociation between available beams to reduces the chances of losing a user. This can happen sometimes at the beam selection level while sometimes changing a fixed beamformer is required. Note that the overheads simultaneously rely on ergodic capacity, BS height and densities, a number of antenna sub-arrays in the BS, antenna elements in each antenna sub-array, beam switching time, blocker speed and density, degree of multi-connectivity, and employed connectivity strategies.

We have seen that analogue beam codebooks can be of immense benefits in beam management. Also structured random sensing of codebook concentrates power in sectorized cell's local angle coverage, eventually reducing the signalling and storage overhead of the codebook. For a detailed discussion on this see (Raghavan *et al.*, 2019) and (Tsai and Wu, 2018). A more relevant approach shows the relying on dual connectivity or low complexity reactive multi-connectivity of users especially at the cell edge lavages the overall capacity without additional overheads (Gerasimenko *et al.*, 2019). This approach also ensures that in case of active connection being lost, interactive beam selection algorithms do not decorate the overall ergodic capacity of the system. The approach in (Hegde and Srinivas, 2019) can also be used at the user end for beam-selection.

Additional antennas and electronics pose additional pressure power management unit and on the mobile terminal battery.

2.2. HOW TO SOLVE BLOCKAGES DUE TO MOBILE TERMINAL CASING?

The radiations from a mmWave beamformer printed on circuit board of a mobile terminal are affected by guided waves trapped within the substrate layers, superstrates and surface currents on the chassis or battery. This makes the beamformer design a challenging task. Spherical coverage of a mobile terminal is shown to be severely disturbed due to the presence of casing or other electronic equipment (K. Zhao *et al.*, 2018). One most prominent technique used to reduce the blockages at mmWave handsets is by modifying the metallic portion in the casing. For example, an antenna with vertical polarization is coupled with a metallic strip in a way that it does not hinder its radiation performance. The disadvantage is the same metallic form in casing can hinder the other polarization signal. A mmWave Vivaldi antenna performance, operating from 25.25 to 27.5 GHz, is kept intact when metallic strip casing is avoided to block the mmWave signal reception (Rodriguez-Cano *et al.*, 2019). Antenna array

in this work can scan up to 120° with a gain of 7 dBi. Another antenna operating from 27.2 to 28.2 GHz is shown to be mounted on a fully metallic handset casing. The antenna consists of two sub-arrays placed on the backside of the casing when each subarray has 8 rotated slot antenna elements. Dynamic switching is proposed to select the operating antenna (Bang and Choi, 2018).

A new technique in which mmWave beamforming antenna is collocated with a printed inverted-F antenna (PIFA) is shown in (Taheri *et al.*, 2019). The general principle of reducing blockages due to casing is the same, this time the metallic guiding strip is operating at low frequency on another application standard (4G cellular or Wi-Fi). It is shown that the metallic strip is considered “transparent” for mmWave propagation because of the introduction of grating strips between the mmWave radiator and metallic strip (of PIFA). mmWave antenna operates from 22 to 31 GHz. The radiation patterns of the mmWave antenna achieve a scan angle of 100° and considered not to be disturbed by the presence of closely spaced low-frequency antenna. Peak gain achieved in 9.5 dBi at 28 GHz. A mmWave 5G antenna is shown to be placed in a metallic rimmed handset casing, and performance is optimized in (Kurvinen *et al.*, 2018). The same principle is shown where mmWave beamforming antenna is isolated from closely spaced metallic strip, which in this case is an LTE antenna. The mmWave antenna has a peak gain of 7 dBi.

Cavity backed radiator is another advantageous solution that can compensate for the casing blockages of mobile terminals. The main advantage of the cavity is the confinement of EM energy within the structure and enhancing the gain. One example is shown in (Tan *et al.*, 2018), where beam tilt of 94° is shown using a cavity-backed antenna structure. Peak gain of 8.4 dBi is achieved when antenna is operating from 27.8 to 30.9 GHz where the cavity used is substrate integrated waveguide-based. 4 quasi-canonical antennas operating at 28 GHz are attached to a 5G handset model and multiple housing effects are tested separately in (Xu *et al.*, 2018). One conclusion is interesting. It is shown that finding equivalent current obtained by an inverse source technology can help design engineers to find the best antenna array configuration. One drawback is that this technique requires EM design on the entire handset with main circuit and peripherals, which is a cumbersome task to perform. Another parameter along the same theory i.e. effective beam scanning is used to estimate and optimize the beamformer performance in the presence of housing.

Similar to the cavity/reflector backed antennas concept (Tan *et al.*, 2018) (Yu, Yang and Yang, 2017), focus energy in defined direction using lenses is also used in recent literature. Note that this seems more obvious at the fixed beamformer end due to large relative sizes of lens antenna, however, works like (Kim *et al.*, 2018) have used small lens structure excited by a 4 element antenna array. The resulting gain is 3.8 dB higher compared antenna structure without the lens. The lens is placed at a half-wavelength distance from the antenna array. It is shown that when the phase offset between antenna elements changes from 45° to 90° and 180° , the relative gain enhances to 3.4, 3 and 2 dB respectively. The most important bottleneck in designing such systems is the cavity effects induced when lens structures are placed close to antenna element. This effect magnifies when the distance between the lens and other structures is reduced, which is the most desirable design step for handset antenna design.

A wideband mmWave antenna operating from 27.5 to 40 GHz shows 94° beam steering capacity at 32 GHz (Naeini, Fakharzadeh and Farzaneh, 2019). Here, $10 \times$ unit cells forming an array covers 6 cm space on a handset. Ideally, the antenna is shown to have a gain of 4 to 11 dBi across the band from 27.6 to 36.5 GHz. Another beamformer design at 28 and 38 GHz has shown to achieve circular polarization in both bands (Mahmoud and Montaser, 2017). Peak gains of 7.68 and 7.73 dB is achieved at both frequency bands respectively. Total 12 antennas are used in this array design and mounted at the edge of the handset. Placement of human hand around the handset is further investigated in multiple scenarios. A novel approach of practical phased array designed on metallic casing of the handset antenna is shown in (Yu,

Yang and Yang, 2017) where 16 cavity-backed slot antennas are implemented. Two sets of 8 element arrays are built on left and right side of the casing to achieve a high gain value of 15 dBi. The antenna operates at 27.5 to 30 GHz with sustainable performance with the presence of a hand.

A quasi-yagi directional antenna operating from 26.3 to 29.75 GHz with a gain of 5.51 dB is proposed to be used for directive beamforming avoiding the impact of the casing (Hwang *et al.*, 2019). The structure is designed on multilayer PCB while vias are applied to minimize the antenna footprint. Radiation, in this case, is from the top and one side of the handset. Another Multi-element quasi-yagi antenna array shows good radiation performance and beamforming from 25 to 30 GHz. The antenna works with an aid of capacitively-loaded loop unit cell (Wani, Abegaonkar and Koul, 2019). Two antennas are shown to be separated by half wavelength at 28 GHz. Antenna operating from 25.05 to 34.92 GHz is shown in (Ullah and Tahir, 2019), fed by a 4-way feeding network. The antenna is proposed to be isolated from the surroundings by vias arranged a U-shaped structure. In an ideal environment, the antenna shows a radiation efficiency minimum of 85% and a peak gain of 12.15 dBi.

In line with the concept of using multiple antennas on hand-set, a switched based beamformer is studied in (Chen *et al.*, 2019). Mutual coupling impact is thoroughly investigated with different inter-element spacing and different orientational configurations of antenna units. It is concluded that the outage capacity of mmWave antenna clearly reduces when the mutual coupling is also considered as a part of design equation. A more comprehensive study with rigorous measurements on this is required to fully understand the implications. Mutual coupling impact is also vital for tightly coupled antennas like in (Shim, Go and Chung, 2019). A dipole antenna array operating from 22.5 to 32.5 GHz is shown to provide beam scanning capacity of 30° and due to impedance mismatch, radiation efficiency is low. Another dipole antenna using visa, mounted at the mobile edge, features wideband operation in (El-Halwagy *et al.*, 2017). The beamwidth is sacrificed to enhance the gain by implementing a V-shaped bisection parasitic via. The feed made of vias surrounding the antenna structure is shown to suppress back radiation, consequently enhancing the front-to-back radiation ratio. To feed the antenna structure, a substrate integrated waveguide to parallel stripline transition is defined. 1, 2 and 4 antenna element arrays are fabricated, and results show that the dipole cover bandwidth of 7.23 GHz with beamwidth of 133.1°. The technique has shown achievable gain of 12.61 dBi and radiation efficiency of 95.8%.

Moving higher in the frequency spectrum, issues related to blockages become higher. One solution solving this problem is a four polarization states antenna exhibiting radiation from 57 to 64 GHz (J. Zhu *et al.*, 2018). The polarization states are vertical linear polarization, vertical horizontal polarization, left-hand circular polarization and right-hand circular polarization. Dynamically switching the excitation ports enable the selection of each polarization state. If in housing, one of the polarization states is blocked, signal reception is possible at another polarization state. Another antenna operating from 57.2 to 63.4 GHz show circular polarized end-fire radiation (X. Cheng *et al.*, 2018). The antenna comprises a substrate integrated waveguide with four tapered slots and three open-ended stacked layers. More challenging topologies like Fabry-Pérot cavity-based antenna with a capability of switch-beam radiation is shown in (Guo and Wong, 2019). The antenna array operation shows an aperture efficiency of 76% at 60 GHz with a realized gain of 16 dBi. The array shows beam switching from -18° to +18° while keeping the gain value consistent. Prototype validates the antenna bandwidth of 24% and measured directivity of 18.8 dB. Blockages due to casing are not explicitly identified and additional research effort is expected around the same. Further beamforming topologies even at higher frequencies (above 100 GHz) can be found in (Rappaport *et al.*, 2019).

2.3. DOES ATMOSPHERE AFFECTS MMWAVE MOBILE BEMAFORMERS:

Degradation of a signal link due to the atmosphere in mmWave communication is generally handled as a part of channel model. It also has a direct link to the design on mobile beamformers for mmWave satellite transceivers, where propagation loss, as well as refractive index of the propagation medium, have strong impact of mmWave signal (Balal and Pinhasi, 2019). In non-satellite mmWave networks, atmospheric impact becomes more relevant when atmosphere between fixed and mobile beamformers is likely to change, for example when mobile BS mounted on unmanned aerial vehicle (UAV) is to serve mobile terminals (Rupasinghe *et al.*, 2018). When we look at this in terms of the promised quality of service at 5G mmWave, link degradation due to atmosphere becomes prominent, and sometimes deal breaker. Un conventional approaches based on outage probability (Rupasinghe *et al.*, 2018) are most commonly used to accurately understand the effects of environment on the communication quality. Note that atmospheric impact is different for different frequency bands within a mmWave spectrum. In (Meng *et al.*, 2018), the atmospheric impacts are considered based on backhaul position signals, when UAV positions are optimized based on the best signal levels. BS transforms the antenna direction by focusing energy to the leading UAV and consequently enlarging the number of receivers per BS. A sub-clustering of users within a single fixed beamformer (as shown in (Wang *et al.*, 2019)) is also helpful in mitigating the environmental effects in mmWave channels. If not considered appropriately, atmospheric effect can alter the measurements evaluated using systems like the one proposed in (Fernandez, Lopez and Andres, 2018). This work presents the capability of antenna measurements using low-cost UAV. By considering the atmospheric impacts, the accuracy of system can be further enhanced.

3. HEALTH CONCERNS OF MMWAVE BEAMFORMERS

Health concerns are rising as the commercialization efforts are leaning towards using mmWave beamformers in the mobile terminal. This is especially prominent for the mobile terminals that are to operate close to the human body (like handsets, laptop computers and smart wearable devices etc.). There is nothing new in this. With every growing technological advancement in wireless communication, health concerns also emerged. To ensure successful connectivity, mmWave mobile beamformers are bound to form beams in all directions. Unlike sub-6 GHz antenna arrays where the amount of power delivered to the fixed radio is low since the required signal level is achievable even at low power excitations. Beamforming in mmWave radios first use higher power compared to sub-6 GHz counterpart, and secondly focus beam in defined directions and hence increases the health concerns.

In literature, most common parameter to estimate the impact of radio on human tissue is the specific absorption rate (SAR) defined as the amount of radio power in Watts absorbed by a tissue of 1-kilo gram. An important to note is that in terms of radiofrequency exposure, time duration of the exposure is critical in addition to the SAR level. In case of a mobile beamformer, the total exposure of a user over a period can be averaged based on amount of radiated mmWave power, proximity to the body tissues, and handling of the mobile terminal (e.g. talking position, placement in pocket, placed on a desk in front of a user etc.). In this case, *peak-spatial SAR* is considered, averaged over a time period on a mass of tissue, typically 10 grams or 1 gram ('IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz', 1999). Human tissue exposure is more prominent from the mmWave energy focused towards the body as shown in Figure. 4. In case of fixed beamformer, exposure is directly linked to the radial distance since the nature of radiated power by a fixed mmWave beamformer placed at an access point of BS is expected to impact body in a non-localized fashion. In this case, *whole-body SAR* is considered (Guideline, 1998). A study shows another way of looking at the impact of 28 GHz 5G radio on human head model by the numerically analyzing temperature (He *et al.*, 2017).

Figure. 4. Mobile mmWave beamformers in proximity to the human tissues and fixed beamformer at a radial distance.

It has been shown that the mmWave energy from 40 to 60 GHz is not enough to change the chemical composition within the cell structure of human tissues. However, the impact of prolonged mmWave exposure reflects in terms of induced rotation of the molecules, eventually increasing the cell's temperature (Le Dréan *et al.*, 2013). High-intensity mmWave exposure is found to generate heat sensations in skin, followed by pain if the power intensity is increased. Experiments in (Walters *et al.*, 2000) verifies the same. Similar conclusions are expected to hold valid for mmWave frequencies beyond the bands focused in these studies. The intensity of radiation to achieve reasonable signal to interference and noise ratio for communication is not at the level of immediate threat. Nevertheless, it is always useful make radiating elements, specially in mobile beamformers, to cultivate beams that induce minimum energy foot print on human tissues. This can be done by controlling the coupling of antenna elements that are most likely responsible for radiation towards body (see Figure. 4). Studies like (Bang and Choi, 2018) suggest careful designing of the antenna and handset casing to reduce the SAR level. In another example, antenna operating on 28 GHz and 38 GHz is tested in the presence of human hand and head (Mahmoud and Montaser, 2017).

4. CONCLUSION

This chapter provides a comprehensive tutorial of mmWave beamforming for communication systems. For ease in understanding, we classified the study into fixed and mobile beamformers. First, the requirements, implications and operations of fixed beamformers are studied thoroughly. Second, the design specifications, technological advancements at the system level, operation, standard examples and special cases of mobile beamformers are discussed. In order to understand one of the most important issues associated with mmWave beamforming, i.e. health concerns, we discussed some of the most prominent and latest studies in the final sections of the chapter.

Figure captions

Figure. 1. Non-uniform full-dimensional massive MIMO fixed beamformer serving mobile terminals

Figure. 2. A typical mmWave channel with obstacles where line-of-sight and non-line-of-sight connections are established between fixed and mobile beamformers.

Figure. 3. Antenna or antenna array placement to achieve beamforming, energy focusing, and spatial diversity illustration in mmWave mobile beamformers.

Figure. 4. Mobile mmWave beamformers in proximity to the human tissues and fixed beamformer at a radial distance.

Further Reading/Resources

T. S. Rappaport et al., "Wireless Communications and Applications Above 100 GHz: Opportunities and Challenges for 6G and Beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019.

S. Ghosh and D. Sen, "An Inclusive Survey on Array Antenna Design for Millimeter-Wave Communications," *IEEE Access*, vol. 7, pp. 83137–83161, 2019.

Related Articles (See Also)

Cross-references (to other articles in Wiley 5G Ref. A cross-reference list can be found under 'Instructions & Forms' on the ScholarOne site
<https://mc.manuscriptcentral.com/Wiley5GRef>

Article ID
e.g. 5GRef001

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