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A Survey of the Challenges, Opportunities and Use of Multiple Antennas in Current and Future 5G Small Cell Base Stations

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ABSTRACT Small cell base stations (SBSs) and multiple antennas are seen as fundamental technologies in the emergence of the next generation [i.e., 5th generation (5G)] of cellular wireless technology. This paper provides a comprehensive survey of literature relating to the applications and challenges associated with using multiple antennas in SBSs. The use of multiple antenna techniques in conventional wireless base stations has undergone much study and is widespread. With heterogeneity in current networks and a furthering of this theme together with greater densification expected in 5G systems, their use in SBSs is at an evolutionary stage. In this paper, unique design challenges associated with size, cost, and performance in SBSs are presented. We present a clear understanding of this increasingly important research area, identifying a clear classification of use and design guidelines. We present a state-of-the-art review of the literature to show how researchers are using and considering the use of multiple antennas in small cells. Attention is given to current generation networks, and with SBSs being a dominant technology necessary for 5G, we also provide insights into the design challenges in such possible future networks.

INDEX TERMS Multiple antennas, small cell base stations, 5G.

I. INTRODUCTION

The recent advancement of wireless networks have seen a change from traditional macrocell base stations (MBSs) covering a wide areas e.g. 10s of kilometres, to the introduction of much smaller footprint small cell base stations (SBSs). These typically include picocells, femtocells, and ultra-dense small cells covering 100s to 10s of meters. Furthermore, it is widely agreed that increasing the number of cells with small radii will be the main contributor of the next generation cellular system (i.e. 5G) to increase the network capacity and to provide required data rates [1]. Recent most vision papers on 5G also point out small cells as the key technology to achieve 5G requirements [1], [2]. Hence, SBS are the expected approach in achieving 5G targets. Indeed, reducing cell sizes through the use of heterogeneous networks (HetNets), employing greater spectral efficiency at each BS and, an increase an in spectrum are seen as solutions to meet the requirements of future wireless networks [3], [4]. These fall under the category of ''network densification'', provided by spatial densification and spectral aggregation [4]. Spatial densification is achieved by increasing the number of antennas at the SBS and increasing the density of SBSs per m^2.

A. FEMTOCELL SBSs

SBSs are small, low cost, energy efficient and in the case of Femtocell BSs (FBSs), generally self-installable. Originally provided to solve coverage problems they are now being seen as a means to satisfy increasing data rate volume requirements. They are seen as an alternative to traditional MBSs for increasing coverage, quality of service (QoS), capacity and energy efficiency (EE) [5], [6]. Operating alongside surrounding MBSs they provide an additional layer in HetNets where they can offer high QoS access over a small and focused area. FBSs are typically installed impromptu in the residential domain or small office/home Office (SOHO) and provide wireless cellular access to a closed or open group of subscribers as configured by the subscriber and/or the service provider [5].

FBSs, which currently account for 96% of all SBSs [7], were originally targeted for residential use. Installed by the end user in the home, backhaul connectivity is usually over

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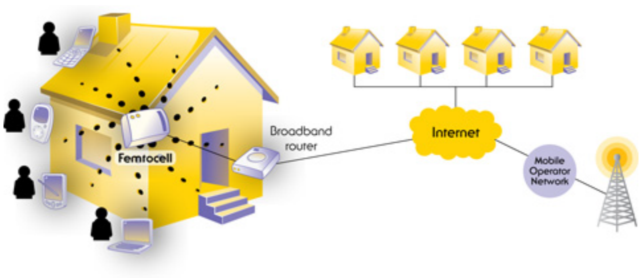

FIGURE 1. The Residential Femtocell Concept.[1]

the consumer's wired broadband e.g. asymmetric digital subscriber line (ADSL) or fiber connection as shown in Figure 1. In common with all SBS classes, FBSs typically operate in licensed spectrum and may or may not use the same frequency as the overlaying macrocell network.

Current generation SBSs, and in particular FBSs, employ single, static, omni-directional antennas [8]. This is largely driven by original need as well as practical considerations such as cost and physical limitations. The use of multiple antenna techniques to overcome interference with surrounding MBSs and other co-located SBSs in co-channel deployments has recently received much attention. There is also an increasing pressure to use advanced antenna techniques, to maximize spectral efficiency (SE), to cope with the relentless demand for increased data rates [1], [9].

Advanced antenna techniques such as multiple input, multiple output (MIMO) spatial multiplexing (SM) and beamforming techniques are fundamental parts of wireless standards such as IEEE 802.11n Wi-Fi, IEEE 802.16 WiMAX (World Interoperability for Microwave Access) and 3GPP (Third Generation Partnership Project) HSPA and LTE/LTE-Advance (LTE-A). They are commonplace in MBSs. Given the high data rate demand for particularly indoor use, advanced antenna techniques will see increasing use in smaller cells. Furthermore with multi-layered heterogeneity and densification being dominant themes for future wireless networks [4], those beyond 4G (B4G) and fifth generation (5G), SBSs will play an ever increasingly important role. More advanced antenna techniques are needed for 5G to foresee operation at tens of GHz with ultra-dense small cells. With an anticipated 1000 fold data increase by 2020 [10], MBSs augmented with a layer of multi-standard, spectrally efficient SBSs equipped with advanced antenna techniques will provide an evolutionary step for 5G towards these predicted demands.

The aim of this article is therefore to provide a survey of the literature over the period 2007-2015 covering the use of multiple antenna techniques for current generation SBSs and to provide insights into their anticipated use in future 5G networks. We aim to provide an overview and description of the challenges faced and techniques used when using multiple antenna techniques for small cells. To the best of the authors' knowledge, this article for the first time brings together key areas of consideration for the use of multiple antennas in SBSs. The article is organized as follows - Section II discusses unique challenges when considering the use of multiple antennas for SBSs. Section III overviews the use of advanced antenna techniques. Section IV provides a discussion into recent research surrounding the use of multiple antennas in current generation SBSs to overcome interference problems in HetNets. Section V discusses the implications on design for 5G. Section VI provides a synopsis of recent commercial developments in SBSs. Concluding remarks are provided in section VII.

[1]Image provided courtesy of Small Cell Forum-www.smallcellforum.org.

II. DESIGN CHALLENGES

This section discusses the challenges associated with using multiple antennas in SBSs in general. We consider the small cell environment and elaborate on complexity issues faced when designing a multi-antenna system for a SBS. The types of antenna elements for SBS are also discussed.

A. DESIGN CONSIDERATIONS

Originally targeted for residential (home) deployment, the cell radius is limited to the local area of the property and the user mobility is always pedestrian. With random end user deployment, in user premises, there is a likely need for 360° coverage in a similar fashion to a Wi-Fi router. The role of the small cell is also considered for use in the enterprise (office, campus) environment [8]. Here the cell radius is likely to be greater, a greater number of users will exist and the spread of the user locations will be more diverse. The users will still be typified by low mobility but the coverage area and cell radius will be increased.

Unlike conventional BSs, SBSs may not serve a fixed direction or BS sector. In addition, unlike MBSs where interference is typically concentrated in azimuthal plane, SBS will suffer random azimuthal as well as vertical interference, particularly in a multi-story building environment where vertical frequency reuse may be employed [11]. These factors need to be considered in the choice of antenna scheme a SBS will use. Characteristics of small cells, their challenges and possible exploitations and considerations when implementing a multiple antenna scheme can be summarised as follows:

1. Users in residential small cells, may be in one of a few fixed locations.
2. Users will be more randomly scattered in enterprise and public small cells.
3. Users will be either stationary or slow moving. Doppler frequency shift will be non-existent for all practical purposes considering current wireless carrier frequencies (2GHz band) and the frequencies use for 5G.
4. Due to constrained user equipment (UE)/user mobility, fixed beam phased array is an alternative solution compared to more complex adaptive array.
5. Given short SBS to UE distances, high angular spread of UEs surrounding the SBS is more likely (unlike sectored macro).

6. Form factor/physical dimension impose stronger constraints on SBS antenna design compared to MBS.
7. Cost and complexity constraints in SBSs antennas are also more important factors compared to MBSs.

There is therefore a diverse range of deployment scenarios that need consideration when attempting to design an appropriate multiple antenna solution for future networks. There is unlikely to be a single antenna solution for all radio environments and the optimal antenna solution will depend on the local environment and channel characteristics. As in conventional BSs, the physical layer/air interface will also likely impact the optimal multiple antenna scheme.

1) COMPLEXITY

With the FBSs primarily intended for residential/home deployment, this type of small cell can be considered as a consumer based product and as such will be required to be low in cost [8] and therefore low in implementation and operational complexity. Indeed their lower transmit power requirements dictate that the cost is much less due to the much reduced cost of the power amplifier stages. Since they will, by and large, be deployed by the end user in an ad-hoc manner where there will be limited or no operator intervention, they are required to be essentially 'plug and play', 'zero-touch' devices. This is a key factor in their adoption and mass deployment. Any techniques that extend to multi-element antenna systems should, ideally, satisfy these requirements and ensure that such schemes are low in cost and complexity.

2) SIZE – FORM FACTOR

The intended deployments: SOHO, indoor enterprise and outdoor seamless deployments (e.g. through lamp posts) put practical limitations on the physical dimensions and form factors of SBSs. This is particularly relevant for FBSs. Examples of commercially deployed residential FBSs are shown in Figure 2. A summary of some commercially deployed FBSs and their physical dimensions is provided in Table 1. These are similar in size and form factor comparable to Wi-Fi routers.

FIGURE 2. (Left to right) Vodafone, Ubiquisys, AT&T 3G Microcell, Vodafone V3.

As highlighted from [16] smaller form factors are being introduced and indeed are envisioned for the future [17]. SBSs and particularly FBSs will require the antenna arrays to be designed efficiently with small antenna sizes, close antenna spacing and mitigation techniques for potential increased mutual coupling effects.

TABLE 1. Commercially available small cell dimensions.

Small cell	Dimension h,d,w (mm)
Vodafone Sure Signal v1	190 x 150 x 37
IP Access Nano3G [12]	170 x 125 x 25
IP Access NanoLTE+ [13]	274 x 213 x 56
AT&T 3G Microcell [14]	216 x 160 x 38
Fujitsi, LS100 Series Residential Femtocell [15]	189.5 x 45.5 x 89.5
Vodafone Sure Signal v3[16]	142 x 72 x 38

3) SPATIAL CORRELATION AND ANTENNA MUTUAL COUPLING

Specific to the SBS, in a similar manner to a UE handset, is the degree of channel correlation between the individual transmit or receive antennas. In this respect, the limited dimensions shown in Table 1 present unique design challenges. It is well known that the capacity of a MIMO system not only depends on the number of channels ($M \times N$), where M and N are the numbers of receive and transmit antennas respectively, but also depends on the correlation between the channels. In general, the greater the channel correlation, the smaller is the channel capacity. Channel correlation of a MIMO system is mainly due to two components: spatial correlation and antenna mutual coupling, both of which are affected by the physical distance between the antenna elements. The degree of correlation between the individual antennas is a complicated function of antenna spacing at the transmitter and the receiver and the scattering in the environment [18]. The channel transfer matrix, $\mathbf{H}$, is often modeled as:

$$\mathbf{H} = \mathbf{R}_{\mathrm{R}}^{1/2}\mathbf{G}\mathbf{R}_{\mathrm{T}}^{\mathrm{T}/2} \tag{1}$$

where $\mathbf{R}_{\mathrm{R}}$ and $\mathbf{R}_{\mathrm{T}}$ describes the correlation between the signals at the receiver and transmitter elements, respectively, and $\mathbf{G}$ is a matrix with independent and identically distributed (i.i.d) complex Gaussian entries. Antenna mutual coupling can be represented by transmit and receive mutual impedance matrices. Combining the channel correlation with the effects of mutual antenna coupling the MIMO system can be modeled as:

$$\mathbf{V}_{OC}^{'} = \mathbf{Z}_r^{-1}\mathbf{H}\mathbf{Z}_t^{-1}\mathbf{v}_{\mathbf{s}} + \mathbf{v}_n, \tag{2}$$

where $\mathbf{V}_{OC}^{'}$ is the open circuited output voltage, $\mathbf{Z}_r^{-1}$ and $\mathbf{Z}_t^{-1}$ are the receive and transmit antenna array mutual impedance matrices respectively. $\mathbf{v}_s$ is the excitation voltage vector and $\mathbf{v}_n$ is the channel noise vector not assumed to be affected by mutual coupling. When considering spatial multiplexing and diversity schemes, channel correlation between multiple antennas needs to be minimized to maintain the optimal efficiency of the antennas [19], [20].

In the case of the SBS it could be that the antennas are so closely spaced because of the physical form factor, that all the elements of $\mathbf{H}$ (the MIMO channel) will be fully correlated. In this case the spatial diversity gain will be diminished to one whereas the aim will be to maximize this to be equal to the number of receive and transmit antennas i.e. MN. With rich scattering, it is generally accepted that the separation required is of the order of half the carrier wave wavelength ($\lambda/2$) of the operating frequency [18]. In ideal conditions, where the channel elements are perfectly uncorrelated, $\mathbf{H} = \mathbf{H}_w$ the classical i.i.d frequency flat Rayleigh fading MIMO channel, where optimal spatial diversity of the order MN can be achieved [16]. High correlation between elements will lead to poorer performance for systems employing antenna diversity schemes such as receive diversity and transmit diversity through space time transmit-diversity (STTD) Alamouti codes [22].

4) NUMBER OF ANTENNA ELEMENTS

Size and form factor will directly impact the number of antenna elements possible. For example if we consider transmit or receive frequency of 2GHz, the corresponding wavelength (λ) would be 0.15m. Considering the dimensions in Table 1, this would limit the number of antennas to three or four assuming antenna spacing requirements are satisfied as discussed above. For beamforming, the number of antenna elements directly affects the beamwidth, and the number of concurrent beam and null patterns.

B. POWER AND ENERGY EFFICIENCY

SBSs and in particular FBSs are considered as a low power and inexpensive alternative for operators to extend their coverage, and more importantly, capacity particularly in the indoor space. Predicted figures for their anticipated growth have varied over the past six years. Recent figures provided in [23] anticipate that there will be up to 70 million SBSs deployed by 2017. In fact, their demand has led some to predict that in the next 10-15 year timeframe the number of BS including SBSs will meet or exceed the number of cell phone subscribers [17], [24]. With the proliferation of various deployment types (residential/home, enterprise, urban, rural), it is likely that SBSs will dominate in the future. It is therefore clear that there is a need to address EE of the SBS as potentially vast networks will be deployed. SBSs are already considered to be 'green', i.e., energy efficient [25], largely related to the fact that they are in close proximity to their served UEs, hence the required transmit power is very low when compared to a MBS. Methods and techniques that are used to extend the range or increase the SE of the SBSs with multiple antennas should ideally strive to be low in power and complexity.

C. TYPES OF ANTENNA USED IN SMALL CELLS

In first generation SBSs, the antenna system is of a static nature. Usually such installations use simple dipoles or printed circuit board antennas (PCB-antenna) with low gain and rather omni-directional, fixed patterns [26]. The use of multiple antennas in SBSs face several challenges such as complexity, increased signal processing, cost and physical limitations associated with the form factor of small cell housings [8], [9]. Microstrip patch antennas are generally chosen as the technology for diversity antennas for both mobile BSs and terminals because of its advantages of compactness and easy fabrication [27], [28]. Patch antennas are a form of microstrip antenna based upon printed circuit board (PCB) technology to create flat radiating structures on top of dielectric, ground–plane backed structures [29]. These have suitability for SBSs because of their low cost and high reliability. The use of planar inverted-F (PIFA) antennas are another form of microstrip antenna which are popular in mobile phone/UE technology because they are resonant at l/4 λ [30], where λ is the wavelength corresponding to the frequency of operation. They are therefore attractive in terms of their physical properties, which makes them equally suitable for SBSs. The use of E-plane horn antennas, a physically flared (in the direction of the electric E field) antenna which is a natural evolution of the idea that any antenna represents a region of transition between guided and propagating waves [29], have also found use in SBSs applications [31]. E-plane horns offer moderate directivity and since they do not have any resonant elements they can operate over a wide range of frequencies. The pros and cons of various antenna types and their inclusion in the literature are highlighted in Table 2.

TABLE 2. Antenna types and properties.

Type	Typical Features
PCB dipole	Low cost Low profile Omni-directional
Microstrip Patch [29]	Low cost, Low profile Easy to fabricate Resonant at $\lambda/2$
PIFA [21][26][28][31]	Low profile Resonant at $\lambda/4$ Physically small
E-Plane[32][33][34][35]	Moderate directivity High bandwidth

III. APPLICATION OF ADVANCED ANTENNA TECHNIQUES IN CURRENT SBSs

Figure 3 lists the advanced antenna techniques which can be used in small cell wireless networks. Here we have related these approaches to their heritage from the literature. The associated references are by no means exhaustive. Nonetheless they still present the main picture of ongoing attempts to use multiple antennas in SBSs. As in conventional MBSs generally the techniques are used to either improve the signal-to-interference-plus-noise-ratio (SINR) or share the available SINR. Improving the SINR arises when the multiple copies of a transmitted signal combine constructively at the intended receiver or when sufficient diversity is present in the channel such that variation in SINR at the receiver is reduced. Alternatively and rather than increasing the modulation order and coding rate to increase the data rate for a given SINR, multiple N antennas at the transmitter and receiver are used

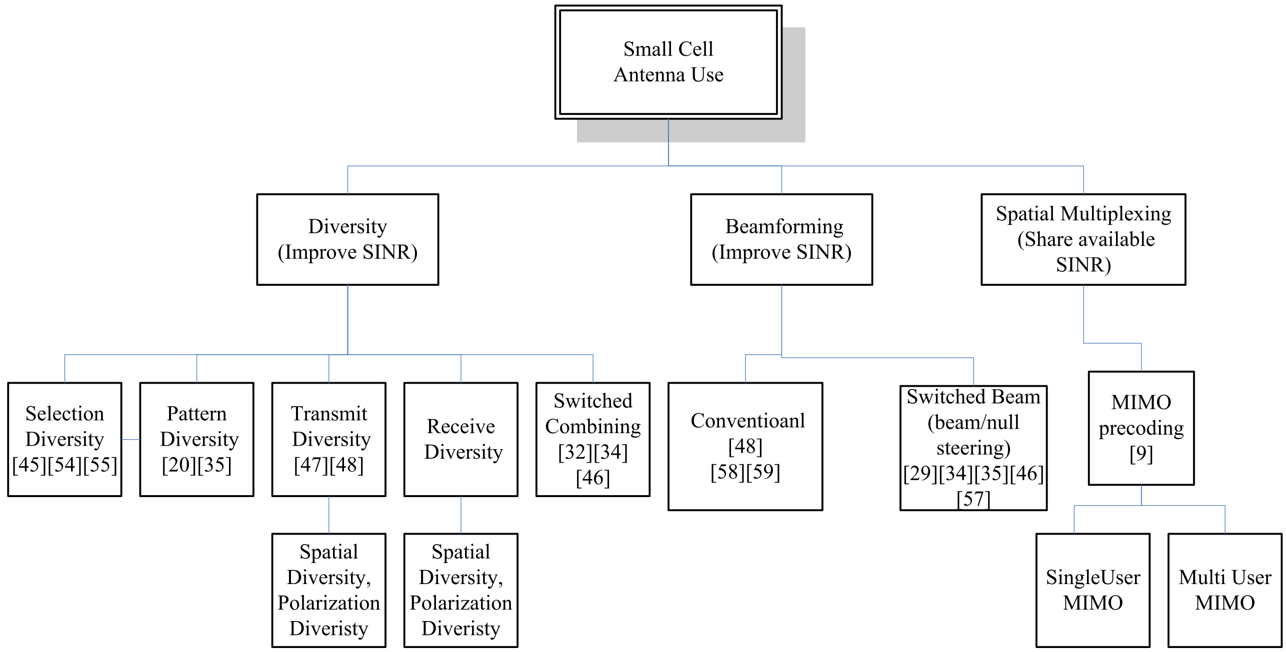

FIGURE 3. Multiple antennas for small cells.

to convey multiple N individual data streams using MIMO spatial multiplexing. In this sense the SINR is shared and is common for the N data streams. In the following we discuss the use of such techniques in the context of small cells.

A. DIVERSITY

Featuring heavily in current SBS approaches is the use of antenna diversity. Traditionally used on the uplink/receive side of a BS, can be used to provide multipath diversity due to the spatial separation of the antennas at the receiver. Antenna diversity can also be employed in the downlink/transmit side. This configuration is common in MBSs, since it is easier, cheaper and more effective to employ multiple antennas at a single BS compared to multiple antennas at each UE. This is of course also true in the case of SBSs. Specific codes can be designed for the transmit diversity system. Perhaps the most simplest of these, and therefore applicable for a SBS because of its low complexity, is the Alamouti space time code scheme [22]. This actually forms part of the third and fourth generation cellular standards being employed in both wideband code division multiple access (W-CDMA) and LTE (OFDMA) standards for downlink transmission. A comprehensive survey of the value of spatial diversity techniques such as those mentioned above can be found in [35].

B. BEAMFORMING

Beamforming is a signal processing technique whereby signal streams from multiple elements in a phased array antenna network can be combined in both a constructive and destructive way [36]. Beamforming at the SBS can be provided on both uplink [37] and downlink [38].

1) THE ROLE OF CSI

Uplink (or receive) beamforming multiplies the receive data received on each antenna with a weight derived from the channel properties, known as the channel state information (CSI). The CSI represents the combined effect of, for example, scattering, fading, noise, and power decay with distance. If only the phases of the received signals are manipulated then the overall antenna pattern remains unchanged and solely an angular shift results [39]. If the amplitudes are also scaled based on the CSI it is possible to modify the shape of the overall antenna array pattern [39]. An array with N antenna elements will permit N-1 angles from which the antenna pattern can be a maximum (for desired users) or a null (for undesired users) [39]. Similarly in downlink (or transmit) beamforming knowledge of the channel properties experienced in the transmit path for each antenna element are required. BSs, including SBSs, invariably transmit on separate frequencies in both uplink and downlink due to frequency division duplex (FDD) schemes being popular. Since the effects of fading will be governed by the frequency of operation it is impossible to determine the effects on the downlink transmit path based on the uplink. Usually a feedback from the UE is used to provide CSI at the transmitter, to overcome this problem. Additional signal processing uses this information to appropriately weight the transmissions on the downlink to form the necessary beam pattern. High mutual correlation/coupling between each of the antennas is possible in a SBS [9]. In this case the frequency selective fading may be the same, or highly correlated, across each of the antenna elements. This makes beamforming possibly simpler since independent CSI associated with each of the individual antenna elements may not be needed.

2) SWITCHED BEAMS

Complexity will drive antenna schemes for SBSs. A way to reduce the signal processing burden is to incorporate the use of fixed switched beams [40]. A switched-beam antenna system consists of several highly directive, fixed, pre-defined beams stored as antenna weights. In general such systems detect signal strength, or best SNR, choose one of the fixed beam weights then subsequently switch from one beam to another as the user moves through the cell. Such schemes for indoor use are discussed in [32]. Beam patterns can be selected to not only provide directivity but to provide nulls to interfering signals. Another method is to switch between antenna patches to provide spatial diversity. Here multiple antenna patterns can be provided by the use and combination of multiple antenna patches intended for particular directions as discussed in [8].

C. SPATIAL MULTIPLEXING

Having both multiple antennas at the BS and the served UEs, provided the channel conditions are favorable, can increase the capacity of the wireless communications link. The capacity of such a system is proportional to l where l corresponds to the number of $(M \times N)$ antenna pairs at the receiver and transmitter [41]. With massive demand for increased data rates, the trend in emerging as well as future networks is to use MIMO-SM as an essential part of both the UE and the BS. Theoretically, MIMO-SM provides increase in data rate for no additional transmission power or bandwidth expenditure compared to the single input, single output (SISO) system. Array gain, spatial diversity gain, spatial multiplexing gain and interference reduction all help to increase the possible throughput of the system [40]. For the same data rates the conventional SISO scheme would be required to transmit at a much higher power or require much higher bandwidth. These recent developments have seen use of MIMO-SM in traditional BSs to increase the SE.

To visualise the key factors that govern the performance of the MIMO system we can refer to (3). Considering a MIMO system and assuming perfect CSI at the transmitter and receiver and an average power constraint, the capacity in bits/s/Hz can be determined from:

$$C = \log_2[\det(\mathbf{I}_M + \frac{\rho}{N}\mathbf{H}\mathbf{H}^{+})], \tag{3}$$

where $\mathbf{H}$ is the $M \times N$ channel matrix, $\mathbf{I}_M$ is the identity matrix of size M and ρ is the average signal-to-noise ratio (SNR) at each receiver branch. $\mathbf{H}^{+}$ is the transpose conjugate of the $\mathbf{H}$ matrix. The SNR, number of transmit-receive pairs and correlation of the MIMO channel $\mathbf{H}$ contribute to the capacity of the system. Capacity can be increased by using a larger number of antennas (assuming suitable correlation characteristics between the transmitter and receiver). As discussed in Section II the degree of correlation of the elements of $\mathbf{H}$ will impact the performance of the MIMO channel.

D. RESEARCH TO DATE

The use of multiple antennas to cope with the effects of interference in HetNets have, by far, attracted the most attention in the literature [42]–[48], [50], [54]. Focusing on indoor coverage (IC) scenarios has also been a dominant theme with measures to address SE and EE seeing less research activity. Regardless of application area their use in such scenarios is complicated by the design challenges associated with SBS antenna design as discussed in Section II.

IV. CURRENT GENERATION SBSs-INTERFERENCE

The creation of HetNets gives rise to two layers or tiers in the wireless network: the macrocell layer and the small cell layer. It is well recognized that a key challenge in the adoption of HetNets is cross tier interference between the small cell and macrocell network [1], [40], [43] particularly when the small cell networks share the same frequency band as the surrounding macrocell network. This means that small cells may cause and suffer co-channel interference with the overlaying macrocell network. In addition, interference between co-located small cells (co-tier) is also a challenging problem due to possible close proximity of a large numbers of small cells. The types of interference in two tier small cell networks are depicted in Figure 4.

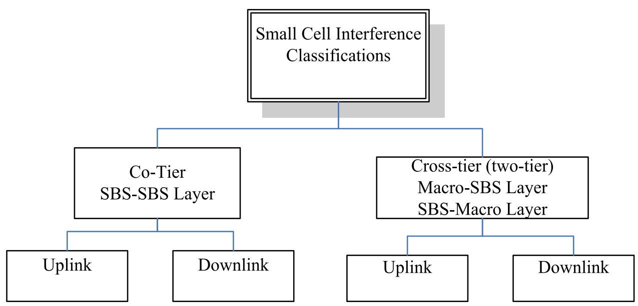

FIGURE 4. Interference classification.

Figure 5 illustrates how interference in a HetNet can occur. Uplink co-tier interference will be caused by surrounding, co-located UEs creating interference or a rise in the noise level to nearby SBSs.

Downlink co-tier interference will be caused by SBS transmissions interfering with neighbouring small cell's UEs [43]. Uplink cross-tier interference can take place when a small cell UE acts as a source of interference to the macrocell BS, or vice-versa. Downlink cross-tier interference can be caused by a SBS transmitting to close to a macrocell UE. Measures taken to avoid interference issues are key to the success of small cell take-up. In order to address these issues the use of power control, interference mitigation and resource partitioning have been discussed in [49]–[52]. Early interference mitigation techniques have assumed the use of single antenna FBSs. The remainder of this section discusses the use of FBSs equipped with multiple antennas aimed at tackling the interference problem.

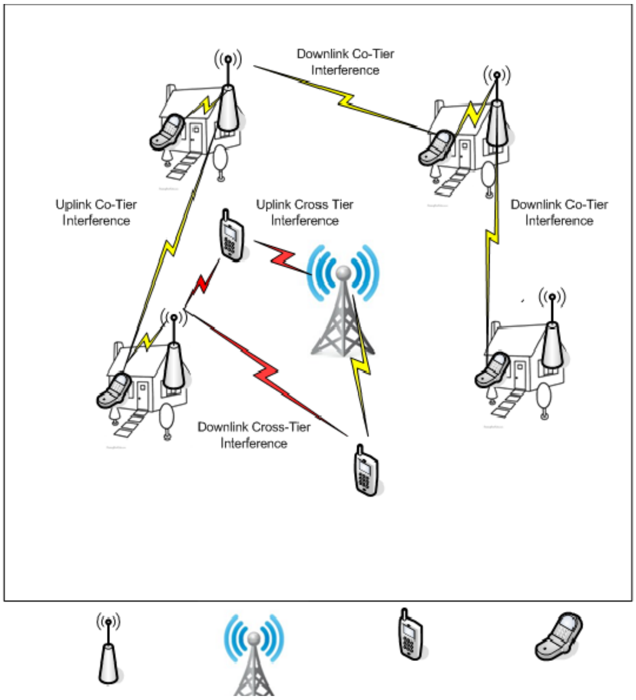

FIGURE 5. Co and cross tier interference.

A. ANTENNA SELECTION DIVERSITY SCHEMES

As the authors in [53] emphasise, the main requirements of practical FBSs are reduced cost, size and energy consumption. In [40], authors also highlight that it's not the antenna elements but the associated radio frequency (RF) circuits that substantially increase the cost and energy requirements of the system. In keeping with the low complexity goals of commercial FBSs, computationally simple and low cost solutions are sought. Antenna switching or selection schemes aim to improve the SINR by antenna diversity. In these systems only one of a group of available antennas are used in the receiving and demodulation process or conversely used for the transmission of the signal [29].

1) RECEIVE ANTENNA SWITCHING/SELECTION

Antenna switching is the simplest of all forms of antenna diversity whereby a single antenna is used and is only switched to another if the current antenna signal falls below a pre-defined threshold [29]. In contrast antenna selection is a more computational complex solution. Here the receiver selects the antenna branch that has the instantaneous best SINR [29] and requires that all receiving circuitry and associated signal processing chains are active. Combining a subset of antennas to a set of receiver chains and combining them provides an alternative solution to improve the SINR and still maintain the complexity cost low. Here the number of antennas available in an antenna array may be greater than the number of available receiving circuits.

The use of antenna switching and selection methods for interference mitigation in FBSs, have been given consideration in [53] and [54]. The authors in [53] consider the use of antenna selection for an LTE FBS. The basic principle can explained as follows: Considering an N–element antenna array denoted as $\{a_1 \dots a_M\}$, for a transmitted signal there are $\{y_1 \dots y_M\}$ set of observations on the antenna array and channel coefficients of $\{h_1 \dots h_M\}$. Assuming all observations and channel coefficients are available at the receiver and assuming additive white Gaussian noise (AWGN) of equal power on each of the antenna elements a maximum ratio combiner (MRC) produces a received signal of:

$$r_{mrc} = \sum_{m=1}^{M} h_m^* y_m \tag{4}$$

This maximises the signal to noise ratio (SNR) [53]. Residential, office and small office propagation channels were used to compare a single antenna scheme with a 4 antenna selection scheme. SINR measurements over one second duration were used to determine the appropriate antenna selections using a commercially available LTE FDD FBS. The authors in [53] discuss the need for possible preamble based antenna training to cater for channel variation and fading as well as discussing possible losses in such systems as practical RF switching fabric insertion loss. Such losses in the system have an adverse, negative effect on any gains made. Uplink gains of between 1-2dB are shown in the analysis, under indoor propagation conditions and in the absence of interferers.

With complexity being a key constraint the authors of [43] examine receiver antenna selection schemes with exact channel information over exhaustive best antenna selection schemes. The use of the channel co-variance matrix (which provides long-term statistical information about the channel) of the interference plus noise at the receiver was used and is shown to almost be as good as an exhaustive search of the best possible antenna selection scheme but being much reduced in complexity.

B. SWITCHED ANTENNA FOR PATTERN DIVERSITY

Pattern diversity can be used in small cells as a way to mitigate co-channel interference with surrounding macro-cells and provide additional gains in a system employing more than one antenna [55]. In addition as recognized in [26] and [45], large scale deployment of FBSs can cause a significant increase in mobility events (e.g. handovers or idle mode mobility). Claussen and Pivit showed how the loading of the core network signaling, in a W-CDMA system, could be reduced with a switched multi antenna element FBS compared to that with a single antenna [8]. As part of their investigations four antennas, two patch and two inverted-F-antenna (IFA) were housed in a commercially available FBS to give four distinct and complimentary radiation patterns, as well as a selection of combined radiation patterns from any two antennas. This gave a total of 10 patterns to switch to at any one time. Antenna or pattern switching was based on limiting mobility events while maximizing the indoor coverage by a combination of historical event logging and path loss measurements respectively. The analysis concluded that the core network loading was considerably reduced and indoor coverage was increased. The most used patterns were the most spatially diverse i.e., those with the least pattern similarity. A significant conclusion from the analysis being that design of such antenna systems should strive to include as much diversity in antenna response patterns as possible.

The work by the authors in [8] was extended and a switched multi-element antenna (SMEA) was proposed in [44] with the objective of protecting FBS users against uplink interference. Downlink interference from the FBS to other users is simultaneously reduced as a by-product of the system. To overcome excessive packet errors and decreased QoS during antenna selection, because the possible antenna patterns are diverse and therefore may give rise to periodic poor QoS, dynamic self-configuration for the selection of antenna patterns is assisted by reinforcement learning (a sub-area of machine learning concerned with how an agent should take actions in an environment as to maximise its long-term reward). The results show a 2.5dB gain on uplink and a 1 dB gain on the downlink compared to omni-directional antennas. Importantly the design was cost effective and low complexity.

Specifically addressing the 802.16m OFDMA air interface for FBSs, the authors in [31] address the use of switched directional antennas for interference reduction to the macrocell network and improved reliability of the FBS system. The authors claim an improved small cell capacity using a reconfigurable, single transceiver, switched beam E-plane horn antenna, small enough in size to be suitable for a small cell application (19.2cm × 19.2cm × 9.5cm) when compared to 0dB and 3dB omni-directional antennas. Using the same antenna configuration, the work was extended to consider the use of the switched beam antenna with sub-channel allocation in [40]. OFDMA carrier sub-channel allocation is used to reduce interference to and from the macrocell network and is complimented with the selection of antenna beam pattern based on location awareness of small cell users in a campus small cell deployment. The work was further extended in [33] to consider using the switched beam antenna combined with location awareness, as specified in the 802.16m standard, of small cells users to reduce interference between indoor small cells and outdoor macrocells.

Addressing the needs of coverage and interference (between FBSs) in an enterprise FBS deployment, the authors in [34] analyse the performance of an E-plane horn directional antenna scheme. Switching between 4 directional antenna patterns and one omni-directional patterns is considered. A two-stage optimisation algorithm is used firstly to optimise the pilot power to maximise coverage and reduce overlap between small cells then an antenna patterns selection algorithm is employed to optimise the network of FBSs.

To mitigate co-channel interference to the macrocell as well as to provide optimal coverage for an indoor FBS, the use of switched antenna beams are discussed in [55]. A user assisted scheme was devised whereby the user manually walks around the dwelling and using a UE transmits signals from crucial places (CPs) in the building. The CPs correspond to either places in the dwelling which can cause easy leakage to the overlaying macrocell or places that are difficult to provide coverage to. The FBS was equipped with a 6 element (PIFA) antenna scheme which was used to derive approximate direction of arrival (DOA) information of the transmitted signal. Based on this information beamforming weights are formulated to maximise the indoor coverage and minimise the pilot leakage to the surrounding macrocell. The signal processing involved in this scheme was kept simple, where DOA is limited to six regions, each of 60° azimuthal range, to provide a complete 360° coverage in the dwelling. The actual DOA algorithms were kept simple also by approximating DOA by correlation of a six region steering vector with channel correlation matrix. The techniques were low in complexity, however there was the requirement for manual user intervention when the FBS was installed, moved or the physical properties of the building changed. This in itself imposes a constraint on exploitation of this technique in wide scale FBS deployment where self-install and no intervention by skilled personnel are key.

C. BEAMFORMING FOR INTERFERENCE

1) DOWNLINK

The authors in [56] consider transmit beamforming has an efficient approach to interference management when used in the FBS downlink transmission. They assumed perfect CSI was available to correctly formulate the beamform weights. In [57] the authors address the problem of imperfect CSI, where either the CSI is limited or is erroneous. An outage based robust beamforming design for non-perfect CSI was provided by characterising the non-probabilistic CSI that may be obtained in multiple-input single-output (MISO) based systems. Here it was assumed that a FBS is equipped with multiple antennas whereas the FBS UE uses only a single antenna. The use of practical transmit beamforming techniques (those based on 3GPP) are discussed in [56]–[58] as an interference suppression method for closed access small cell FBSs. Two antennas were assumed at the FBS, with a single antenna at the receiving UE. Closed loop mode 1 transmit diversity as defined by 3GPP [59] was used as the basis for interference mitigation, which is extended to provide phase and ranked antenna weightings. Performance was compared against transmit antenna selection. The study concluded that interference suppression by simple transmit beamforming provides significant gains but at the cost of increased higher precision feedback from the UE when compared to using transmit beamforming for improved signal strength. The work was extended to consider the use of transmit beamforming for FBS using (High Speed Downlink Packet Access) HSDPA in [58]. Using a control channel only connection to an interfering FBS, a UE subject to interference signaled back CSI to the offending SBS such that it provided null steering of its downlink to the UE. The notable finding of the study was that reasonable null steering attenuation towards the strongest interferers can be achieved by limited feedback signaling through a control channel-only connection between an interfered UE and the interfering small cell. By linearly combining the beamforming weights of a wanted UE with nulling weights to an adjacent, but non-served UE, the authors in [36] show how scaling these quantities can affect the performance of small cell co-tier downlink interference and therefore network performance. The aim of the study was to design beamformers that would balance the interest of the UEs in the two cases.

The authors in [60] consider the case of single user (SU) and multi-user (MU) multiple antenna methods to mitigate the 'near-far' deadspot coverage in a two tier network with multiple antenna equipped FBSs. In the SU case beamforming array gain was provided to assist overcoming interference. The work determined the maximum number of transmitting multiple antenna equipped FBSs that were needed to meet a per-tier outage probability in a closed access/closed subscriber group femtocell network. SU transmission in either tier was shown, analytically, to provide superior performance and spatial re-use. MU transmission was shown to suffer from residual cross-tier interference.

2) UPLINK

Adaptive antennas combined with the use of dynamic spectrum management are used to show the effect of uplink interference mitigation on the uplink of a FBS in [47]. Dynamic spectrum management was used in the FBS to switch between spectrum allocations to avoid interference to its uplink from the macrocell. This is complimented with null steering whereby the azimuthal location of interferers are located and nulled by an adaptive antenna array. The key finding of the study is that simple null steering of this form is useful in small cell deployment scenarios where there is likely to be a dominant interference source and where the number of users in the cell will be small.

V. FUTURE CHALLENGES FOR 5G

To meet the explosive growth of wireless data traffic and to satisfy the needs of 5G, where there is an anticipated 10,000 fold increase in capacity by 2030 [61], radical approaches and novel technologies are needed. A brief overview of candidate 5G technologies and how they relate with SBS is presented in the remainder of this section.

A. mm-WAVE TECHNOLOGY-BEAMFORMING

Traditional wireless systems generally restricted their operation to a narrow range of radio frequencies that ranging from several hundreds MHz to few GHz (correspondingly few centimeters to about a meter). Almost all spectrum in the radio frequency region is already occupied; though, by modernising the spectrum access, allocations and regulatory policies an efficient spectrum access and more bandwidth can be achieved but to fulfill 5G requirements more Hz are required. This can be achieved by (1) moving up in the frequency i.e. towards mmWave spectrum (2) making efficient use of WiFi unlicensed 5GHz spectrum. Fortunately, large portions of mmWave spectrum in the range of 30-300GHz are idle and can be utilised for 5G. This spectrum lies idle due to the bad propagation characteristics, high pathloss and atmospheric absorption etc. in the mmWave region.

There is a growing momentum of using unused frequency bands in the mmWave band for 5G services [62]. Of interest are the bands of 20-90GHz and more specifically 28 and 38GHz bands (where there is 3-4GHz available) and the 70 and 80GHz E-band where there is 10GHz available [3]. Such frequency ranges are typified by high path loss and high atmospheric and rain attenuation. Attenuation ranges from 0.06dB/km and 0.3dB/km for 28GHz and between 70 and 90GHz respectively. Considering small cells with 200m cell radii, air and rain attenuation will be of little significance over such distances [4]. In fact, such absorption would be beneficial as it may increase the isolation of SBS and hence reduces interference. Hence, the usage of mmWave technology fits well to fulfill 5G requirements and envisioned for 5G [63]. mmWave path loss measurement data for the 28 and 73GHz bands are provided in [64] Experimentation performance of small cell performance in the 73GHz band is provided in [65].

Beamforming is a key enabling technology for 5G mmWave technology to overcome reduced path loss and eroded link margin compared to lower conventional frequency bands (2-4GHz) [66]. A large number of antennas are required. The availability of high bandwidth coupled with the use of large antenna arrays (massive MIMO) with as many as 8 to 256 elements (9 to 24dB in link budget gain) at both the transmitter and receiver make this an attractive proposition for 5G systems [4]. We note large antenna arrays with high beamforming gain are required to overcome adverse propagation conditions possible in mmWave [66] although, limited to indoor localised coverage, the losses are unlikely to be as severe. Of particular significance to SBSs is the reduced carrier wavelength which permits many antenna elements to be implemented in very small, flexible form factors.

For transceivers, the small size ($\lambda/2$ dipoles) and separation (also around $\lambda/2$) of mmWave allow a large number of antennas and consequently a high beamforming gain in a relatively small area. This makes the technology attractive for SBSs as well as UE devices.

Full digital beamforming, where a transceiver stage is required per antenna, is seen as impractical because of the excessive power requirements the analogue to digital conversion (ADC) and digital to analogue converter (DAC) stages of each transceiver incur at mmWave frequencies [67]. In addition, as the sampling rate of such ADCs increases so does the inaccuracy of the conversion due to aperture jitter [68]. This has led to alternative approaches being considered such as designing systems that would traditionally require 8-12 bits of dynamic range to use less than this e.g. 4 bits, such that the overall ADC power is reduced. These systems are suited to applications requiring smaller dynamic range such as LOS communications employing small constellations [69]. Whether a communications can be constrained to such levels of quantization is subject to debate. Alternatively the authors

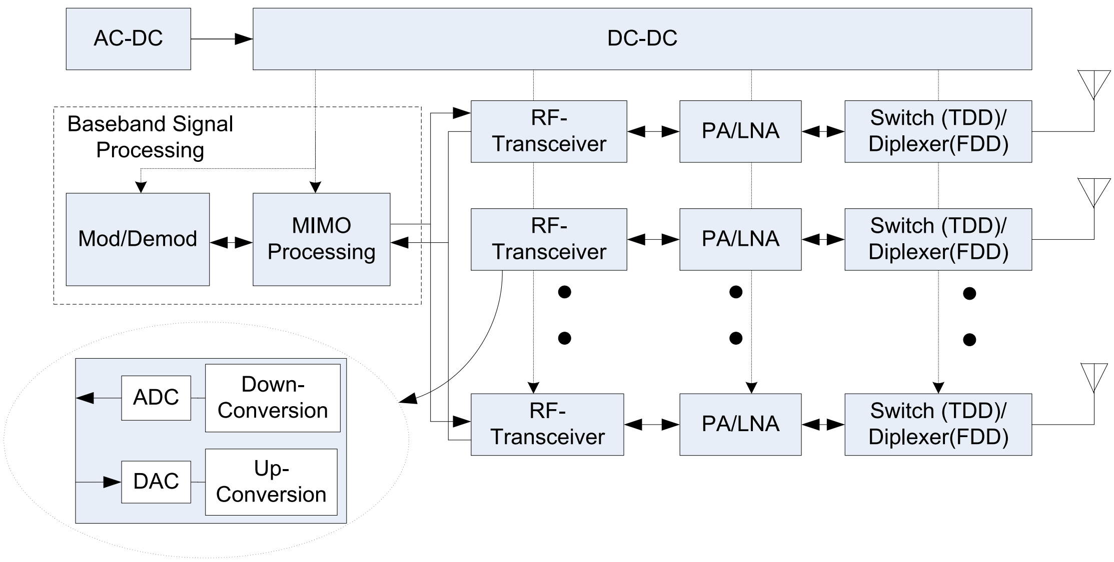

FIGURE 6. **Digital beamforming model.**

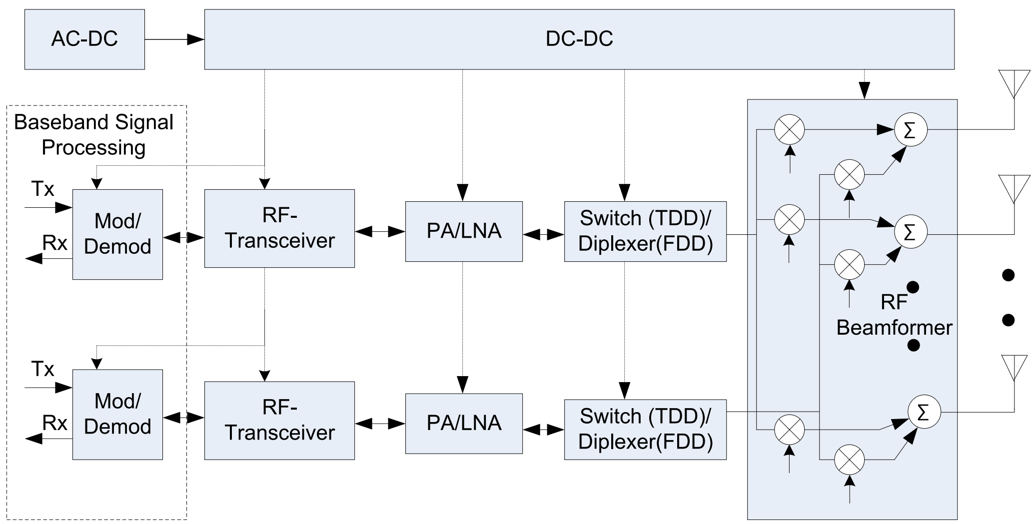

FIGURE 7. **RF beamforming model.**

in [69] consider using a number of low speed, high precision ADCs operating in parallel to synthesize a high-speed, high precision ADC. This approach is subject mismatches between sub-component ADCs which require compensation.

The main approach to overcome the ADC/DAC problem is to employ beamforming at the RF level rather than at the digital baseband. In this case the many antenna elements are served by only a single ADC/DAC per sector [69]. Digital beamforming is illustrated in Figure 6 and shows the requirement for an RF transceiver comprising up and down conversion together with DAC and ADC devices. Each transceiver is required for every antenna element in the system. The approach is common in current 3G and 4G systems employing MIMO technologies but is thought to be unsuitable to satisfy the low power requirements of 5G. The alternative RF beamforming approach is illustrated in Figure 7. Here a single transceiver drives an antenna array. Channel weights associated with the intended user, or group of users are applied at the RF with simple phase changing components. The choice of implementation is biased by the power usage argument but there are advantages and disadvantages of both approaches. These are outlined in TABLE 3.

B. DOPPLER

Other considerations include the Doppler frequency (f_d). Doppler frequency of a wireless channel depends on the carrier frequency (f_c) and the speed of the UE wrt to the BS. It increases linearly with carrier frequency and can

TABLE 3. Advantages and disadvantages of beamforming approach.

Type	Advantages	Disadvantages
RF Beamforming	Single or few transceiver chains meaning lower power consumption due to limited nos. of ADC/DAC for many antennas.	Less flexible than digital beamformer. Implies users are separated in time thus puts constraints on implementation. Difficult to get channel estimates if at RF.
Digital Beamforming	Null steering/zero forcing possible since channel responses known at baseband. Best performance/higher degree of freedom	Significant power consumption and cost due to high speed ADC/DAC required in each transceiver.

therefore present a more significant design challenge in mmWave frequencies. Doppler will affect the variation in the channel which is likely to impact the requirement of CSI needed for a particular antenna scheme. Since the users served by a SBS, particularly those in indoor deployments, are likely to be pedestrian or stationary there will be some inherent mitigation to Doppler frequency.

C. BLOCKING

mmWave, particularly for short distances such as indoor scenarios, is susceptible to multipath dispersion which can be caused by reflection from blockages or the physical properties of the building concerned. Here, non-line of sight (NLOS) communication may be the only possible means to overcome such effects. The reliability of such links may be challenging when relying on beamforming alone where the multipath may appear outside of the antenna beam [70]. Re-acquisition, identification and further antenna steering or beamforming may be required to find any available multipath energy.

D. DENSIFICATION

A simple, straightforward and most effective way to increase system capacity is to reuse frequencies more and more by making cells smaller and smaller. In theory, cell size can be reduced indefinitely to an extent when each SBS serves a single user or remain idle. However, with extreme network densification there are some associated challenges: (1) high cost of installation, maintenance and backhaul (2) too much signalling overhead (3) mobility management in such a heterogeneous network (4) associations between users and base stations across multiple radio access technologies. The usage of SBS and mmWave increases complexity but at the same time solves some of the mentioned challenges.

Recently, Prof Jeff Andrews and his group argued that the extreme densification of network using FBS might lead us to a point where adding more infrastructure does not result any further increase in throughput. Hence, it seems there must be some fundamental limits to the amount of network extreme densification that is possible. More research work is needed to calculate these fundamental limits and do optimisation.

VI. ADVANCED ANTENNA TECHNOLOGIES

A. LATEST TRENDS IN SBS TECHNOLOGY

In line with enhancing the small cell layer with more powerful and flexible SBSs, multi-standard SBSs are now being offered by small cell providers. As an example NTT DOCOMO's Xi FBS [71] is capable of both 3G (W-CDMA) and 4G (LTE). SISO downlink/uplink rates of 14Mbps and 384kbps for its 3G mode and downlink/uplink rates of 112.5/37.5 for its 4G mode are supported. Further developments are likely to see additional antenna elements and higher order modulation schemes to further improve the data rates. Airspan, a leading provider of LTE SBSs, recently demonstrated the use of it's, so called, lightweight–CoMP technology in the 3.5GHz band [72]. This showed how a cluster of SBSs can operate in a single radio cluster with joint transmission to improve the outdoor and indoor coverage, network capacity and the quality of user experience of a rooftop MBS deployment. Beamforming, using a six-element array is used in Apple's Airport device [73]. This is a WiFi router product operating at 2.4GHz and 5GHz but nonetheless illustrates use of advanced antenna techniques in a small form factor similar to a FBS. Additional techniques to address capacity such as multi-carrier and carrier aggregation will push data rates yet further but will eventually reach the limits of the technology and resources.

VII. CONCLUSIONS

This article has addressed the use of multiple antennas in SBSs in current and emerging 5G cellular networks. An overview of associated challenges of using such techniques has been provided. This shows that although SBSs will be required and are expected to provide high data rate services with MIMO spatial multiplexing to maximise the SE and use multiple antennas to mitigate interference in HetNets, there are unique and challenging hurdles to overcome because of the physical size constraints the consumer based SBS present. In addition we have stressed the impact of cost and complexity which has to be kept to a minimum to satisfy the operators and consumer requirements to ensure widespread roll out of such technologies for 5G. We have discussed the issues surrounding the use multiple antenna based SBS for future 5G networks using possible new frequency spectrum. We have discussed what this may mean for SBS design and technologies associated with massive MIMO.

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