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Citation for published version:
Wang, C-X, Haider, F, Gao, X, You, X-H, Yang, Y, Yuan, D, Aggoune, HM, Haas, H, Fletcher, S & Hepsaydir, E 2014, 'Cellular Architecture and Key Technologies for 5G Wireless Communication Networks', *IEEE Communications Magazine*, vol. 52, no. 2, pp. 122-130.

Cellular Architecture and Key Technologies for 5G Wireless Communication Networks

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Abstract

The fourth generation wireless communication systems have been deployed or are soon to be deployed in many countries. However, with an explosion of wireless mobile devices and services, there are still some challenges that cannot be accommodated even by 4G, such as the spectrum crisis and high energy consumption. Wireless system designers have been facing the continuously increasing demand for high data rates and mobility required by new wireless applications and therefore have started research on fifth generation wireless systems that are expected to be deployed beyond 2020. In this article, we propose a potential cellular architecture that separates indoor and outdoor scenarios, and discuss various promising technologies for 5G wireless communication systems, such as massive MIMO, energy-efficient communications, cognitive radio networks, and visible light communications. Future challenges facing these potential technologies are also discussed.

Introduction

The innovative and effective use of information and communication technologies (ICT) is becoming increasingly important to improve the economy of the world [1]. Wireless communication networks are perhaps the most critical element in the global ICT strategy, underpinning many other industries. It is one of the fastest growing and most dynamic sectors in the world. The European Mobile Observatory (EMO) reported that the mobile communication sector had total revenue of €174 billion in 2010, thereby bypassing the aerospace and pharmaceutical sectors [2]. The development of wireless technologies has greatly improved people's ability to communicate and live in both business operations and social functions.

The phenomenal success of wireless mobile communications is mirrored by a rapid pace of technology innovation. From the second generation (2G) mobile communication system debuted in 1991 to the 3G system first launched in 2001, the wireless mobile network has transformed from a pure telephony system to a network that can transport rich multimedia contents. The 4G wireless systems were designed to fulfill the requirements of International Mobile Telecommunications-Advanced (IMT-A) using IP for all services [3]. In 4G systems, an advanced radio interface is used with orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output (MIMO), and link adaptation technologies. 4G wireless networks can support data rates of up to 1 Gb/s for low mobility, such as nomadic/local wireless access, and up to 100 Mb/s for high mobility, such as mobile access. Long-Term Evolution (LTE) and its extension, LTE-Advanced systems, as practical 4G systems, have recently been deployed or soon will be deployed around the globe.

However, there is still a dramatic increase in the number of users who subscribe to mobile broadband systems every year. More and more

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people crave faster Internet access on the move, trendier mobiles, and, in general, instant communication with others or access to information. More powerful smartphones and laptops are becoming more popular nowadays, demanding advanced multimedia capabilities. This has resulted in an explosion of wireless mobile devices and services. The EMO pointed out that there has been a 92 percent growth in mobile broadband per year since 2006 [2]. It has been predicted by the Wireless World Research Forum (WWRF) that 7 trillion wireless devices will serve 7 billion people by 2017; that is, the number of network-connected wireless devices will reach 1000 times the world's population [4]. As more and more devices go wireless, many research challenges need to be addressed.

One of the most crucial challenges is the physical scarcity of radio frequency (RF) spectra allocated for cellular communications. Cellular frequencies use ultra-high-frequency bands for cellular phones, normally ranging from several hundred megahertz to several gigahertz. These frequency spectra have been used heavily, making it difficult for operators to acquire more. Another challenge is that the deployment of advanced wireless technologies comes at the cost of high energy consumption. The increase of energy consumption in wireless communication systems causes an increase of CO_2 emission indirectly, which currently is considered as a major threat for the environment. Moreover, it has been reported by cellular operators that the energy consumption of base stations (BSs) contributes to over 70 percent of their electricity bill [5]. In fact, energy-efficient communication was not one of the initial requirements in 4G wireless systems, but it came up as an issue at a later stage. Other challenges are, for example, average spectral efficiency, high data rate and high mobility, seamless coverage, diverse quality of service (QoS) requirements, and fragmented user experience (incompatibility of different wireless devices/interfaces and heterogeneous networks), to mention only a few.

All the above issues are putting more pressure on cellular service providers, who are facing continuously increasing demand for higher data rates, larger network capacity, higher spectral efficiency, higher energy efficiency, and higher mobility required by new wireless applications. On the other hand, 4G networks have just about reached the theoretical limit on the data rate with current technologies and therefore are not sufficient to accommodate the above challenges. In this sense, we need groundbreaking wireless technologies to solve the above problems caused by trillions of wireless devices, and researchers have already started to investigate beyond 4G (B4G) or 5G wireless techniques. The project UK-China Science Bridges: (B)4G Wireless Mobile Communications (http://www.ukchinab4g. ac.uk/) is perhaps one of the first projects in the world to start B4G research, where some potential B4G technologies were identified. Europe and China have also initiated some 5G projects, such as METIS 2020 (https://www.metis2020. com/) supported by EU and National 863 Key Project in 5G supported by the Ministry of Science and Technology (MOST) in China. Nokia Siemens Networks described how the underlying radio access technologies can be developed further to support up to 1000 times higher traffic volumes compared to 2010 travel levels over the next 10 years [6]. Samsung demonstrated a wireless system using millimeter (mm) wave technologies with data rates faster than 1 Gb/s over 2 km [7].

What will the 5G network, which is expected to be standardized around 2020, look like? It is now too early to define this with any certainty. However, it is widely agreed that compared to the 4G network, the 5G network should achieve 1000 times the system capacity, 10 times the spectral efficiency, energy efficiency and data rate (i.e., peak data rate of 10 Gb/s for low mobility and peak data rate of 1 Gb/s for high mobility), and 25 times the average cell throughput. The aim is to connect the entire world, and achieve seamless and ubiquitous communications between anybody (people to people), anything (people to machine, machine to machine), wherever they are (anywhere), whenever they need (anytime), by whatever electronic devices/services/networks they wish (anyhow). This means that 5G networks should be able to support communications for some special scenarios not supported by 4G networks (e.g., for high-speed train users). High-speed trains can easily reach 350 up to 500 km/h, while 4G networks can only support communication scenarios up to 250 km/h. In this article, we propose a potential 5G cellular architecture and discuss some promising technologies that can be deployed to deliver the 5G requirements.

The remainder of this article is organized as follows. We propose a potential 5G cellular architecture. We describe some promising key technologies that can be adopted in the 5G system. Future challenges are highlighted. Finally, conclusions are drawn.

A Potential 5G Wireless Cellular Architecture

To address the above challenges and meet the 5G system requirements, we need a dramatic change in the design of cellular architecture. We know that wireless users stay indoors for about 80 percent of time, while only stay ourdoors about 20 percent of the time [8]. The current conventional cellular architecture normally uses an outdoor BS in the middle of a cell communicating with mobile users, no matter whether they stay indoors or outdoors. For indoor users communicating with the outdoor BS, the signals have to go through building walls, and this causes very high penetration loss, which significantly damages the data rate, spectral efficiency, and energy efficiency of wireless transmissions.

One of the key ideas of designing the 5G cellular architecture is to separate outdoor and indoor scenarios so that penetration loss through building walls can somehow be avoided. This will be assisted by distributed antenna system (DAS) and massive MIMO technology [9], where geographically distributed antenna arrays with tens or hundreds of antenna elements are deployed. While most current MIMO systems utilize two to four antennas, the goal of massive MIMO sys-

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The 5G cellular architecture should also be a heterogeneous one, with macrocells, microcells, small cells, and relays. To accommodate high-mobility users such as users in vehicles and high-speed trains, we have proposed the mobile femtocell concept, which combines the concepts of mobile relay and femtocell.

tems is to exploit the potentially large capacity gains that would arise in larger arrays of antennas. Outdoor BSs will be equipped with large antenna arrays with some antenna elements (also large antenna arrays) distributed around the cell and connected to the BS via optical fibers, benefiting from both DAS and massive MIMO technologies. Outdoor mobile users are normally equipped with limited numbers of antenna elements, but they can collaborate with each other to form a virtual large antenna array, which together with BS antenna arrays will construct virtual massive MIMO links. Large antenna arrays will also be installed outside of every building to communicate with outdoor BSs or distributed antenna elements of BSs, possibly with line of sight (LoS) components. Large antenna arrays have cables connected to the wireless access points inside the building communicating with indoor users. This will certainly increase the infrastructure cost in the short term while significantly improving the cell average throughput, spectral efficiency, energy efficiency, and data rate of the cellular system in the long run.

Using such a cellular architecture, as indoor users only need to communicate with indoor wireless access points (not outdoor BSs) with large antenna arrays installed outside buildings, many technologies can be utilized that are suitable for short-range communications with high data rates. Some examples include WiFi, femtocell, ultra wideband (UWB), mm-wave communications (3–300 GHz) [7], and visible light communications (VLC) (400–490 THz) [10]. It is worth mentioning that mm-wave and VLC technologies use higher frequencies not traditionally used for cellular communications. These high-frequency waves do not penetrate solid materials very well and can readily be absorbed or scattered by gases, rain, and foliage. Therefore, it is hard to use these waves for outdoor and long distance applications. However, with large bandwidths available, mm-wave and VLC technologies can greatly increase the transmission data rate for indoor scenarios. To solve the spectrum scarcity problem, besides finding new spectrum not traditionally used for wireless services (e.g., mm-wave communications and VLC), we can also try to improve the spectrum utilization of existing radio spectra, for example, via cognitive radio (CR) networks [11].

The 5G cellular architecture should also be a heterogeneous one, with macrocells, microcells, small cells, and relays. To accommodate high-mobility users such as users in vehicles and high-speed trains, we have proposed the mobile femtocell (MFemtocell) concept [12], which combines the concepts of mobile relay and femtocell. MFemtocells are located inside vehicles to communicate with users within the vehicle, while large antenna arrays are located outside the vehicle to communicate with outdoor BSs. An MFemtocell and its associated users are all viewed as a single unit to the BS. From the user point of view, an MFemtocell is seen as a regular BS. This is very similar to the above idea of separating indoor (inside the vehicle) and outdoor scenarios. It has been shown in [12] that users using MFemtocells can enjoy high-data-rate services with reduced signaling overhead. The above proposed 5G heterogeneous cellular architecture is illustrated in Fig. 1.

Promising Key 5G Wireless Technologies

In this section, based on the above proposed heterogeneous cellular architecture, we discuss some promising key wireless technologies that can enable 5G wireless networks to fulfill performance requirements. The purpose of developing these technologies is to enable a dramatic capacity increase in the 5G network with efficient utilization of all possible resources. Based on the well-known Shannon theory, the total system capacity C_{sum} can be approximately expressed by

$$C_{\text{sum}} \approx \sum_{\text{HetNets}} \sum_{\text{Channels}} B_i \log_2\left(1+\frac{P_i}{N_p}\right) \qquad (1)$$

where B_i is the bandwidth of the ith channel, P_i is the signal power of the ith channel, and N_p denotes the noise power. From Eq. 1, it is clear that the total system capacity C_{sum} is equivalent to the sum capacity of all subchannels and heterogeneous networks. To increase C_{sum}, we can increase the network coverage (via heterogeneous networks with macrocells, microcells, small cells, relays, MFemtocell [12], etc.), number of subchannels (via massive MIMO [9], spatial modulation [SM] [13], cooperative MIMO, DAS, interference management, etc.), bandwidth (via CR networks [11], mm-wave communications, VLC [10], multi-standard systems, etc.), and power (energy-efficient or green communications). In the following, we focus on some of the key technologies.

Massive MIMO

MIMO systems consist of multiple antennas at both the transmitter and receiver. By adding multiple antennas, a greater degree of freedom (in addition to time and frequency dimensions) in wireless channels can be offered to accommodate more information data. Hence, a significant performance improvement can be obtained in terms of reliability, spectral efficiency, and energy efficiency. In massive MIMO systems, the transmitter and/or receiver are equipped with a large number of antenna elements (typically tens or even hundreds). Note that the transmit antennas can be co-located or distributed (i.e., a DAS system) in different applications. Also, the enormous number of receive antennas can be possessed by one device or distributed to many devices. Besides inheriting the benefits of conventional MIMO systems, a massive MIMO system can also significantly enhance both spectral efficiency and energy efficiency [9]. Furthermore, in massive MIMO systems, the effects of noise and fast fading vanish, and intracell interference can be mitigated using simple linear precoding and detection methods. By properly using multi-user MIMO (MU-MIMO) in massive MIMO systems, the medium access control (MAC) layer design can be simplified by avoiding com-

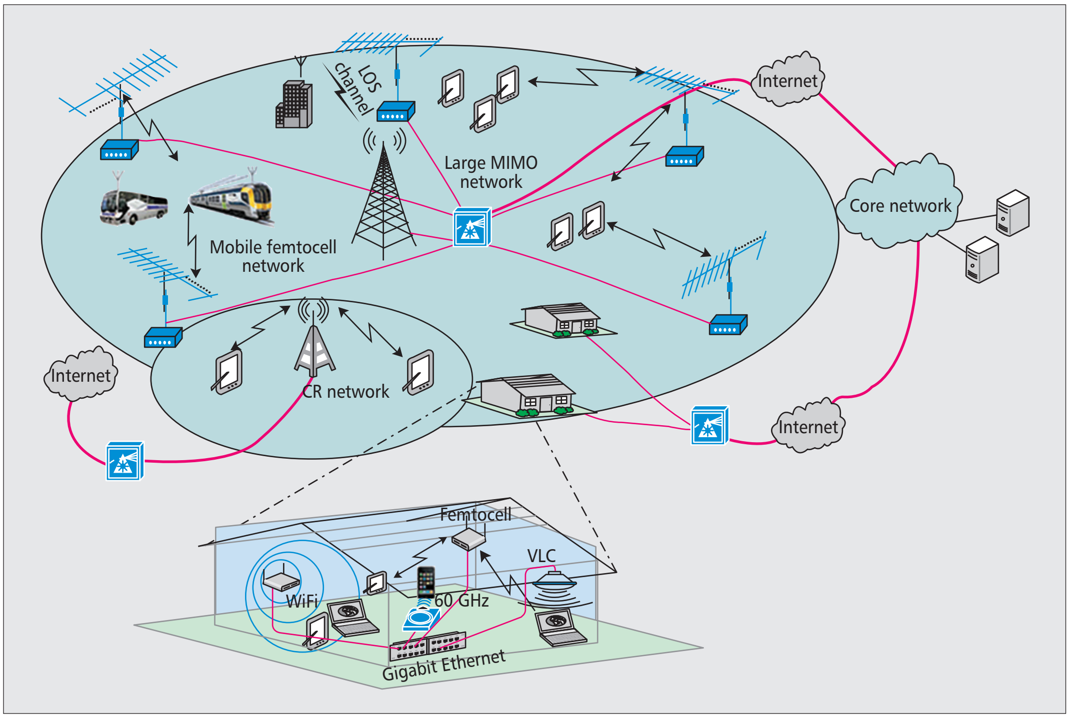

Figure 1. *A proposed 5G heterogeneous wireless cellular architecture.*

The 5G CR network is an innovative software defined radio technique which has been considered as one of the promising technologies to improve the utilization of the congested RF spectrum. Adopting CR is motivated by the fact that a large portion of the radio spectrum is underutilized most of the time.

plicated scheduling algorithms [14]. With MU-MIMO, the BS can send separate signals to individual users using the same time-frequency resource, as first pro. Consequently, these main advantages enable the massive MIMO system to be a promising candidate for 5G wireless communication networks.

Spatial Modulation

Spatial modulation, as first proposed by Haas *et al.*, is a novel MIMO technique that has been proposed for low-complexity implementation of MIMO systems without degrading system performance [13]. Instead of simultaneously transmitting multiple data streams from the available antennas, SM encodes part of the data to be transmitted onto the spatial position of each transmit antenna in the antenna array. Thus, the antenna array plays the role of a second (in addition to the usual signal constellation diagram) constellation diagram (the so-called spatial constellation diagram), which can be used to increase the data rate (spatial multiplexing) with respect to single-antenna wireless systems. Only one transmit antenna is active at any time, while other antennas are idle. A block of information bits is split into two sub-blocks of $\log_2(N_B)$ and $\log_2(M)$ bits, where N_B and M are the number of transmit antennas and the size of the complex signal constellation diagram, respectively. The first sub-block identifies the active antenna from a set of transmit antennas, while the second sub-block selects the symbol from the signal constellation diagram that will be sent from that active antenna. Therefore, SM is a combination of space shift keying (SSK) and amplitude/phase modulation. Figure 2 shows the SM constellation diagram with 4 transmit antennas ($N_B = 4$) and quadrature phase shift keying (QPSK) modulation ($M = 4$) as an example. The receiver can then employ optimal maximum likelihood (ML) detection to decode the received signal.

Spatial modulation can mitigate three major problems in conventional MIMO systems: inter-channel interference, inter-antenna synchronization, and multiple RF chains [13]. Moreover, low-complexity receivers in SM systems can be designed and configured for any number of transmit and receive antennas, even for unbalanced MIMO systems. We have to point out that the multiplexing gain in SM increases logarithmically with the increase in the number of transmit antennas, while it increases linearly in conventional MIMO systems. Therefore, the low implementation complexity comes at the expense of sacrificing some degrees of freedom. Most research on SM focuses on the case of a single receiver (i.e., single-user SM). Multi-user SM can be considered as a new research direction to be considered in 5G wireless communication systems.

Cognitive Radio Networks

The CR network is an innovative software defined radio technique considered to be one of the promising technologies to improve the utilization of the congested RF spectrum [9]. Adopting CR is motivated by the fact that a large portion of the radio spectrum is underutilized most of the time. In CR networks, a secondary system can share spectrum bands with the licensed primary system, either on an interference-free basis or on an interference-tolerant basis [9]. The CR network should be aware of the surrounding radio environment and regulate its transmission accordingly. In interference-free CR networks, CR users are allowed to borrow spectrum resources only when licensed users do not use them. A key to enabling interference-

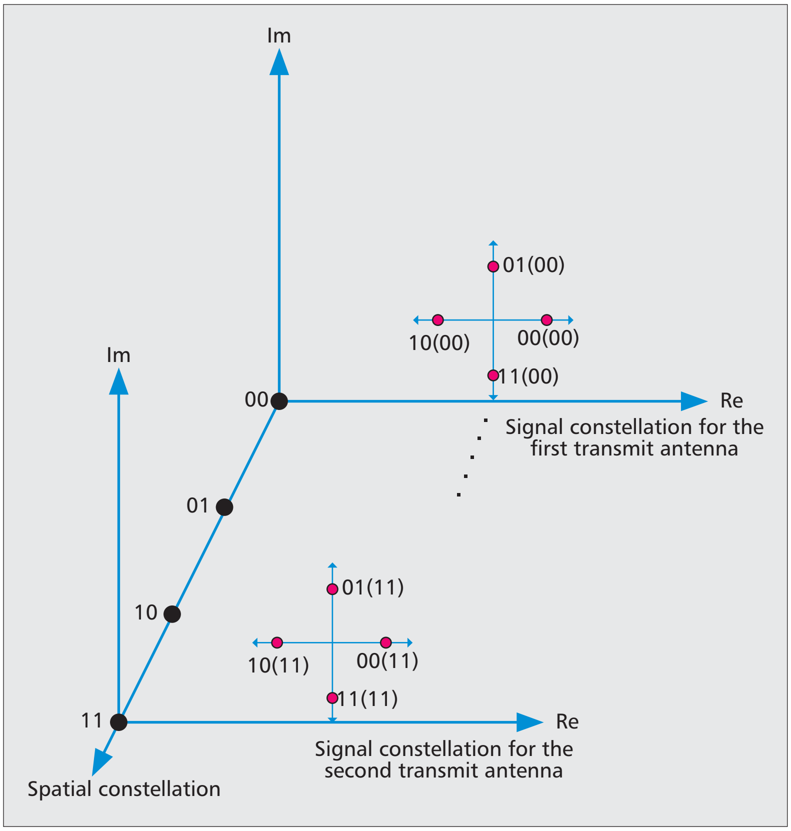

Figure 2. *SM constellation diagram using four transmit antennas ($N_B = 4$) and QPSK modulation.*

free CR networks is figuring out how to detect the spectrum holes (white space) that spread out in wideband frequency spectrums. CR receivers should first monitor and allocate the unused spectrums via spectrum sensing (or combining with geolocation databases) and feed this information back to the CR transmitter. A coordinating mechanism is required in multiple CR networks that try to access the same spectrum to prevent users colliding when accessing the matching spectrum holes. In interference-tolerant CR networks, CR users can share the spectrum resource with a licensed system while keeping the interference below a threshold. In comparison with interference-free CR networks, interference-tolerant CR networks can achieve enhanced spectrum utilization by opportunistically sharing the radio spectrum resources with licensed users, as well as better spectral and energy efficiency. However, it has been shown that the performance of CR systems can be very sensitive to any slight change in user densities, interference threshold, and transmission behaviors of the licensed system. This fact is illustrated in Fig. 3, where we notice that the spectral efficiency decreases quickly with the increase in the number of primary receivers. However, the spectral efficiency can be improved by either relaxing the interference threshold of the primary system or considering only the CR users who have short distances to the secondary BS. In [15], hybrid CR networks have been proposed for adoption in cellular networks to explore additional bands and expand the capacity.

Mobile Femtocell

The MFemtocell is a new concept that has been proposed recently to be a potential candidate technology in next generation intelligent transportation systems [12]. It combines the mobile relay concept (moving network) with femtocell technology. An MFemtocell is a small cell that can move around and dynamically change its connection to an operator's core network. It can be deployed on public transport buses, trains, and even private cars to enhance service quality to users within vehicles. Deployment of MFemtocells can potentially benefit cellular networks. First, MFemtocells can improve the spectral efficiency of the entire network. To demonstrate this fact, Fig. 4 compares the average spectral efficiency of the direct transmission scheme and an MFemtocell-enhanced scheme with two resource partitioning schemes (i.e., orthogonal and non-orthogonal resource partitioning schemes) as a function of the percentage of users associated with MFemtocells. Also, the comparison is done between maximum signal-to-noise ratio (MAX-SNR) and proportional fairness (PF) scheduling algorithms. We can see that increasing the percentage of users that communicate with the BS through MFemtocells leads to an increase in spectral efficiency, which is much better compared to the case where users communicate directly with the BS (i.e., the direct transmission scheme). Second, MFemtocells can contribute to signaling overhead reduction of the network. For instance, an MFemtocell can perform a handover on behalf of all its associated users, which can reduce the handover activities for users within the MFemtocell. This makes the deployment of MFemtocells suitable for high-mobility environments. In addition, the energy consumption of users inside an MFemtocell can be reduced due to relatively shorter communication range and low signaling overhead.

Visible Light Communication

Visible light communication uses off-the-shelf white light emitting diodes (LEDs) used for solid-state lighting (SSL) as signal transmitters and off-the-shelf p-intrinsic-n (PIN) photodiodes (PDs) or avalanche photo-diodes (APDs) as signal receivers [10]. This means that VLC enables systems that illuminate and at the same time provide broadband wireless data connectivity. If illumination is not desired in the uplink, infrared (IR) LEDs or indeed RF would be viable solutions. In VLC, the information is carried by the intensity (power) of the light. As a result, the information-carrying signal has to be real valued and strictly positive. Traditional digital modulation schemes for RF communication use complex valued and bipolar signals. Modifications are therefore necessary, and there is a rich body of knowledge on modified multi-carrier modulation techniques such as OFDM for intensity modulation (IM) and direct detection (DD). Data rates of 3.5 Gb/s have been reported from a single LED. It has to be noted that VLC is not subject to fast fading effects as the wavelength is significantly smaller than the detector area. While the link-level demonstrations are important steps to prove that VLC is a viable technique to help mitigate spectrum bottlenecks in RF communications, it is essential to show that full-fledged optical wireless networks can be developed by using existing lighting infrastructures. This includes MU access techniques, interference coordination, and others. To this end, let us assume multiple light fixtures in a room. Each of these light fixtures is envisaged to function as a very small optical BS resulting in a network of very small cells called *optical attocells*. This is in analogy to femtocells in RF communications and in recognition of the fact that a single room can be served by many of these very small cells. An optical attocell covers an area of 1–10 m^2 and distances of about 3 m. It is well known in cellular RF communications that small cells have significantly contributed to recent improvements in network spectral efficiency. However, the main limiting factor is interference. Optical attocells are less subject to interference since lightwaves do not propagate through walls. The ratio of the area spectral efficiency (ASE) in bits per second per Hertz per square meter attained for the attocell network and the ASE for the femtocell network is illustrated in Fig. 5 against a varying number of femtocells per floor. The number of optical access points per room varies from one to four. The gains diminish as the number of femtocells per floor is increased as expected, but the gain is still above 100 for 20 femtocells per floor and 4 optical attocells per room. The maximum gain in ASE is close to 1000. As an example, let us assume a typical ASE of 1.2 b/s/Hz/m^2 for the optical attocell network and a bandwidth of 10 MHz for LED and RF. This would mean that users can on average share a total of 300 Mb/s in a 5 m × 5 m × 3 m room in the case of the optical attocell network. In the case of the RF femtocell network and the best case of 20 femtocells per floor, the attainable capacity for the same room is only about 3 Mb/s.

Green Communications

The design of 5G wireless systems should take into account minimizing the energy consumption in order to achieve greener wireless communication systems [5]. Wireless system operators around the world should aim to achieve such energy consumption reductions, which consequently contribute to the reduction of CO_2 emissions. The indoor communication technologies are promising deployment strategies to get better energy efficiency. This is because of the favorable channel conditions they can offer between the transmitters and receivers. Moreover, by separating indoor traffic from outdoor traffic, the marcocell BS will have less pressure in allocating radio resources and can transmit with low power, resulting in a significant reduction in energy consumption. VLC and mm-wave technologies can also be considered as energy efficient wireless communication solutions to be deployed in 5G wireless systems. For example, in VLC systems the consumed energy in one bulb is much less than that in its RF-based equivalents for transmitting the same high-density data.

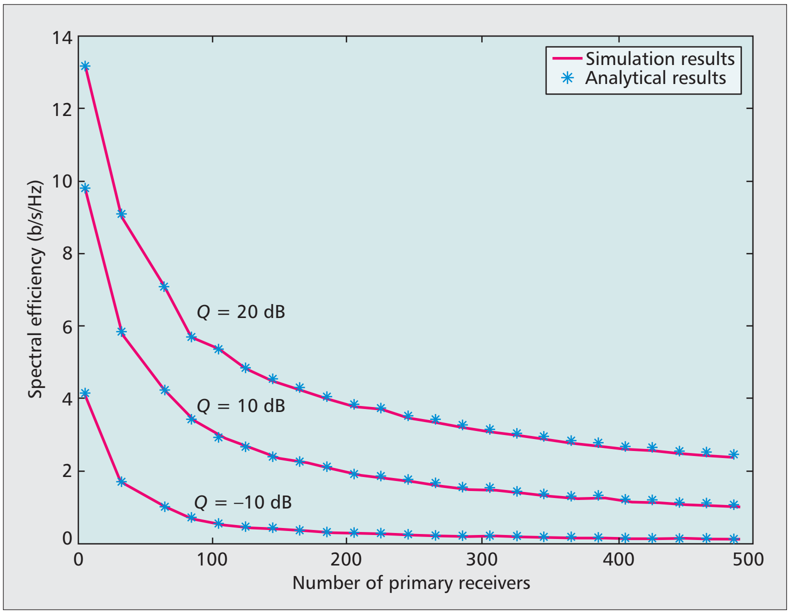

Figure 3. *The average system spectral efficiency of a CR network as a function of the number of primary receivers with different values of interference thresholds Q (number of secondary receivers = 20).*

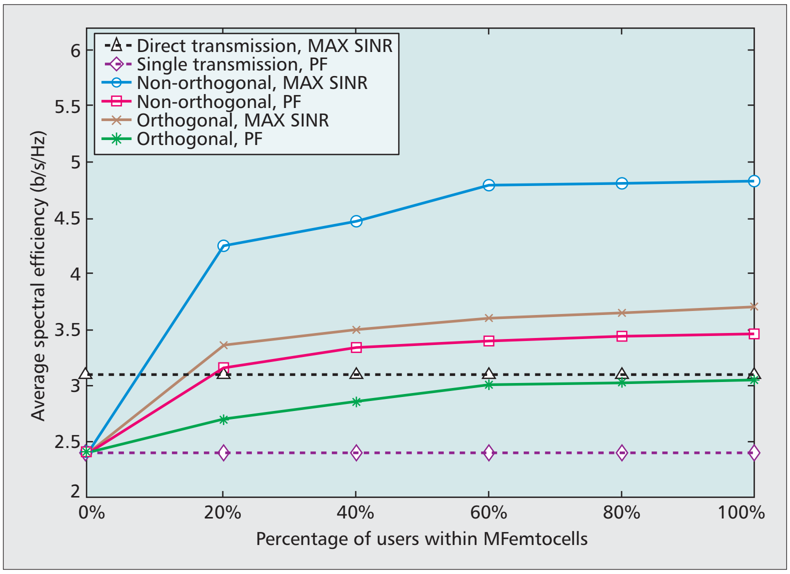

Figure 4. *Average spectral efficiency of system-level MFemtocells with multi-user scheduling and resource partitioning schemes.*

Future Challenges in 5G Wireless Communication Networks

Although there have been some developments in the above potential key 5G wireless technologies, there are still many challenges ahead. Due to the limited space, in this section we only discuss some of these challenges.

Optimizing Performance Metrics

The evaluation of wireless communication networks has been commonly characterized by considering only one or two performance metrics while neglecting other metrics due to high com-

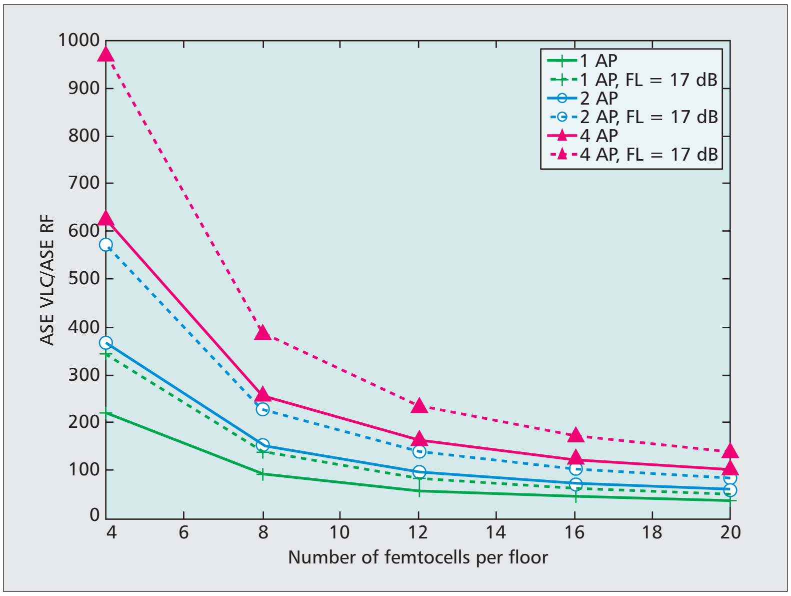

Figure 5. *The ratio of ASE attained for the optical attocell network to ASE for the femtocell network against varying numbers of femtocells per floor.*

plexity. For a complete and fair assessment of 5G wireless systems, more performance metrics should be considered. These include spectral efficiency, energy efficiency, delay, reliability, fairness of users, QoS, implementation complexity, and so on. Thus, a general framework should be developed to evaluate the performance of 5G wireless systems, taking into account as many performance metrics as possible from different perspectives. There should be a trade-off among all performance metrics. This requires high-complexity joint optimization algorithms and long simulation times.

Realistic Channel Models for 5G Wireless Systems

Realistic channel models with proper accuracy-complexity trade-off are indispensable for some typical 5G scenarios, such as massive MIMO channels and high-mobility channels (e.g., high-speed train channels and vehicle-to-vehicle channels). Conventional MIMO channel models cannot be directly applied to massive MIMO channels in which different antennas may observe different sets of clusters. Massive MIMO channel models should take into account specific characteristics that make them different from those in conventional MIMO channels, such as the spherical wavefront assumption and non-stationary properties. Also, 3D massive MIMO models, which jointly consider azimuth and elevation angles, are more practical but more complicated. Some existing massive MIMO channel models are briefly summarized and classified in Table 1 [14].

Compared to conventional low-mobility wireless channels, high-mobility channels have greater dynamics and possibly more severe fading, and are essentially non-stationary. How to characterize non-stationary high-mobility channels is also very challenging.

Reducing Signal Processing Complexity for Massive MIMO

One technical challenge in developing massive MIMO systems is the signal processing complexity. As transmit and receive signals are quite lengthy, the search algorithms must be performed over many possible permutations of symbols. In the current literature, massive MIMO research is often treated as a detection problem based on a search motivated by the well-known ML criterion. The existing detection algorithms assume that the channel has been perfectly estimated, which appears to be an unreasonable assumption given the size of the channel matrix and thus amount of channels to be tracked. A possible solution to this problem is to apply the SM concept to massive MIMO systems. In this case, the spatial signature of each antenna needs to be different from the point of view of the receiver because data is encoded into the choice of transmit antenna active in the transmit array. It is therefore possible that channel estimation does not need to be exact but rather be merely sufficient to distinguish each transmit antenna. This may be a reasonable prospect, especially if the receive array is large, in which case each transmit antenna would have a quite detailed and thus distinct spatial signature.

Interference Management for CR Networks

A major issue in interference-tolerant CR networks in 5G is how to reliably and practically manage the mutual interference of CR and primary systems. Regulating the transmit power is essential for the CR system to coexist with other licensed systems. An interference temperature model is introduced for this purpose to characterize the interference from the CR to the licensed networks. Interference cancellation techniques should also be applied to mitigate the interference at CR receivers. Another issue in interference-tolerant CR networks is that a feedback mechanism is important to periodically inform the CR network about the current interference status at the licensed system. A practical solution is that the interference state information can be sent from licensed systems and collected by a central unit (or a third party system). Any CR network should first register to the central unit in order to be updated regarding the allowed spectrum and interference. Alternatively, the CR transmitters can listen to beacon signals transmitted from the primary receivers and rely on the channel reciprocity to estimate the channel coefficient. In this case, the CR transmitters can cooperate among themselves to regulate the transmit power and prevent the interference at the primary receivers being above the threshold.

Conclusions

In this article, the performance requirements of 5G wireless communication systems have been defined in terms of capacity, spectral efficiency, energy efficiency, data rate, and cell average throughput. A new heterogeneous 5G cellular architecture has been proposed with separated indoor and outdoor applications using DAS and massive MIMO technology. Some short-range communication technologies, such as WiFi, femtocell, VLC, and mm-wave communication technologies, can be seen as promising candidates to provide high-quality and high-data-rate services to indoor users while at the same time reducing the pressure on outdoor BSs. We have also discussed some potential key technologies that can be deployed in 5G wireless systems to satisfy the expected performance requirements, such as CR networks, SM, MFemtocells, VLC, and green communications, along with some technical challenges.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of this work from SNCS Research Center, the University of Tabuk, the Ministry of Higher Education in Saudi Arabia, the Opening Project of the Key Laboratory of Cognitive Radio and Information Processing (Guilin University of Electronic Technology), Ministry of Education (No. 2013KF01), Hutchison 3G UK, Natural Science Foundation of China (No. 61231009), the STCSM (No. 11JC1412300), the International Science & Technology Cooperation Program.

Channel model	Complexity	Description	Ready for massive MIMO?
Narrowband i.i.d. Rayleigh	Low	Uncorrelated model	No
Narrowband CBSM (Weichselberger)	Medium	Jointly correlated model	No
Narrowband CBSM (Kronecker)	Medium	Classic correlated model	No
Wideband elliptical GBSM [14]	High	Massive MIMO properties considered	Yes

Table 1. *Recent advances in massive MIMO channel models.*

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