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Key techniques for 5G wireless communications: network architecture, physical layer, and MAC layer perspectives

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Abstract The fourth generation (4G) mobile communication systems are offering service worldwide steadily. Although 4G systems could be loaded with much more services and data than previous systems, there is still a dramatic gap between the people's practical requirements and what can be offered by the 4G technologies. Consequently, the research and development for the fifth generation (5G) systems have already been started. This article presents an overview of potential network architecture and highlights several promising techniques which could be employed in the future 5G systems. These techniques include non-orthogonal multiple access (NOMA), massive multiple input and multiple output (MIMO), cooperative communications and network coding, full duplex (FD), device-to-device (D2D) communications, millimeter wave communications, automated network organization, cognitive radio (CR), and green communications. The state-of-art and implementation issue of these techniques are also addressed.

Keywords 5G, software defined network, non-orthogonal multiple access, massive MIMO, full duplex, device-to-device communications, millimeter wave communications, cognitive radio

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1 Introduction

It seems that the huge demand for wireless data transmission is never satisfied. After more than 30 years' rapid development, mobile communication systems have stepped over the 3G and are embracing the 4G era. Although the data transmission rate increases 1000 times than the first generation of cellular mobile communication systems, the explosion of data transmission and service demands still face big challenges. While IMT-Advanced and beyond are on their ways [1], the IMT-2020 which is dedicated to 5G has been kicked off in 2013. It is difficult to say what are the specific features of 5G. However, relative to today's mobile communication systems, it is estimated that 5G should have 1000 times higher mobile data volume per area [2], 10 to 100 times higher typical user data rate and number of connected devices, and 10 times longer battery life for low power devices and reduced end-to-end (E2E) latency. Many countries

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have spent tremendous efforts and resource on promoting the research of 5G, such as: the Ministry of Science and Technology (MOST) in China set up National 863 Key Project in 5G; European Union (EU) set up project METIS 2020 (https://www.metis2020.com/); United Kingdom and China sponsored international cooperation project UK-China Science Bridges: (B)4G Wireless Mobile Communications (http://www.ukchinab4g.ac.uk/) [3]; and Japan launched the “2020 and Beyond Ad Hoc” for 5G. In addition to these official efforts, the industries have also paid great enthusiasm to 5G. Huawei has invested R&D for 5G since 2009 and focused on three objectives: (1) Capability for massive capacity delivery and massive connectivity; (2) Support a variety of users/services/application with extremely polarized requirements; (3) Use highly distributed spectrum efficiently for different scenarios. ZTE was devoted to massive multiple input and multiple output (MIMO), cloud radio and software defined air interface (SDA), etc. Ericsson put emphasis on ultra high data volume and rate, ultra-reliable communication, abundant low power machine-type communication (MTC) devices and more than 10GHz spectrum usage. Nokia proposed that the highlight of 5G should be intensive network. All these attempts have one goal: to put 5G into the commercial service by 2020.

In addition to technical revolution, 5G is also expected to offer the revolution of wireless communication styles. From 1G to 4G, the cellular mobile communication systems were designed to meet human being’s demands, which is essential to a human-centralized communication system. However, it is desired to consider the thing-centralized communication in 5G as well, which means device-to-device (D2D) [4] or machine-to-machine (M2M) communications [5] will be taken into serious consideration. This would cause overwhelming challenges for the 5G, because it may face difficulties to support very dynamic applications. For example, data transmission may vary from 10 kbps to 10 Gbps; desired delay may vary from 1 ms to a few seconds; the number of online access may vary from several hundreds to several million; signalling ratio may vary from less than 1% to 100%; the duty ratio may vary from 0 to several days.

However, all the promising imaginations of future 5G should be realized by techniques. Thus, what techniques is it that the 5G should use? The answer to this question is not certain yet. There must be a set of revolutionary techniques to meet the 5G requirements. In this paper, we will give an overview of some competitive techniques.

2 Network architecture

Cellular-based network architecture design, from traditional circuit switch (CS) + packet switch (PS) 2G to all-IP flat 4G, enables mobile communications to achieve unprecedented success. Today, the cellular networks have evolved into a huge multi-radio access technology (multi-RAT) and multi-layer heterogeneous network. However, in face of emerging mobile internet applications and digital floods, this architecture becomes more and more incompetent. And traditional single-RAT base station deployment becomes an unbearable cost, operating and maintenance burden to operators. Therefore, some state-of-art techniques, such as cloud and software defined network (SDN) [6], are gradually introduced to cellular networks. Network architecture based on cloud RAN (C-RAN) [7–10] and SDN [11–15] attracts both academic and industrial great attention. According to the above researches, a novel network architecture is presented in Figure 1. The architecture consists of application cloud, SDN controller cloud, SDN-based C-RAN, SDN-based transport network, and SDN-based core network [12,15]. Application cloud provides various services, such as network management and performance monitor etc. SDN controller cloud transforms policies from application cloud and provides centralized control services for objective network elements by these policies, such as C-RAN, transport network, and core netwrok. The SDN-based C-RAN consists of large-scale baseband unit (BBU) pools, radio-over-fiber (RoF) systems [8], and distributed radio access points (RAPs) and light RAPs (LRAPs). The BBU pools provide centralized baseband signal processing far beyond single base station. RAPs achieve signalling coverage like macro cell, while LRAPs achieve data transmission like small cell [11,13]. The RAPs and LRAPs connect BBU via the RoF system. The RoF system achieves intelligent connections between RAPs/LRAPs and BBU. The SDN controller provides dynamical bandwidth adjustment of each RAP/LRAP to BBU connection and BBU pools management including network RAT and version. The SDN-based transport

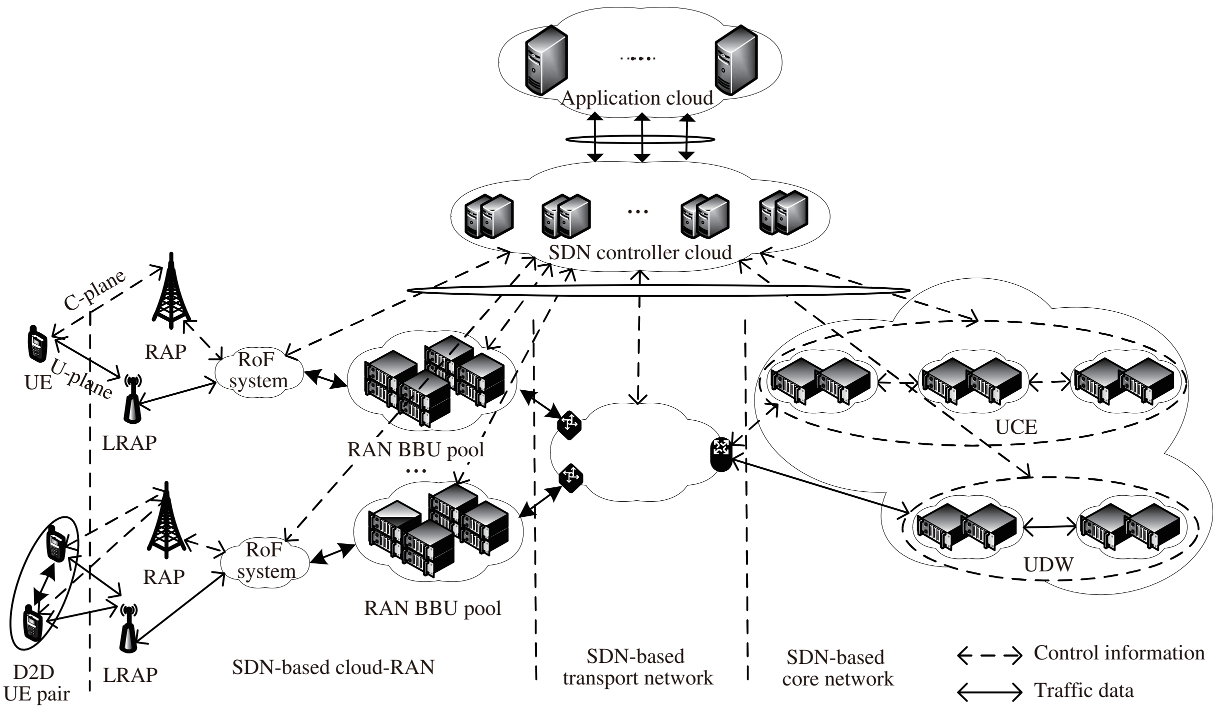

Figure 1 Network architecture.

network achieves flexible backhaul networks management and selection, dynamical transport bandwidth adjustment of each RAN to core network connection, and route selection. The SDN-based core network consists of unified control entity (UCE) and unified data gateway (UDW). UCE achieves unified control function, which integrates mobility management entity (MME), service gateway control plane (SGW-C), and packet data network gateway control plane (PGW-C). UCE together with SDN controller manages general packet radio service (GPRS) tunnelling protocol for user plane (GTP-U) tunnels. UDW achieves data forwarding function, which integrates service gateway data plane (SGW-D) and packet data network gateway data plane (PGW-D).

The cloud technique has several benefits as follows: (1) The large-scalely centralized deployment provides processing capacity far beyond single deployment; (2) Virtualization enables the logical separation of software and hardware, which reduces complexity of processing and expands capacity of hardware; (3) New service solutions to dense network deployment, such as radio access network as a service (RANaaS) [9]. In the architecture, application server, SDN controller, RAN and core network adopt the cloud deployment. The SDN decouples network control from individual network devices and migrates it into accessible computing devices, which enables the underlying infrastructure to be abstracted for applications and network services, i.e., the network is treated as a logical or virtual entity [6]. Therefore, the SDN can quickly respond to changing network devices, business needs or user demands etc. The SDN architecture consists of application layer, control layer, and infrastructure layer. The interface between application layer and control layer is open application programming interfaces (APIs), while it is control/data plane interface between control layer and infrastructure layer. In the architecture, the control and data plane of RAN and core network are separated. For RAN, RAPs achieve signalling coverage to maintain user connection like macro cell, while LRAPs achieve data transmission like small cell. RAPs equiped massive MIMO can also provide data transmission. Because LRAPs are closer to users, it improves channel condition to achieve better performance. For core network, GTP-U tunnel management function is decoupled from SGW and PGW. However, due to special characteristics of cellular networks, some technical problems encountered in applying cloud and SDN techniques still need to be further studied. C-RAN requires huge fronthaul networks deployment between RAP/LRAPs and BBU pools. The capacity of fronthaul networks needs to be further enhanced to satisfy the requirements of C-RAN deployment. In addition, it still needs to be considered that RAPs provide data transmission and LRAPs achieve signalling coverage for specific scenarios, such as indoor etc. Because it is difficult to ensure that users are in the coverage of RAP and LRAP in such scenarios. The radio protocol architecture needs to be as flexible as possible to support control/data plane separation and combination. Moreover, the interface between SDN controller layer and infrastructure layer, such as UDW, still needs to be further standardized.

3 Key enabling techniques

3.1 Non- and quasi-orthogonal multiple access

The quest to improve the spectral efficiency has been regarded as the most important but yet challenging task in the design of future wireless communication systems, due to the fact that the rapid growth of multimedia services, such as interactive game and television applications, cannot be coped with the scarce radio frequency (RF) spectrum resources. Non-orthogonal multiple access (NOMA) [16] and sparse code multiple access (SCMA) [17] are the latest two members of the wireless multiple access technique family to meet future demand for mobile broadband spectrum. NOMA multiplexes multiple users in the power-domain, while SCMA exploits sparse codes to achieve that purpose.

3.1.1 *NOMA*

The key feature of NOMA is that multiple users will be allocated at different power levels, depending on their channel conditions, where it is worth pointing out that the communication with these users is happening at the same time, code and frequency channels. For example, consider a cellular scenario with two users in one cell, where User 1 is close to the BS of the cell and User 2 is close to the boundary of the cell, i.e., $|h_1|^2 > |h_2|^2$, where the channels from the BS to the two users are denoted by h_1 and h_2, respectively. The key idea of NOMA is to ask the BS to deliver two messages to the users simultaneously, but with different transmission power. In particular, User 2 will be served with more transmission power since its channel condition to the BS is poor, i.e., $P_1 < P_2$, where P_i denotes the transmission power allocated to the ith user. On the user side, User 1 observes the superposition of two messages which are for two users individually. Therefore, the signal model at User 1 can be viewed as a special case of multiple access channels (MAC), to which the successive detection strategy, i.e., detecting User 2's message first and then removing it from the mixture, is optimal in terms of achieving the MAC capacity [18]. User 2 simply treats User 1's message as noise and detects its own message directly.

Initial studies about NOMA in terms of analytical and system-level evaluation have been carried out in [16,19], which demonstrate that NOMA can achieve better spectral efficiency compared to other orthogonal multiple access techniques, such as time division multiple access (TDMA), orthogonal frequency division multiplexing (OFDM) and code division multiple access (CDMA). The main reason for such a performance gain is that NOMA has utilized the conditions of wireless channels opportunistically, whereas existing orthogonal multiple access techniques do not take channel conditions into consideration. Taking the two-user scenario described above as an example, the achievable rate for User 1, the user with better channel conditions, is $\log(1+\frac{P_1|h_1|^2}{P_N})$, and the achievable rate for User 2, the user with poorer channel conditions, is $\log(1+\frac{P_2|h_2|^2}{P_1|h_2|^2+P_N})$, where P_N denotes the noise power and User 1's rate is conditioned on that it can detect User 2's rate successfully. Considering a conventional TDMA scheme which serves User 2 solely, it yields a rate of $\log(1+\frac{(P_1+P_2)|h_2|^2}{P_N})$. For an extreme case that $|h_2|^2 \to 0$, i.e., User 2 is very far from the BS, the TDMA scheme has a rate close to zero, but NOMA can still offer a significantly large rate of $\log(1+\frac{P_1|h_1|^2}{P_N})$. A more rigorous way to evaluate the performance of NOMA is to consider that not only the small scale fading gains are randomly distributed, but also the distances from the users to the BS are also random. Stochastic geometry is an ideal mathematical tool to capture the random location of the mobile users, and has been applied to NOMA in [19], which demonstrates that even if mobile users are randomly deployed, NOMA can still achieve better performance than conventional orthogonal multiple access techniques.

3.1.2 *SCMA*

SCMA is a multi-dimensional codebook-based non-orthogonal multiple access technique. The key component is SCMA encoder which joins modulation and spreading. It maps user's data bits to a K-dimensional complex sparse codeword selected from the given codebook, where K is the length of an SCMA codeword. In other words, user's data bits are spread on K resources after SCMA encoder. An SCMA encoder contains J separate layers, where $J = \binom{K}{N}$ and N is the non-zero dimensions of the sparse codeword. J layers are multiplexed over K resources, which generates overloading with factor J/K. A user can be assigned one or more different codewords. Thus, SCMA has several advantages as follows: (1) Overloading increases overall throughput and connectivity; (2) Sparsity helps to reduce the complexity of detection; (3) Multi-dimensional codewords bring shaping gain and better spectral efficiency; (4) Spreading with factor K helps to achieve robust link adaptation.

3.2 Massive MIMO

Traditional MIMO has been studied extensively in 3G and 4G systems. It is congenital to believe that the capacity would increase linearly with the scale of antennas array. However, due to the complexity and antennas size issues, the practical number of antennas is no more than 8 even in latest LTE-A standard. It seems a dead end to increase the capacity via increasing the number of antennas. But from the conclusions of [20], if the number of antennas increases largely, i.e., orders of magnitude higher than current configuration, even the simple zero-forcing (ZF) detector would work well, which leads to the so-called massive MIMO.

Next generation mobile communication systems would benefit from massive MIMO as follows:

- Capacity: Let n_t and n_r be the number of transmitting antennas and receiving antennas, and γ be the signal-to-noise ratio. The capacity of MIMO can be bounded by

$$\log_2(1+\gamma n_r) \leqslant C \leqslant \min(n_t, n_r) \cdot \log_2\left(1 + \frac{\gamma \max(n_t, n_r)}{n_t}\right). \tag{1}$$

In a cellular system, it is likely that the base stations are equipped with massive MIMO antennas while the user equipments (UEs) only have a limited number of antennas, e.g. less than 8. From (1), the capacity would increase dramatically in both uplink (UL) and downlink (DL) transmission.

- Latency: The latency of wireless data transmission is deeply affected by fading, because the retransmission or low rate error control coding would be adopted to resist fading. By employing massive MIMO, the receiving signal would benefit from a large number of space diversity and MIMO signal processing, such as beamforming and precoding, which could compensate the fading.

- Cost and power: Although the number of antennas of massive MIMO is up to the hundreds, the radiated energy efficiency is improved by the hundreds as well [20]. By sharping the signal in a very small region, massive MIMO can obtain a higher gain with a much lower emitting power per antenna. Actually, the total power of massive MIMO is even much less than traditional MIMO, which means that the low-cost and low-power amplifiers with milli-Watt emitted power would replace the traditional much more expensive ultra-linear amplifiers with tens of Watt power.

Although the massive MIMO has lots of features which would meet the requirements of next generation mobile communication systems, there will be still a long way to go before it is used. Some unsolvable problems and future directions include:

- Advanced signal processing algorithm: Coordinating the hundreds antennas to form the beamforming signal is not an easy task. On the other hand, although the emitted power level is lowered by massive MIMO, the power consumption of baseband signal process is increased for more complex process. It is required that signal process algorithms should be simple and effective. Some linear and nearly linear algorithms which could be processed in real time have been proposed [21]. And the tradeoff between complexity and performance should be optimized.

- Channel estimation: The channel estimation could be accomplished by each UE's pilots in uplink. However, the estimation for the downlink is much more sophisticated. It is required that the downlink has to have the same number of orthogonal pilots according to the number of hundreds antennas, which would cause the so-called pilots contamination. The possible ways to work this out are optimization of pilots allocation [22], powerful or blind channel estimation algorithms [23,24] and contamination precoding [25], etc.

- Hardware implementations: Although each single antenna unit is simplified and low-cost, its capability to resist phase noise and I/Q imbalance should not be reduced. Especially in high-order modulation, phase noise caused by non-linearity of amplifier will dominate the impairments instead of additive white gaussian noise (AWGN). It is necessary to design sophisticated phase noise compensation algorithms.
- Deployment Scenarios: 5G must face many new deployment scenarios, such as density deployment, D2D communications, relaying coordinated multi-point (CoMP) transmission and reception [26,27], etc. How to employ massive MIMO technique in these scenarios effectively still needs further research.

3.3 Relaying and network coding

3.3.1 *Relaying*

In LTE-Advanced (LTE-A) Release 10, the relaying has been first specified and named Relay Node (RN) [28]. A RN can be a simple repeater or a fully functional entity, depending on the deploying scenarios.

The use of relaying also enables the wireless communication to work in a cooperative way. In cooperative relaying wireless communication systems, the message sent to intended destinations is transmitted through various routes which may consist of one or more hops via RNs and be combined at the destinations [29]. In 5G systems, it is estimated that the cooperative relaying would be deployed large-scaled to improve the coverage and throughput. Cooperative relaying communication can benefit from cooperative diversity, distributed space time coding and network coding. The key techniques related are:

- Relay selection: When multiple relays are deployed in one eNB cell, the transmission should choose the best RN to cooperate opportunistically. This is similar to the antenna selection in multiple antennas systems, but in a manner of slow basis and consisting of the distance and large-scale fading gain [30].
- Relay combining: When receivers have full knowledge of channel state information, relays combining offers the better performance [31]. To do this, a distributed beamforming coefficient is multiplied at each relay, respectively. The perfect channel aware techniques are crucial to this coherent combining.
- Distributed space-time coding: Distributed Space Time Block Coding (D-STBC) can obtain the spatial diversity as in MIMO systems. Relaying Alamouti STBC scheme is the one of such practical schemes. The achievable diversity gain depends on particular type of STBC codes [32]. However, imperfect synchronization would invalidate the diversity gain. Some works are proposed to perform distributed space-time coding in an asynchronous manner [33].
- Network coding: Due to its butterfly transition among the multiple-hop network, network coding linked relaying system naturally. Cooperative network coded communication systems would be overviewed in details in Subsection 3.3.2.

3.3.2 *Network coding*

The most suitable network coding form for wireless communications is physical layer network coding. The collision of signals in air can be viewed as the process of network coding instead of interference. And this could save up to 50% transmission resource and increase the throughput greatly [34]. There are some proposals for network coding usage in IMT-Advanced, for example, network coded relaying for multicast transmission, UL unicast transmission and DL unicast transmission [35], etc. The employment of network coding for 5G is not a simple change at a specified layer, but involves the cross-layer design [36]. Since D2D communications are most likely to be a key feature of 5G cellular networks, there is a large space for network coding relaying applications [37]. The key techniques which can support network coding relaying in 5G include:

- Signal level coding: Most of literatures have assumed the network coding is performed at bit-level, for which the simple XOR operation is good enough. This could limit the modulation types to a bipolar form. But for future 5G, the high-order modulation would be used extensively. Therefore, the symbol-level or even the signal-level network coding is necessary [38,39]. Nested lattice codes seems to be a promising solution [34]. Nested lattice coding can be looked on as a generalization of physical layer network coding. It can work on any basis of Galois Field or even continuous signal space by modulo operation. In AWGN channel it can achieve the capacity of $\frac{1}{2}\log(1+\gamma)$ [40]. When combined with relaying, a compute-and-forward strategy is employed and can be applied in various wireless communication scenarios [41], such as two-way relaying [42] and multiple access channel [43], etc.

- UEs grouping: When the number of active UEs is large in the network, it is obliged to group UEs to perform network coding. Such a scenario is common when D2D communications are enabled [37]. It is essentially an optimization problem, which depends on what performance measures are adopted. The common optimization objective functions could be the measure of sum rates, outage or bit error rate (BER)/frame error rate (FER) [44].
- Relay selection: Like non-network-coded cooperative relaying communication systems, the selection of relays is critical to the performance. An inappropriate use of relays would not only bring no coding gain, but also distort the whole network behavior. Relay selection for network coding is also an optimization problem of solving a certain cost function in terms of the sum-capacity [45] or some other system performance measurements.
- Network coded cooperative channel coding: Using network coding alone does not help reliability transmission, and it may even decrease the BER/FER performance due to error propagation. A powerful channel coding is necessary to work with network coding jointly to guarantee performance. Christoph Hausl constructed network coded Turbo codes by combining convolutional codes and network coding and showed the performance gain [46]. They also applied this idea to low density parity check codes (LDPCs) [47]. To obtain the soft values, a scheme of generating log likelihood ratio (LLR) values directly was studied in [48]. A joint coding which consists of network coding and repeat accumulation codes has been proposed in [49]. These joint network coding and channel coding schemes can be the candidates for the future 5G systems.

3.4 Full duplex

In 4G systems, both frequency division duplex (FDD) and time division duplex (TDD) require two separate channels to realize orthogonal transmission and reception, which wastes half of radio resources. Full-duplex can double spectrum efficiency by simultaneous transmission and reception on the same frequency and time resource. In addition, full-duplex also helps to reduce E2E packet delay and improve network efficiency in contention networks by mitigating the hidden terminal problem. Due to double spectrum efficiency, full-duplex is widely considered as one of the promising techniques in 5G systems. To promote full-duplex research and application, EU FP7 launched DUPLO project. However, there are still some technical obstacles to be overcome before full-duplex is really put into practice.

- Self-interference cancellation and suppression: As radio signals quickly attenuate over the distance, signals from local transmitting antennas may be hundreds or thousands of times stronger than those from other BSs. It is the power difference between transmit and receive antennas that generates very strong self-interference. Hence, it has been generally believed that full-duplex transceivers are unfeasible for a long period in the past. Antenna cancellation [50] uses two transmit antennas and one receive antenna with proper distance to overcome self-interference. Combining RF with digital interference cancellation, antenna cancellation allows full duplex operation. There are several self-interference cancellation and suppression techniques [50–68], which are summarized in Table 1. Current studies mainly adopt two methods: passive suppression and active cancellation, and concentrate on four stages: antenna stage, RF stage, analog stage, and digital stage. The gains of self-interference processing are mainly obtained from antenna and RF stages. Real-time online automated tuning is a challenge for signal processing in self-interference cancellation. Performance of self-interference suppression and cancellation of wideband signals with high transmit power is still undesirable. High performance digital cancellation solutions still need further investigation.

- Performance analysis and verification: Rate gain region [69,70] and design trade-off [69] for single antenna, achievable rates under limited dynamic range [71] and fast fading channels with imperfect

Table 1 Summary of self-interference cancellation and suppression techniques

Solution	Technical features	Main evaluation	Shortages
Antenna cancellation	Two Tx and one Rx antenna with proper distance between antennas [50]	About 30 dB	Two Tx + one Rx; bandwidth constraint; manually tuning the phase and amplitude of the #2 Tx
RF suppression	Directional isolation and cross-polarization antenna [51]	Over 48 dB	Specific antenna design and distant antenna placement
	Antenna selection, beam selection, null-space projection, MMSE filtering [52]	About 40 dB	Depends highly on the rank of the loop channel
	Time-domain transmit beamforming (TDTB) [53]	About 50 dB	Extra specific the number of auxiliary generators; high insertion power loss
	Balanced feed network on single antenna [54]	About 40–45 dB	Expensive (two circulators + two quadrature hybrids); specific antenna design (two feeds on single antenna)
RF cancellation	Recreate the RF SI signal by Tx digital baseband signal [55]	Over 30 dB	Extra components to recreate RF SI signal
	Using a circulator, a variable attenuator and phase shifter with a general antenna [56]	About 75 dB	Gains vary over bandwidth; high power-handling capability
	Convex reformulation for tuning attenuation and phase shift parameters of multiple-tag analog SI canceller [57]	About 40–65 dB	Exact delay, attenuation and phase shift estimation
	Balanced/unbalanced (Balun) transformer [58]	At least 45 dB	One Tx + one Rx with distant antenna placement; expensive programmable analog attenuator and delay lines; frequency retuning; high insertion loss
Analog cancellation	Recreate self-interference analog signal by transmit analog signal [59]	About 10 dB	Exact SI channel gain estimation and strict analog signal alignment
Digital cancellation	2-stage iterative echo canceller [60]	Overall channel capacity increased by a factor between 1.4 and 1.8	Wider dynamic range analog-to-digital converters (ADCs); an extra ADC
	Adaptive filter LMS based [61]	About 20 dB	Fair stabilization; fixed step
	Joint LS estimation based common phase error (CPE) cancellation and MMSE based intercarrier interference cancellation [62]	Up to 9 dB more cancellation gain than only CPE cancellation	Perfect self-interference and signal-of-interest signal channels at the receiver
	Estimate PA nonlinear SI channel [63]	Up to 10 dB higher transmit power	Exact SI channel parameters estimation
	Joint iterative channel and successive nonlinearity coefficients estimation [64]	Higher cancellable self-interference power	Orthogonal training sequence; iteration brings more complexity
	Wide-linear least-squares parameter estimation [65]	About 15 dB with transmit power below 15 dBm	Sharply decline after median-high transmit power

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continued

Solution	Technical features	Main evaluation	Shortages
	Joint augmented cancellation of nonlinear distortion and conjugate self-interference [66]	About 15 dB with transmit power below 15 dBm	Slowly decline after median-high transmit power
Antenna separation + antenna suppression	Directional separation, RF absorptive shielding and cross-polarization antenna [67]	Over 70 dB	Specific antenna design; not effective in reflection path; frequency selectivity
Antenna suppression + RF suppression	Dual-polarized dual-feed antenna and electrical balance duplexer [68]	Both over 50 dB, size of duplexer and antenna is small	High Tx insertion loss (3.4 dB) and cascaded Rx noise figure (7 dB); only supports up to 0 dBm Tx signals

channel estimation [72], precoding [73], and degrees of freedom [74] for multi-antenna, precoding [73] and transmission strategies [75] for multi-user, and average rate gain under multi-cell scenarios [76] have been investigated. However, current studies mostly focus on theoretical analysis and experiments based on very simple models. The analyses for complex scenarios, such as massive MIMO and large scale multi-cell multi-user field verification, are still lack. Meanwhile, as FD is more suitable for short range communication, research on small cell scenarios with multiple users may attract more attention in the future.

3.5 Device-to-device communications

Proximity-based D2D communications underlaying cellular networks are a highly efficient way to enhance system capacity and improve spectrum efficiency because it can directly communicates with each other by sharing network frequency resources. Besides, D2D UEs (DUEs) can act as transmission relays for each other to set up multi-hop communication links. Therefore, it also helps to improve and extend network coverage by DUE relaying. The gain of D2D communications depends on the number of available DUE pairs in various application scenarios. The standardization of this technique is on-going in 3GPP and will be available in Release 12 [77,78]. In 5G era, with the wide use of various smart terminal devices, the communication range between users will be shortened, and the interaction frequency between users will increase dramatically. D2D communications will play a more important role. To apply this new technique to 5G systems, the following issues need to be addressed at least:

- Direct discovery: Devices must know their neighbors before directly communicating with each other. Thus, proximity-based device discovering and services discovering are two of the major issues in D2D communications. Direct discovery includes two models: model A (“I'm here”) and model B (“Who is here”/“are you here”) [77]. In model A, discoveree UE announces its existence with certain information about itself; discoverer UE will read and process the information only if it is interested. In model B, discoverer UE transmits a request with certain information about what it is interested to discover; discoveree UE will respond if it meets such a request. The 4G systems adopt the evolved packet core (EPC)-level ProSe discovery solution [77], which relies on the location services (LCS). The solution includes five stages: DUE registration, proximity request, location reporting, proximity alert and direct discovery. As the solution requires terminal devices to report location information before executing discovering, it increases complexity and delay. Moreover, the accuracy of LCS also influences the performance of discovering.

- Interference management: As D2D communications share resource in cellular networks, it inevitably generates interference among UEs [79]. Various interference scenarios in full-duplex D2D communications are summarized in Figure 2. It seems that D2D pairs should keep a certain distance away from BS and primary cellular UEs (CUEs) to avoid acting as aggressors and victims. As D2D communications introduce many new interference scenarios, interference management is critical. Current research topics of interference management include mode selection, resource allocation and power control. Several modes including reuse mode, dedicated mode and cellular mode [80] are applicable for D2D communications. In

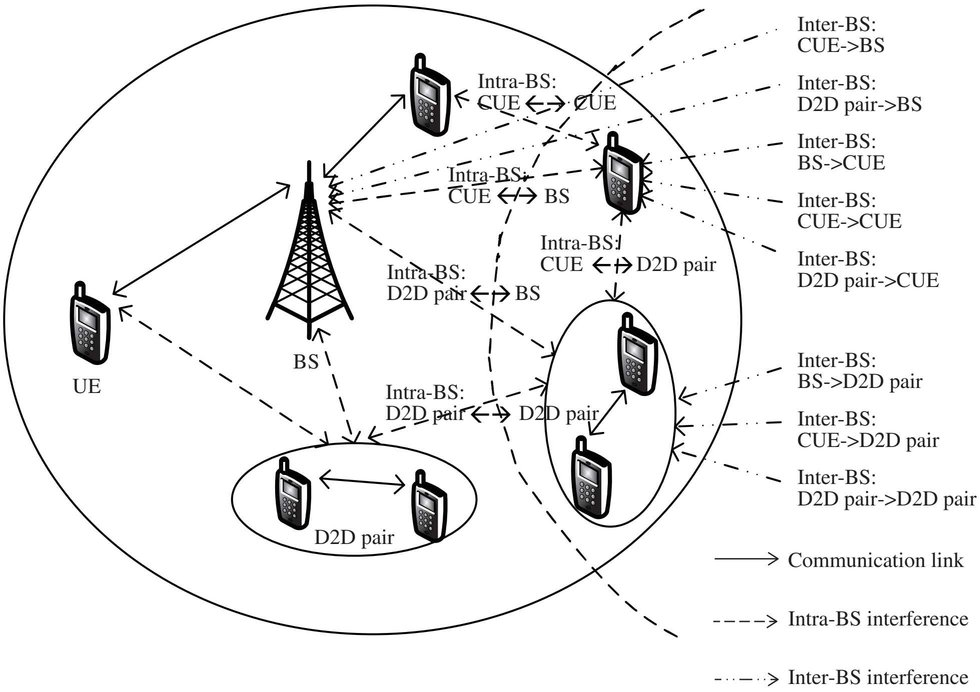

Figure 2 Interference in full-duplex D2D communications.

reuse mode, DUEs share the total network frequency resource, which improves spectrum efficiency but causes severe interference. In dedicated mode, DUEs take a certain portion of available resource from the CUEs, which avoids interference between DUEs and CUEs but increase the probability of interference among DUEs. In cellular mode, two DUEs communicate with each other through a BS, that is, DUEs act as traditional CUEs. Centralized and distributed resource allocations are available to D2D communications. In centralized resource allocation, BSs are in charge of controlling and allocating resource of DUEs. Although centralized resource allocation improves resource efficiency and the performance, it is unbeneficial for D2D deployment under such scenarios as out of network coverage. In distributed resource allocation, DUEs sense the network environment and select D2D resource from the resource pool by itself, which improves the flexibility of D2D deployment, but reduce resource efficiency and the performance of interference management. In D2D communications, CUEs communication has higher priority. Power control is used to control the transmit power of DUEs so as to keep the interference from DUEs to CUEs below a certain level.

- Direct communication: In 4G systems, physical channels of direct communication link reuse physical uplink shared channel (PUSCH) structures [78]. As single carrier frequency division multiple access (SC-FDMA) has low peak-to-average power ratio (PAPR), it reduces the dynamic range requirements of power amplifier (PA) and improves power efficiency. While in 5G systems, the available frequency resources may disperse in several frequency bands. To flexibly utilize these dispersed frequency resources, new multi-carrier technologies like filter bank multi-carrier (FBMC) are considered. How to design D2D direct communication link is still a hot topic.

3.6 Millimeter wave communications

One of the efficient ways to satisfy rapid increase of data rates, especially those up to tens of Gbps in 5G systems, is bandwidth expansion. Most of the cellular networks work below 3 GHz which has been fully occupied already. Bandwidth shortage has motivated the exploration of the rich millimeter wave (mmWave) frequency spectrum which ranges from 3 to 300 GHz. There are potential dozens of GHz available frequency resources at 28, 38, 45, and 60 GHz. It is expected that the gains of network capacity up to 10 times can be obtained from mmWave frequency spectrum [2], which is quite attractive

Table 2 Atmospheric attenuation windows

Frequency (GHz)	3	23	31	60	78	119	127	183	214	325	341
Atmospheric attenuation (dB/km)	0.0075106	0.19488	0.10003	15.17285	0.35743	2.04379	0.86255	28.36202	2.72848	38.59649	9.87251

for 5G systems. There are already on-going academic and industrial efforts to study the feasibility of mmWave communications. EU FP7 launched the MiwaveS project, facing beyond 2020 heterogeneous wireless networks with mmWave small cell access and backhauling. Samsung has demonstrated over 1 Gbps download rate at 28 GHz frequency band. Although some progress in mmWave communications has been made, there is still a long way before realizing practical 5G mmWave communications. The main technical obstacles include the following aspects:

- Propagation characteristics and measurements: Since the radio waves of different frequency bands have different propagation characteristics, the channel models of traditional cellular wireless communication cannot be directly applied to mmWave communications. The first task of mmWave communications is to understand the propagation characteristics. Several measurements campaigns have been conducted [81–87]. As is shown in the Figure 5 in [81], the atmospheric attenuation is 0.01–40 dB/km at mmWave frequency, which is much higher than 0.001–40 dB/km of frequency bands used by traditional cellular networks. Moreover, there are five atmospheric attenuation windows, which is shown in Table 2. The rain attenuation up to 0.001–40 dB/km varies with frequency and rain rate at mmWave frequency, which is much higher than 0–0.001 dB/km level of traditional used frequency bands; the reflection coefficients are up to 0.896 outdoor and 0.74 indoor separately, which are still higher than traditional used frequency bands, which is shown in Table 3. The path loss exponent is slightly higher than 2 for line-of-sight (LOS) channels and 4 for nonlinear-of-sight (NLOS), which is shown in Table 4, but in some specific environments, such as in vehicles, the path loss exponent can be up to 7. The root mean square (RMS) delay spread of LOS has little change and the RMS delay spread of NLOS decreases with frequency, which is shown in Table 5; besides, the RMS delay spread of NLOS also decreases with distance. Table 6 shows that mmWave communications suffer from severe outage when distance is beyond 200 m. From the above discussion, mmWave communications suffer from severe path loss for NLOS, rapid channel fluctuations and intermittent connectivity, and is extremely sensitive to shadowing. Thus, it seems that the effective communication distance of mmWave signals is within 200 m [85].
- Antenna arrays: Because of the unfavorable mmWave propagation characteristics, it can be used for short range communication in 5G systems if steerable directional antennas are employed. Antenna arrays are considered as a key technique to achieve mmWave communications. Large antenna arrays with beamforming [88–90] can provide sufficient gains to overcome the severe propagation loss. However, the narrow beams increase sensitivity to movement caused by pole sway and other environmental concerns. Besides, it also needs to adapt promptly when beams are blocked, which increases the processing complexity. Hence, high efficiency low complexity adaptive antenna array processing algorithms need to be further studied.
- Hardware implementation: Another challenge is the hardware constraints for wideband mmWave communication systems. One of the major challenges comes from the high power consumption of mixed signal components, such as the analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). The wideband mmWave signals up to 1 GHz are far more than bandwidth of current ADCs/DACs. Besides, increasing transmit power requires highly linear and efficient PAs. It also requires more stages to achieve up/down conversion between baseband signals and mmWave RF signals. Large array antennas also need innovative hardware architecture of transceiver.

3.7 Automated network organization

It is expensive for operating expenditure (OPEX) of manual involvement in network deployment, operation and maintenance in traditional cellular networks. Self-organized network (SON) with self-configuration, self-optimization, and self-healing attracts great attention after being proposed. SON

Table 3 Reflection coefficients at 28 GHz [86]

Environment	Location	Material	Angle (°)	Reflection coefficient
Outdoor	ORH	Tinted Glass	10	0.896
		Concrete	10	0.815
			45	0.623
Indoor	MTC	Clear Glass	10	0.740
		Drywall	10	0.704
			45	0.628

Table 4 Path loss exponents

Frequency (GHz)	28 [87]	38 [83]	40	60 [83]	72
Path loss exponents (LOS)	2.55	2.0	—	2.23	—
Path loss exponents (NLOS)	5.76	4.57	—	4.19	—

Table 5 RMS delay spreads

Frequency (GHz)	28 [84]	38 [83]	40	60 [83]	72
RMS delay spread (LOS) (μs)	0.878	1.2	—	0.8	—
RMS delay spread (NLOS) (μs)	47.2	23.6	—	7.4	—

Table 6 Outage statistic at 38 GHz [85]

Tx location	Height (m)	Outage (%) for 160 dB PL sensitivity	Outage (%) for 150 dB PL sensitivity
TX1 ENS	36	18.9% within 400 m, 0% within 200 m	52.8% within 400 m, 27.3% within 200 m
TX2 WRW	18	39.6% within 400 m, 0% within 200 m	52.8% within 400 m, 10% within 200 m

has been widely deployed in 4G network, especially self-optimization functions including auto neighbor relation (ANR), mobility robust optimization (MRO), coverage and capacity optimization (CCO), RACH optimization (RO), mobility load balancing (MLB) [91] and energy saving (ES). Operating results indicate that it can greatly reduce manual involvement in network. Current research trends towards 5G systems mainly concentrate on continued evolution of existing functions and heterogeneous networks and development of new techniques, which means that it will be a super multi-RAT/multi-layer heterogeneous network in 5G era. It seems that automation is the only sensible approach to cost-efficiently manage future operationally complex 5G network. It requires highly intelligent and unified self-management capacities far beyond current SON features. To achieve unified self-management of 5G systems, several technical problems need to be solved:

- Unified self-management architecture: In 4G systems, four architectures including network manager (NM)-centralized SON, element manager (EM)-centralized SON, distributed SON and hybrid SON [92] are available to different SON use cases. The SON functions for different SON tasks are designed as single-RAT stand-alone feature to facilitate the flexible deployment. However, this single-RAT stand-alone feature also brings some drawbacks. It cannot guarantee operating efficiency for several SON functions parallel execution and increasingly complex heterogeneous networks. Above all, the architecture of the self-management systems needs innovation to improve operating efficiency for 5G systems. The SEMAFOUR unified self-management system [93] was proposed. The system consists of an integrated SON management system, multi-RAT/multi-layer SON functions and decision support system (DSS), which achieves coordinated and focused operation of SON. The core part of SEMAFOUR system is the integrated SON management system consisting of policy transformation and supervision, operational SON coordination and monitoring functionalities. The integrated SON management system transforms the network-oriented objectives into dedicated execution policies and rules for individual closed-loop SON functions. The SEMAFOUR unified self-management system will be one of the strong competitors for future SON evolution. In the future, we need to consider SDN concept while designing the unified self-management system.

- SON coordination: To overcome the drawbacks of single-RAT stand-alone SON functions deployment, SON coordination is introduced as an important feature. It plays the role in supervising the functioning of the multitude of SON functions, in detecting and resolving conflicts, system instability and undesired behavior occurring due to the independent operation of individual SON functions. 3GPP SA5 working group, SOCRATES project, UniverSelf project, and SEMAFOUR project have made many efforts in function definition and architecture design. Several conflict resolutions were proposed [94–97]. However, there is still a gap to achieve optimum conflict resolution. As the game-based method can achieve the optimum, more attention should be paid to the application of game theory for solving SON conflict resolution in the future. Besides, conflict detection also needs to be further investigated.
- New SON functions: In 5G systems, many novel techniques will be introduced to meet the requirements, which generates new SON cases. Resource management which supports dual connectivity, dynamic spectrum allocation and interference management, automatic traffic steering and active/reconfigurable antenna systems (AAS) has been considered. More attention should be paid to the intelligent management of front-hual link in C-RAN and multi-layer transport networks.

3.8 Cognitive radio

Frequency spectrum is always scarce for wireless communications. However, the fact is that frequency spectrum is always underutilized by conventional spectrum management approaches. As the cognitive radio (CR) enables secondary users (SUs) to use licensed frequency bands of primary users (PUs) without causing harmful interference, it is widely considered as one of the promising solutions to improve spectrum utilization. CR consists of four major functionalities: spectrum sensing, spectrum management, spectrum sharing and spectrum mobility [98]. In 5G systems, the bandwidth requirement up to 1 GHz will aggravate the "spectrum crisis". Meanwhile, multi-RAT multi-layer heterogeneous network deployment will also affect spectrum utilization. By means of CR, 5G BSs can dynamically utilize the frequency bands of 2G/3G/4G networks; small cells can utilize the frequency bands of macro cells; D2D communications can utilize network frequency resources. To promote practical application of CR, more researches should be aimed at the following aspects:

- Spectrum sensing: The spectrum sensing plays an important role in obtaining awareness of the radio environments and detecting unused licensed frequency bands of PUs. Several spectrum detection methods have been studied [99–102], which are shown and categorized in Figure 3. Cooperative detection methods can obtain better performance than non-cooperative detection methods at the cost of processing complexity. In 5G systems, the wideband signal up to 1 GHz will be a challenge for the conventional detection methods. Cooperative detection, especially cooperative multi-band detection [103] will play an important role. However, few researches discuss the detailed implementation of the cooperative detection. It is still a problem to design cooperative frameworks, choose cooperative SUs and transmit cooperative information.
- Spectrum mobility: As the available licensed frequency bands are time-variant with the movement of PUs, SUs need to dynamically adjust frequency resources. When available frequency bands of PUs are detected, SUs can access licensed frequency bands to gain better quality of service (QoS). When licensed PUs are activated, SUs have to evacuate the channel to guarantee PUs' QoS. This means that the SUs communication would suffer interruption frequently. Spectrum mobility is a key feature to enable continuous SUs data transmission. In 5G systems, it requires higher spectrum handoff success rate and lower handoff delay. Non-handoff, pure reactive handoff, pure proactive handoff and hybrid handoff strategies [104] have been considered. Furthermore, the concept of CR will be extended to new scenarios, such as dynamic spectrum access between inter-RATs or multi-layers. It is no longer a simple point-to-point (P2P) direct communication between two SUs. Thus, this generates a new problem of group handoff of SUs. The framework and algorithms for group handoff of SUs need to be further developed.

- Security: CR is vulnerable to attacks due to frequency sharing. Various attacks and security threats have been discussed in [105]. The behavior of the attackers can be classified into the intentional and

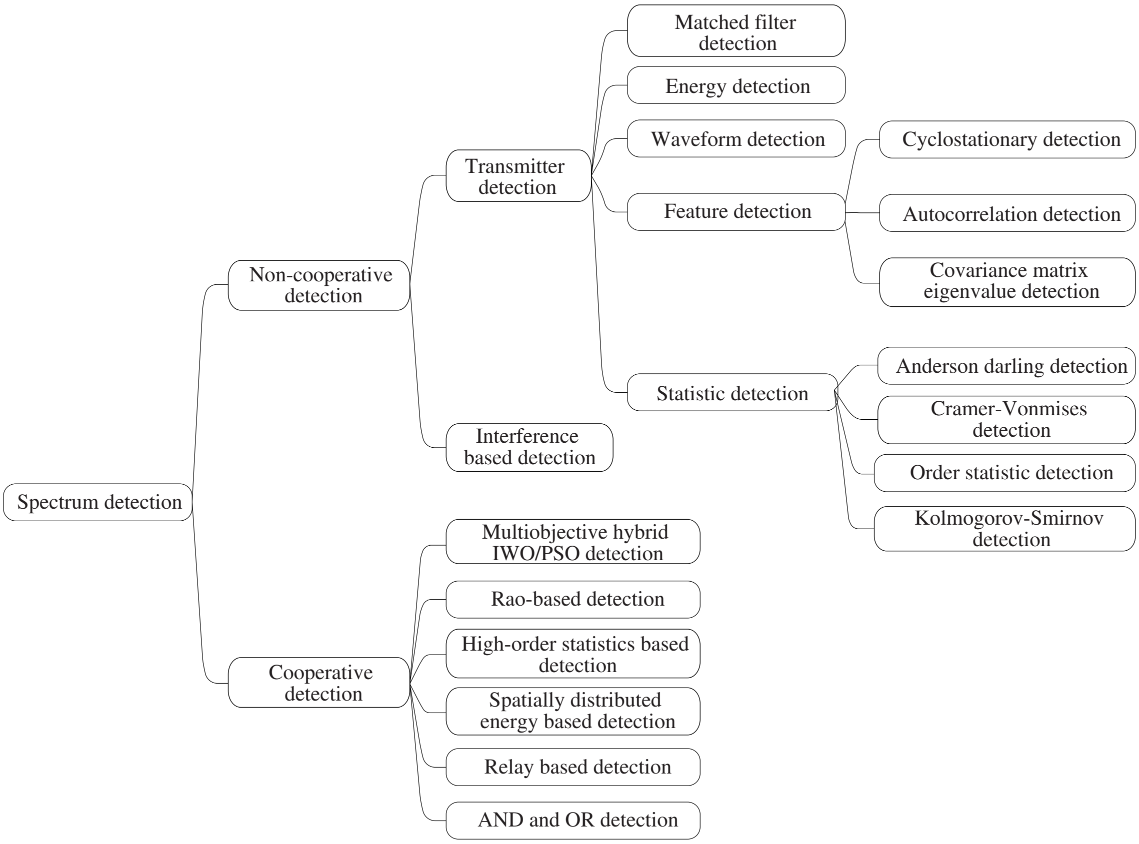

Figure 3 Spectrum detection methods.

unintentional: (1) malicious PUs emulation attack: attackers play as PUs to transmit strong signals in order to interference SUs' detection; (2) unintentional PUs attack: PUs with defects always transmit strong signals for communication cause SUs' detection errors; (3) malicious SUs emulation attack: attackers act as SUs to report false sensing information to mislead spectrum decision; (4) unintentional SUs attack: SUs with defects report inaccurate sensing information; (5) selfish SUs attack: SUs report false sensing information to maximize their aggregate spectrum utilization. For malicious PUs/SUs emulation attacks, authentication technique can be adopted; for unintentional PUs/SUs attacks, it's necessary to identify these users and then change equipments; for selfish SUs attack, punishment mechanisms [106] are evitable.

3.9 Green communications

Large scale mobile communication networks have become a non-negligible part of the world energy consumption. It not only generates enormous CO_2 emission but also occupies quite a proportion of operating costs. Facing huge pressure from energy consumption, energy-efficient green communications become extremely important and urgent. One of the two major themes about 5G systems proposed by China Mobile is green [107]. One of the three efficiency indexes of 5G systems proposed by IMT-2020(5G) PROMOTION GROUP is energy efficiency [108]. According to the analysis of energy consumption in the network of a mobile operator, BSs account for more than 50% of energy consumption in telecommunication systems [109]. Therefore, the key to achieving 5G green communications is to reduce BS energy consumption. Researches on green communications mainly focus on the following aspects:

- Improved network architecture and deployment: Traditional cellular-based designs mainly focus on seamless coverage and system capacity issues. Facing energy consumption pressure, green design of cellular networks is becoming a major issue. Control/user plane separation [110] and heterogeneous networks [111] are considered as promising architectures.

- Green radio resource management: Radio resource management (RRM) is an important part of the RAN and various algorithms have been studied [112–119]. Traditional RRM mainly concentrates on spectrum efficiency and QoS. RRM also plays an important role in reducing energy consumption and green RRM becomes the essence. It requires integrated tradeoffs, such as deployment efficiency and energy efficiency (EE), spectrum efficiency (SE) and EE, bandwidth and power, and delay and power [120]. The game theory based resource allocation algorithm [119] has received special attention because it can make reasonable tradeoff to achieve global optimum. In the future, more efforts should be devoted to the design of unified green RRM frameworks and really understanding the basic tradeoffs limitation.
- Energy efficient power amplifier: Power amplifier is the biggest energy consumption component in BSs which is up to 22% of all energy consumption [121], because the PA works in low efficient condition due to linearity requirements. In 5G systems, data rate up to 10 Gbps requires much wider power range. The contradiction between linearity and efficiency will become more acute. Besides, the bandwidth is up to 1 GHz and disperses at different frequency bands. Current PA techniques can hardly satisfy such requirements. It is necessary to put emphasis on highly linear and efficient wideband multi-frequency band PA.
- Sleeping for BSs: Due to non-uniform traffic distribution, it's a waste of energy to keep all BSs working around the clock. In the period of low traffic, only a fraction of BSs need to provide the service, and other BSs may enter low-power sleeping mode to reduce the power consumption. Several sleeping algorithms have been proposed [122,123]. However, these approaches need to pre-configure coverage cells to guarantee coverage, which adds to configuration complexity. Meanwhile, users are required to be transferred to new coverage cells before switching off energy saving cells, which may affect users' experience. In 5G era, it will be an ultra dense and heterogeneous network, and the problems of how to efficiently select sleeping BSs, wake up slept BSs, and design convergent algorithms are still open.
- Dynamic cell size adjustment: As constant location change and different QoS requirements of the users, it's inefficient to always keep the same cell size. The cell zooming [124] is another efficient approach to reduce energy consumption by dynamically adjusting transmit power to change the cell size based on users' location and QoS requirements. Compared with the sleeping modes, the cell zooming doesn't need to pre-configure coverage cells, move users and wake up slept energy saving cells. However, it requires accurate users' location information and fast power adjustment. Meanwhile, a cell's size adjustment may cause whole network coverage adjustment. If a cell adjusts transmit power, it will generate either interference to its adjacent cells or coverage black holes. To avoid these interference and coverage black holes, its adjacent cells also need to adjust transmit power. In 5G era, network deployment becomes increasingly complex. Convergent algorithms avoiding this butterfly effect are vital to the application of cell zooming. Besides, future researches should consider how to coordinate BSs sleeping and dynamic cell size adjustment.

4 Conclusion

In this paper, a number of potential techniques for the future 5G systems are introduced. Although these techniques may be only a small portion of what would be used in 5G systems, they shed light on promising technology developing trend. To achieve the goal of IMT-2020 and beyond, we believe that there will be greater breakthroughs in wireless communication technology as the further researches and development go. And we also expect that the new network architecture and techniques would come up to promote the current cellular systems.

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