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Review paper

Technical challenges for high-frequency wireless communication

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Abstract: Recent rapid developments in 4G wireless communication have been motivated by breakthroughs in air interface technology, exemplified by the replacement of WCDMA (Wideband Code Division Multiple Access) with OFDM (Orthogonal Frequency-division Multiplexing). Although the protocol to adopt for 5G HF (High-Frequency) wireless communication—including such matters as waveform, network deployment, and frequency range—has been a controversial issue for a number of years, a common view is that there is a large gap between the rapidly increasing requirements pertaining to traffic capacity and the capabilities of current LTE (Long Term Evolution) networks in terms of spectral and power efficiency. A number of technical challenges need to be overcome in order to bridge this gap. In this paper, by briefly reviewing progress in HF technology, we summarize technical challenges ranging from propagation attenuation and the implementation of circuit devices, to signal processing and the Ka-band to offer feasible reflection on the forthcoming technological revolution.

Key words: high frequency, 5G, LTE, Ka-band

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1 Introduction

Since WCDMA was commercially replaced with OFDM in several North European countries at 2009, the 4G wireless communication industry has been on the verge of remarkable developments. While the commercial implementation of 3GPP Release 12 features, which represent 4G+ systems[1], seems premature at present, a revolution in wireless network technology is on the horizon[2], due to enhancements in future releases as well as the wide range of applications, i.e. 5G. The deployment of 5G technology is expected to begin in 2020 and completed by 2030.

5G is expected to support 1000-fold gains in capacity, facilitate connections for at least 100 billion devices, and guarantee a 10-Gbit/s user experience capable of extremely low latency and response times[3]. It can provide an adequately wide pipeline for data streaming for the IoT (Internet of Things), VR (Virtual Reality), cloud storage, and computation (http://bgr.com/2016/02/26/mwc-2016-best-phones-vr-5g), etc.

For 5G, HF bands higher than 6 GHz are superior to those in sub-6G(frequency band under 6 GHz) due to wide signal bandwidths of up to several GHz, the focus on antenna beam, and excellent direction features to suppress inference. In particular, HF

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provides high data rate given rapid mobility.

Unlike 4G systems, 5G does not boast a new air interface technology. There are a number of candidates for waveforms, including F-OFDM(Filtered OFDM), SCMA(Sparse Code Multiple Access), Polar code[4], FBMC(Filter Band Multicarrier), GFDM(Generalized Frequency-division Multiplexing), UFMC(Universal-filtered Multi-carrier)[5], and even the current OFDM. Moreover, since the dominant application scenarios are unclear in this context, no agreement has been reached on network deployment and frequency range, i.e., macrocell, microcell, picocell, and femtocell at frequencies of 28 GHz, 38 GHz, 60 GHz, and 70+ GHz are all still options. As a result, the protocol for 5G has not been launched. Nevertheless, a common view holds that there is a large gap in current LTE networks between rapidly increasing traffic capacity requirements and the capabilities of spectral and power efficiencies.

To bridge this gap, a combination of a wider spectrum, higher spectral efficiency, and decuples of higher network density is necessary. However, to meet this requirement, the industry needs to rise to a cluster of inevitable technical challenges: 1) Propagation attenuation in wireless channels: For an HF EMW (Electromagnetic wave), since there is a higher probability of collision with particles in the air than bypassing them, attenuation is higher. Furthermore, knowledge of the HF channel is incomplete, because of which LoS (Line-of-Sight) and NLoS(Non-line-of-Sight) statistical models should be reconstructed using a large amount of measurement data. 2) Implementation of an antenna and the IF/RF(Intermediate/Radio Frequency) circuit: For example, in HF bands, the PA (Power Amplifier) has limited output power and linearity, whereas the HF receiver yields its worse possible performance. Moreover, the HF component needs to be compact, and incurs greater insertion loss than that of sub-6G. 3) Complex signal processing at the baseband: Since 5G has bandwidth that is scores of times wider than 4G as well as a higher scale of antenna array, data rate is higher and the computational burden due to digital signal processing far heavier. Furthermore, since low-requeney and high-frequency systems are typically combined, the system's algorithms need to exploit the advantages of both. All the above problems need to be solved for 5G HF development.

In this paper, we briefly review the progress of HF technology, summarize the key technical challenges, and introduce solutions by taking the Ka-band as an example.

2 Propagation attenuation

2.1 Comparison of wireless channel between HF and sub-6G

Due to variations in the oxygen and rain attenuations, as well the absorption rate, of EMW, the HF and sub-6G channels are fundamentally different. Furthermore, the components of paths, including direct, reflection, diffraction, and scattering, assume different weights. The measured data has shown that the reflection component of HF channel places the dominance. Some aspects of a comparison of wireless channels between HF and sub-6G are as follows:

1) Large-scale feature

In sub-6G, along the LoS path, propagation is approximate to that in free space. Along the NLoS path, the PLE (Path-Loss Exponent) is small. In HF, large-scale attenuation increases for both LoS and NLoS propagation, i.e., the PLE is higher. For example, the measurement curves of HF path losses in different frequency bands are shown in Fig.1, where values are much greater than those in sub-6G.

With respect to shadowing, for sub-6G, the standard deviation is relatively small and the shadow area is large, such that the classification of the scenario is rough. For HF, the standard deviation is relatively large and the shadow area small, such that the classification of the scenario is precise.

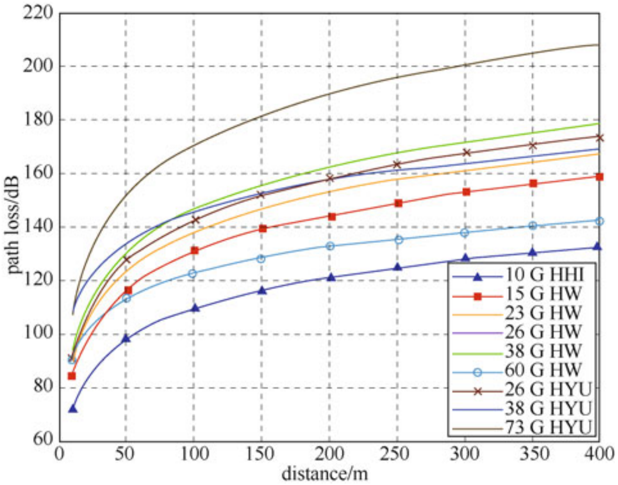

Figure 1 Measurement of NLoS large-scale attenuation in outdoor microcell scenario.

Moreover, the XPR (Cross-polarization Power Ratio) in the HF channel obviously increases while the CPR (Co-polarization Power Ratio) decreases.

Link budget: Since the path loss of HF EMW is greater than that of sub-6G, efficient coverage of the former is much smaller. Using the Ka-band as an example, we show the link budget curves in Fig.2:

The link budget curves in Fig.2 are drawn based on the measured path loss of 28 GHz, where the red and blue curves, respectively, correspond to the single-antenna array and the double-antenna panels. As shown in the figure, since EIRP = 40 dBm and spectral efficiency is 4.6 bit·s^{-1}·Hz^{-1}, the coverage distances of LoS and NLoS are, respectively, 85 m and 10 m; since spectral efficiency is 0.6 bit·s^{-1}·Hz^{-1}, the coverage distances of LoS and NLoS are 406 m and 47 m. This implies that the path loss of NLoS is greater than that of LoS. Furthermore, multiple antenna panels improve the EIRP and the corresponding coverage distance, which is demonstrated by the colored curves in Fig.2. For example, when spectral efficiency is 0.6 bit·s^{-1}·Hz^{-1}, the coverage distances of LoS and NLoS reach magnitudes of 638 m and 73 m, respectively, which are greater than those of the single-antenna array.

2) Composite features

In contrast with sub-6G, the path components for HF vary. This is because the direct path, i.e., the LoS, plays a much more important role in improving channel state, the proportions of reflection increase, and the scattering feature is discrete and locally distributed. With regard to the PDP (Power Delay Profile) of HF, the sparse property of multipath scatteringbecomes prominent, the jump arising from the power against the delay becomes obvious, whereas the conversion from mono-path to continuous scattering becomes insignificant. Further, the delay spread decreases while angular spread increases for the sparse property.

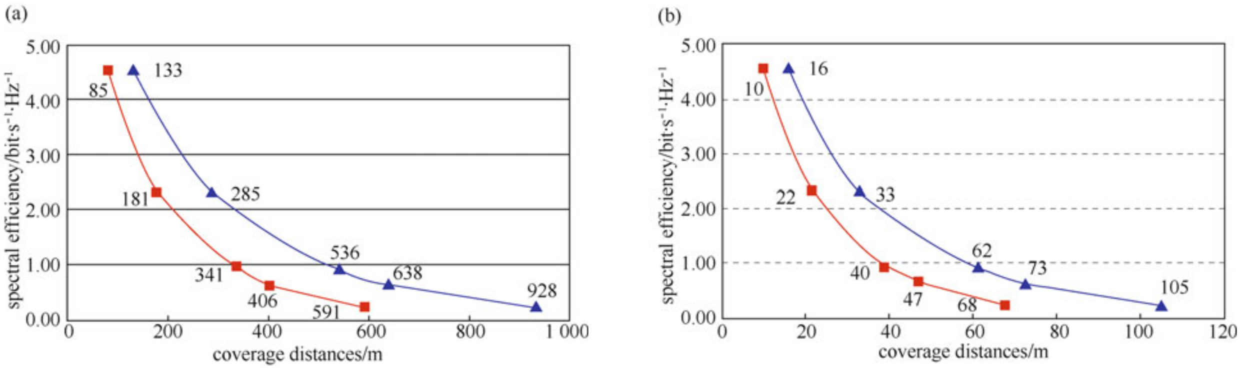

Figure 2 Link budget of the Ka-band: (a) LoS; (b) NLoS

3) Features of wide-band multipath cluster

Compared to sub-6G, HF has higher number of channel clusters and a smaller spread of a single cluster. Furthermore, there are multiple paths in the channel clusters, and are closely related to the circumstance and distribution of scatterers. The channel clusters show a stronger mapping to the physical clusters than that of sub-6G.

2.2 Requirements of channel measurement and modeling

1) Channel feature analysis

Since the 5G network is more complex than 4G, the requirements of HF channel analysis change: it is necessary to research methods of forming omni-patterns with directional antennas, and considering the diversity of the antenna configuration, the performance of the transmission technology system, and model complexity. Moreover, the existence of channel selectivity in the wide-beam domain should be tested by implementing the antenna model with different configurations.

2) Requirements of channel modeling

The following HF channel features should be considered for channel modeling:

- Spatial consistency: the continuous variance in the channel due to the mobility of users
- Massive antenna array: spatial variance of the channel with 1D, 2D, or even 3D large-scale antenna arrays
- Spherical wave channel: location of the scatterer, and an extended statistical model of the scatterer’s distribution
- Small-scale 3D spatial feature: modeling of 3D fine features due to the application of the spatial channel with smaller cell coverage
- Model of dense multilinks: features under multiple coexisting channels due to the rapid increase in the number of mobile users and devices
- System configurations settled as model parameters: HF channel features should be extracted and researched, since the relevance of devices and channel features is strengthened due to the diversity and complexity of 5G applications.
- High-speed mobility: channel modeling under the scenarios of UE(User Equipment) with high-speed mobility and rail transit.
- Low-power, low-velocity, opportunistic transceiver: for signal transmission between D2D and M2M, it is necessary to analyze and model this channel under different scenarios.

In summary, compared with 3G and 4G, the channel model of 5G has different architecture. Furthermore, due to the complexity of 5G systems and the diversity of requirements related to channel features, it has broken the conventional frameworks. Therefore, it is necessary to design measurement devices according to these requirements, research and develop parameter-extraction algorithms, and propose feasible modeling schemes under the conditions of a lack of knowledge and measurement results of 5G HF propagation. This will help meet the requirement of system R&D(research and development) and algorithm design.

3 Implementation of circuit devices

Since path-loss generally increases with increase in frequency, higher EIRP(Effective Isotropic Radiated Power) is needed for sufficient coverage of HF systems. However, power efficiency and receiving sensitivity decrease with increasing EIRP. To overcome this, a larger-scale antenna array is necessary, but leads to problems in the design and fabrication of antenna and RFICs(Radio Frequency-Integrated Circuits). Furthermore, a large bandwidth of HF also limits the implementation of the antenna and the circuit.

3.1 High-frequency antennas

- The size of the antenna is closely related to frequency. Thus, it is 1/10th to even 1/100th of that of the antenna in sub-6G. Such a small size suggests that the HF antenna can be designed on the PCB or inside the chip. Highly integrated with RF circuit, the size of the front end is greatly reduced, so that cost can be reduced.
- The wiring of the HF antenna array is a major problem because the characteristic impedance of the feeder is insensitive to frequency. It thus becomes difficult to implement dual polarization. Furthermore, high-density integration leads to the problem of electromagnetic compatibility. As a result, the homogeneity of the antenna pattern deteriorates.
- The antenna interconnects vertically with the RF circuit to reduce the size of the front end, which results in insertion loss. Therefore, it is a key technology to design an interconnection approach with low insertion loss.
- It is a necessary issue in practice to find the appropriate material for an antenna's radome and an appropriate manner of installation, as problems arising due to HF antenna radomes are unknown.

3.2 The fabrication of high-frequency RFIC

With the requirement for RFICs with increasingly high frequencies, a diversity of fabrication processes has emerged, and is used for centimeter-wave or millimeter-wave RFIC, such as GaN, InP, GaAs, SiGe, CMOS, SOI, heterogeneous integration, and so on. Although the GaN PA exhibits excellent performance with high output power and PAE(Power-Added Efficiency), its operating frequency is usually below 20 GHz, which does not suit higher-frequency RFIC. InP has excellent low-noise performance, but offers only a slight advantage in terms of output power over SiGe. Heterogeneous integration has also been explored for high-frequency RFIC. For example, smaller III-V wafers are bonded to standard CMOS wafers to directly connect the front end PA with LNA. However, the process of the development of heterogeneous integration is still not mature. The GaAs is considered a promising process for high-frequency RFICs, and exhibits advantages in terms of output power and PAE of the PA, the low noise figure of the LNA, and the insertion loss of the switch, due to its high electron mobility, high breakdown voltage, and the availability of high-quality factor passives[6]. However, the cost of this process is much higher than that of SiGe and CMOS, which undermines its potential for commercial millimeter-wave applications. SiGe and CMOS have attracted more research and commercial interest for fabricating high-frequency RFIC due to their low cost and capacity to integrate with digital circuits. Furthermore, SOI is considered a mainstream next-generation IC process, and exhibits a considerably smaller insertion loss in passive devices than SiGe and CMOS in high-frequency bands.

The f_t and $f_{\max}$ of the transistor indicate the maximum frequency of operation, which should be three to five times the application frequency in order to achieve satisfactory performance. The Fig.3 illustrates the f_t and $f_{\max}$ of the SiGe, CMOS, and SOI processes. As can be seen, an f_t of 130 nm for SiGe, 45 nm for SOI, and 40 nm for CMOS is 250 GHz, and these three fabrication processes are sufficient to implement the Ka-band, the V-band, and the E-band in RFIC. Furthermore, the f_t of 90 nm SiGe and 28 nm CMOS/SOI is up to 300 GHz, and these processes can be used to fabricate W-band RFIC or high-frequency RFIC with better RF performance and lower power consumption.

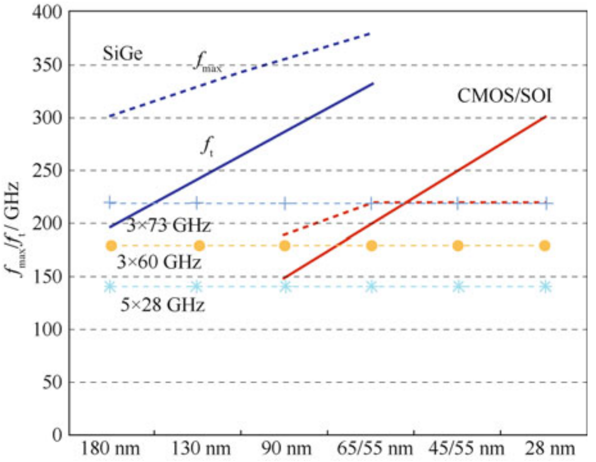

Figure 3 The f_t / $f_{\max}$ of different fabrication processes—from globalfoundries

The trend of high-frequency RFIC is toward low-cost, high-performance, and single-chip solutions. The cost of the SiGe process is lower than that of the GaAs, but is still higher than that of the SOI and the CMOS processes. Compared with CMOS, although SiGe exhibits satisfactory phase noise, output power, and PAE for the VCO and the PA, respectively, concentrated research efforts have drastically reduced the performance gap between CMOS and SiGe. The challenge of the CMOS process for high-frequency RFIC remains to obtain higher output power and higher PAE for the PA, lower noise figure for the LNA, and a low-insertion, loss-passive component. Compared to the CMOS process, SOI has the comparable performance on active devices. However, the insertion loss in passive components fabricated with SOI is much smaller than in CMOS and SiGe. Hence, the SOI process is a good choice for a single-chip solution, which integrates active and passive components on one chip, such as PA, LNA, switch, etc. However, there have been a few reports concerning the modulator, the demodulator, the VCO(Voltage-Controlled Oscillator), PLL (Phase-Locked Loop), and other components fabricated with SOI. The RF devices' modeling of SOI needs to be further researched and explored in the future.

3.3 Integration of antenna array and RF module

Due to oxygen loss, rain loss, etc., the propagation attenuation at high frequency is much higher than in current cellular radio, and limits the distance of coverage of high-frequency base stations. However, two RF approaches can be used to improve coverage: 1) increase in output power of the PA and the number of PAs, and 2) enhancement of gain for the antenna, for example, enhancing the scale of the antenna array by increasing the number of antenna elements. By increasing operation frequency, the wavelength is smaller, and the size of the antenna array becomes smaller as well (the distance between two antenna elements is set to a half the wavelength to reduce the side lobe), which makes possible the integration of the antenna array into the RF module.

The integration of the antenna array with the RF module can minimize the size of the wireless system and lower transmission loss between the RFIC and antenna elements. There are three ways to implement the integration of the antenna array into the RF module, as shown in Fig.4[7]: 1) AoP(Antenna on PCB): RFIC is bonded to the PCB with an embedded antenna on the opposite side; 2) AiP (Antenna in Package): RFICs is flip-chip-bonded to the package, which tiles with an embedded antenna. The tile module is then attached to the mother PCB through BGAs(Ball-Grid Arrays); 3) AoC(Antenna on Chip): the antenna is implemented directly on a glass wafer stacked on the RFICs.

The major challenge of AoP is to design antennas with sufficient gain and efficiency. The interconnect insertion loss degrades as the number of layers of PCB grow, due to the lateral movement of the position of vertical vias arising out of PCB manufacturing tolerances. Moreover, the cost remains

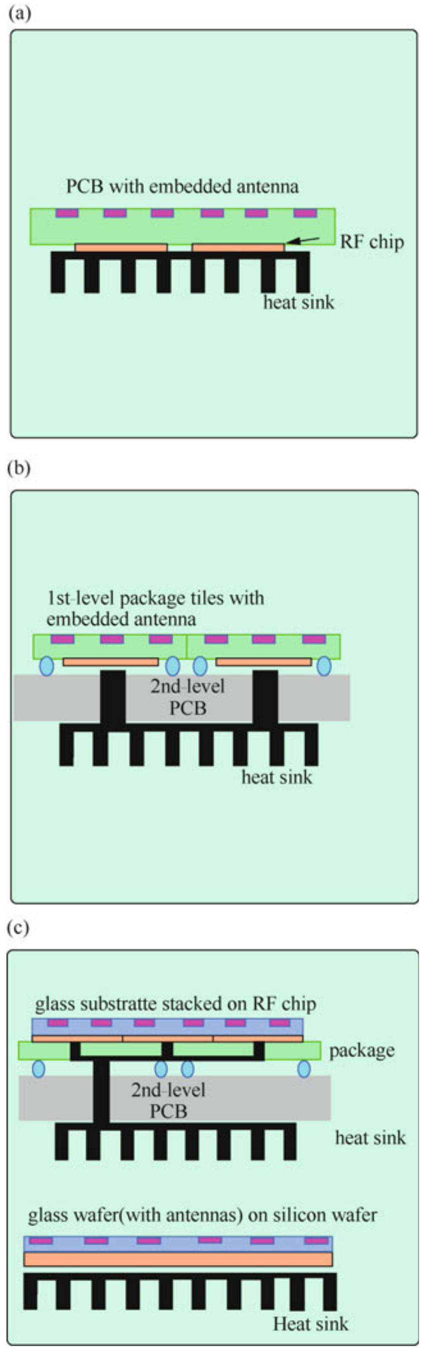

Figure 4 The scheme of integration of the antenna array and the RF module: (a) AoP; (b) AiP; (c) AoC

high and the maturity is unsatisfactory. Although the lateral movement of the position of the AiP vertical vias is better than that of the PCB process, the complexity of system assembly increases. Furthermore, 1) the package solution should be compatible with the mainstream manufacturing and assembly processes, 2) the package materials and layer stack-up must enable excellent RF performance with mechanical reliability, and 3) the heat-removal requirements of the encapsulated RFIC should not degrade antenna performance[8]. The AoC integrates the antenna array with RF front-end circuits on the same chip in silicon technologies. This is usually suited to the THz band (~100 GHz), very short-range wireless communication, and array applications. The gain and the radiation efficiency of the antenna elements of AoC is much lower due to large Ohmic losses and surface waves[9]. Furthermore, the EMI (Electromagnetic Interference) is a related issue to AiP and AoC, and affects the operation of the antenna and the circuits.

3.4 Challenges arising from large bandwidth

The Shannon–Hartley theorem states that channel capacity is proportional to the bandwidth of a communication system. In other words, the data rate can be increased by widening the bandwidth of the system. However, the spectral resources of sub-6 GHz are precious and the bandwidth of current cell radios is only 20 MHz. Fortunately, spectral resources at high frequency are abundant. The centimeter-wave and millimeter-wave communication systems can attain several hundred megahertz or gigahertz of bandwidth, which is 10~100 times that of current LTE cells. The data rate of high-frequency systems also increases 10~100 times, and could reach 10 Gbit/s.

However, given high carrier frequency and wide bandwidth, there are several technical challenges in the design of circuit components and antennas for centimeter-wave and millimeter-wave communication[10]. For example, although the operating bandwidth of 802.11ad is 2.16 GHz, the circuit components and antenna should cover the full RF bandwidth (57~64 GHz), which enhances difficulties in the design and implementation of high-gain and high-efficiency antennas and wideband circuit components. Moreover, the stringent requirement of intra-band gain flatness devices should be considered[11].

Furthermore, with increasing bandwidth, the interference is not dominant, and the thermal noise of the system is comparable or even larger than that of sub-6G[12]. The sensitivity of the HF receiver degrades, the output power density per hertz of the system decreases as bandwidth widens, and the range of coverage shrinks.

4 Signal processing

According to the discussion above, large-scale antenna arrays and wide bandwidth are key features of the 5G HF technology, as both significantly increase the amount of storage and the burden due to digital computation. Therefore, more advanced architectures and signal processing schemes are required. To meet these requirements, several challenges need to be overcome:

4.1 Low-complexity beamforming

Large-scale antenna arrays can provide a beamforming gain sufficient to overcome path loss and then obtain reasonable SNR (Signal-to-Noise Ratio). Further, large arrays may enable the precoding of multiple data streams, which can help improve spectral efficiency and allow systems to approach capacity.

For a sub-6G system, MIMO(Multiple-Input Multiple-Output) processing is mostly implemented digitally at the baseband, where the phase and amplitude of the signal are controlled. However, digital signal processing requires a dedicated baseband and RF hardware for each antenna element, which is costly in terms of power consumption for HF system design. This results in the need for analogous processing on RF units using phase shifters, with a constant modulus.

Analog beamforming has been proposed by leveraging a closed-loop beam training process consisting of beam pattern generation using a codebook at the transmitter, best-beam selection at the receiver, and feedback from the selected beam indices[13,14]. The closed-loop process has the advantage of without the prior channel knowledge at the transmitter. However, it consumes large overhead for the feedback scheme, which results in outage. Moreover, its capability is limited if it does not take into account the digital baseband.

Since the analog process can significantly reduce the complexity of signal processing, it is a better method to combine digital and analog beamformers. Moreover, channel knowledge for the transmitter is obtained by the receiver sounding reference signal, according to channel reciprocity between opposite links, particularly for TDD.

As mentioned in Section 2.1, for HF systems, the channel has the sparse property of multipath scattering, such that channel estimation can be sparse signal recovery, where the MIMO channel matrix with sparse elements of the main channel scattering coefficients is reconstructed. As a result, the process of HBF is a small number of dominant orthogonal propagation paths being selected at the beamspace, which are further digitally combined at the baseband and can be solved through compressed sensing[15,16]. So far, the regular pattern of sparsity of the HF channel should be measured and demonstrated, and the computational burden of compressed sensing methods should be solved. In summary, HBF has a long way to its application.

4.2 RF channel calibration

As mentioned above, large-scale antenna arrays are a significant means of increasing the capacity of wireless systems. For a massive MIMO system, the performance of HBF cannot be optimized unless RF channels are homogeneous. Unfortunately, RF component and array elements cannot be manufactured perfectly, and the difference in the environments of the circuit of the RF channels is inevitable. Therefore, the time-delay error, the amplitude error, and the phase error commonly exist. In particular, for 5G HF systems, even though no common proposal has been proffered for air interface design, a distinct trend is that each resource element has shorter frame and larger sub-carrier. As a result, the requirements for calibrating RF channel errors are distinct from those for sub-6G, e.g., the precision of phase error calibration can be lower, whereas the precision of time-delay error calibration should be higher. However, a dedicated calibration algorithm for HF has not been proposed.

4.3 Coordination of low-frequency and high-frequency systems

The massive capacity of HF systems depends on their large bandwidth. However, the overhead involved in the beamforming process is large. An alternative scheme is the coordination of low-frequency and high-frequency systems. There are three main approaches to this end. The first involves the use of low-frequency subsystems as the control plane searching for UEs while the HF subsystem is used as the data plane providing traffic data. The second is one where the low-frequency subsystem searches UEs with blind-beam steering and captures them at sector-level beams, as the HF subsystem searches based on sector-level beams with beam refinement[17]. The third approach involves provision by the low-frequency subsystem of the initial value of the channel at a given snapshot to the HF subsystem, which fuses the given detected values of both subsystems to give a predicted value of the next snapshot. This process, shown in Fig.5, facilitates quick measurement of the channel.

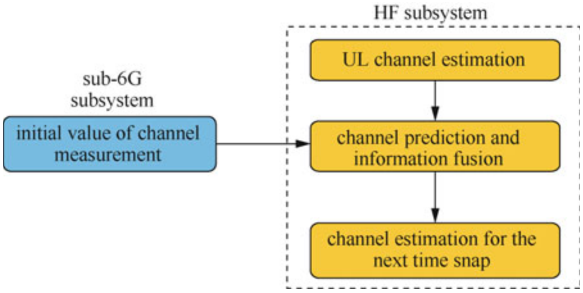

Figure 5 Flowchart of high-low frequency coordination

The architecture coupling HF and low sub-6G bands reduces overhead, and even captures the quickly moving UEs. The concrete algorithm depends on the extent to which overhead is acceptable and the extent of overlapping of coverage of both subsystems.

5 Conclusion and future research

Since the propagation properties of HF EMW are different from those of sub-6G, 5G HF systems should overcome the variety of the large-scale features, composite features and wide-band multipath clutter features in wireless channels through measuring and modeling. Furthermore, due to non-ideal features for the HF devices, the demand for fabrication processes of HF antenna and RFIC is great; last but not the least, the revolution of HF signal processing is benefit for both improving the system capacity and degrading the requirement of design specifications of HF devices.

Therefore, the implementation of the forthcoming 5G HF should greatly depend on the promising design of massive MIMO with low complexity, low power loss, sparse recovery, and channel prediction.

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