

# Up in the air with 5G

F-OFDM, SCMA, and Polar Code are the three key technologies that underpin Huawei's 5G new air interface concept. F-OFDM is a basic waveform technology that supports a unified air interface and uses flexible numerologies to enable radio slicing. SCMA and Polar Code increase the number of connections, reliability, and spectral efficiency.

By Zhang Dong



**A**ir interface technology is the jewel in the crown that differentiates each generation of mobile communications. It also has the most contending technologies, each vying to emerge victorious as the 5G sky begins to clear thanks to 3GPP 5G standardization. Of these technologies, Huawei's series of new 5G air interface technologies is the star that's shining the brightest.



## A matter of design

Requirements guide the goals and direction of 5G research. In June 2015, the ITU-R defined three main 5G application scenarios: enhanced mobile broadband (eMBB); Massive Machine Type Communication (mMTC); and Ultra Reliable & Low Latency Communication (uRLLC). The organization also defined 5G network capability requirements in eight areas, including throughput, latency, connection density, and spectral efficiency.

Future 5G services will be defined by three main characteristics, each of which will place different demands on air interfaces:

**1. Diversity:** All generations up to 4G focused on people-to-people communication via mobile Internet; but, 5G will need to enable the Internet of Things (IoT) and enhance mobile Internet.

An unparalleled flourishing of services and requirements will occur in the 5G era. We will see remote control applications that require ms-level latency; demand for gigabit broadband to support virtual reality (VR), augmented reality (AR), and ultra-high definition video; and LPWA IoT that will require millions of connections per square kilometer.

Air interface design will have to

meet diverse, even conflicting, requirements. Revolutionary new 5G air interface technologies are needed to meet ITU's 5G requirements.

**2. Long-tailed:** 5G will expand the boundaries of mobile communications by embracing verticals and boosting their efficiency. Verticals have extremely varied requirements on mobile Internet services, and as typical long-tailed markets, bring in much lower revenues. The long tail structure dictates that it will be impossible to develop different air interface designs to suit each type of industry. Instead, it will require the use of different parameters (numerology) or radio slicing, so that the air interface can adapt to the requirements of different verticals.

**3. Uncertainty:** The next four to five years will bring a lot of uncertainty, and may include services that were impossible to predict. Therefore, we must consider what drives services as well as keeps our technology a little ahead of the industry. Future 5G services will be diverse, long-tailed, and hard to predict. This will require a new unified air interface that has a high degree of flexibility to adapt to different services. The new air interface design will need to improve spectral efficiency – always a goal of air interface design – given its importance in lowering operator network deployment costs and ensuring the maturity and

prosperity of the entire industry chain.

## New 5G air interface: key enablers

To overcome the challenges described above, Huawei has proposed a new 5G air interface concept and a series of key enabling technologies, covering fundamental waveform, multiple access schemes, channel coding, access protocols, and frame structures. We've also carried out field tests and verification with pioneering operators.

Superstructure is determined by underlying infrastructure. The same applies in air interface design. This article will therefore explore new waveform, new multiple access, and new coding techniques, the critical new technologies of 5G physical layer design.

### Filtered-OFDM: new waveform

Fundamental waveform design enables a unified air interface that supports flexibility and spectral efficiency. To illustrate the case for Filtered-OFDM, it's useful to explore the reasons why OFDM cannot meet 5G requirements.

OFDM modulation converts high-speed data into orthogonal sub-carriers via serial/parallel converters, and uses cyclic prefix (CP) to deal with Inter Symbol Interference (ISI). OFDM was widely used in the 4G era, but the technology's main problem was inflexibility.

In the 5G era, different applications will have very different requirements on air interface

technology. The Internet of Vehicles, for example, requires ms-level latency and very short time symbol duration and TTI (Transmission Time Interval), requiring sub-carrier spacing with wide frequency division. In IoT's massive connections scenario, the overall system must handle a high number of connections even though data transmission from individual sensors is low. For frequency division configuration, this will require relatively narrow sub-carrier spacing. For time division, the ISI problem doesn't need to be considered, and there's no need to use CP because symbol length and TTI are sufficiently long. In addition, asynchronous operations save energy at the terminal side.

OFDM cannot meet these flexibility requirements. OFDM's time-frequency resource allocation is a fixed 15 KHz of frequency division on sub-carrier bandwidth, compared with MBFSFN, which is 7.5 KHz. Once the sub-carrier bandwidth is determined, numerology such as time division symbol length and CP length are also basically determined.

If the system's time-frequency resources are like a train carriage, the OFDM solution is used to furnish it. OFDM can only provide seats (sub-carrier spacing) of a fixed size for all passengers regardless of whether they are fat, thin, rich, or poor. A train design like this would be illogical, insufficiently user-centric, and unable to meet people's diverse needs.

For 5G, the hope is to provide a variety of train seats (spacing) – hard, soft, sleepers, private compartments – all

flexibly customized based on passengers' height and size (service requirements), with whatever adjustments required possible. This would be like the Harmony Express of the China high-speed rail with its many customizable seating arrangements – this is the idea on which F-OFDM is based.

F-OFDM can provide different sub-carrier spacing and numerology for different services to meet time-frequency resource requirements. Sub-carrier spacing in different bandwidths no longer possesses orthogonal properties, so guard bandwidth needs to be used. For example, OFDM requires 10 percent guard bandwidth. Guard band guarantees the flexibility of F-OFDM, but does it lower spectral efficiency? In the past, there's always been a conflict between flexibility and system expenditure. But the optimized filter design of F-OFDM greatly reduces out-of-band leakage, and the spectrum spent on guard bands between different sub-bands can be reduced to around 1 percent, greatly increasing spectral efficiency and making it possible to utilize fragmented spectrums.

F-OFDM has inherited all the advantages of OFDM like high spectral efficiency and MIMO adaptability, but also addresses some of its flaws by boosting

flexibility and spectral efficiency. Thus, it's a key technology for 5G air interface slicing.

### **New multi-access: Sparse Code Multiple Access**

Sparse Code Multiple Access (SCMA) determines the allocation of air interface resources, and is thus a key technology for increasing the number of connections and spectral efficiency. With F-OFDM enabling flexible multiplexing on frequency division and time division and minimizing the use of guard bands, what other domains can multiplexing be applied to that further enhances spectral efficiency?

The two that come to mind are space domain and code domain. Spatial multiplexing MIMO was proposed during the LTE era; it will further flourish in the 5G era thanks to multi-antenna. As for code domain, the technique seems to have been forgotten in the LTE era, so can it be revived in the 5G era? In fact, this is what SCMA does by using sparse codebooks and sparse code multiple access (SCMA) to increase the number of connections threefold.

Returning to the train metaphor, F-OFDM adapts the seats (sub-carriers) according to passengers' needs (service requirements). To further enhance spectral

efficiency, more passengers need to fit into a limited number of seats. For example, squeezing six people into the space of four seats sounds easy enough, and would increase the number of connections by 150 percent, but achieving it is another matter.

This is where low-density spread spectrum comes in. In this first key SCMA technology, the user data of a single sub-carrier is spread on to four sub-carriers, with six users using these four sub-carriers. The name refers to the fact that user data is only spread over two sub-carriers, with the other two sub-carriers empty. This is like six passengers sitting on four seats, with each passenger only able to sit over two seats at most. This is what the "sparse" in SCMA refers to. Why must it be sparse? If data were not sparsely spread, it would be spread over an entire sub-carrier. This would mean the same sub-carrier carrying the data of six users and there would be too much conflict and demodulating the data of the six users would be impossible to complete.

However, once six people sit on four seats, the space between them isn't strictly orthogonal. Each passenger occupies two seats, so the passengers cannot be distinguished by seat number (sub-carrier). On a single carrier, conflict

*Using nonscheduling technology can greatly reduce data transmission latency to meet 1 ms air interface latency requirements.*

still exists between the data of three users, so difficulties with demodulating the data of multiple users remains.

This is where multidimensional modulation (MD) – the second key SCMA technology – plays a role. MD is a very abstract concept because traditional IQ modulation only had two dimensions – amplitude and phase. So what do the extra dimensions represent?

Here we need to engage our imaginations a little. Imagine the process of an Alpha Centaurian alien opening up a proton into a 3D multi-dimensional circuit and then reducing the number of dimensions again. Eventually, a single proton is formed into an all-powerful computer, but the proton is still a proton, except its function has been greatly enhanced.

Similarly, through MD technology, it's still the phase and amplitude that are modulated, but the Euclidean distance between the constellation points of the multi-users is shortened, considerably boosting the performance of multi-user demodulation and anti-interference. Each user data uses sparse codebooks allocated by the system to carry out multidimensional modulation. The system knows each user's codebook, making it possible to demodulate different users when a non-orthogonal waveform is used.

This is equivalent to sticking coloured stickers onto passengers to identify them when it's no longer possible to do so by seat number; the stickers together with the seat numbers make it possible to

distinguish the passengers.

In field validation tests under acceptable levels of complexity, a threefold increase in the number of upstream connections compared to OFDMA has been achieved using SCMA and non-orthogonal sparse code division, as well as significantly improved downstream user throughput (over 50 percent) using non-orthogonal code division and power division multiplexing. In addition, because SCMA allows a certain level of conflict between users, using non-scheduling technology can greatly reduce data transmission latency to meet 1 ms air interface latency requirements.

### **New coding technology: Polar Codes**

#### **The ultimate goal of Polar Codes – Shannon capacity:**

The goal of channel coding is to ensure the reliable transmission of information using the least amount of resources. At a particular error rate, the smaller the amount of resources needed, the higher the coding efficiency, and hence the higher the spectral efficiency. For researchers of channel coding techniques, attaining the Shannon limit is the ultimate goal.

So what is the Shannon limit? Shannon's second theorem states that as long as the information transmission rate is less than the channel capacity, a type of code exists that can enable the information transmission error probability to be made arbitrarily small. In the narrow sense, the Shannon limit describes the minimum signal-to-noise ratio (SNR) required to achieve error-free

transmission using a code. For example, the Shannon limit of an AWGN channel under ideal circumstances is around -1.6 dB. In practice, however, the cost of achieving error-free transmission is too high. In the general definition of the Shannon limit, that's the minimum SNR required for a particular acceptable error rate.

Communications can be likened to logistics. In logistics, the goal is to transport goods to an end point. Take the example of a glass factory, a shipment of glass products needs to be sent from A (information source) to B (information sink). The road between A and B is equivalent to the channel, and the potholes and bumps along the road are channel noises. To reduce the amount of losses due to breakage (errors) during transport, the products need to be packed into cardboard boxes (coding) and then unpacked at point B (decoding). Although packaging (coding) increases overheads and reduces the number of products that can fit into each container (information payload), the method greatly reduces breakage rates (bit error rate). When there is an allowable breakage rate (bit error rate), improving the packaging (coding) method can minimize requirements on the road and transport vehicle (SNR). This minimum requirement (minimum SNR) is the Shannon limit.

Shannon's theorem posits the existence of such a code, but doesn't explain what code can achieve this. This has frustrated coding scientists who, for the past 50 years, have proposed multiple error correction coding techniques, including RS, convolutional

codes, Turbo codes, and LDPC codes, which have been widely applied in different kinds of communications systems. However, no code has been able to achieve the Shannon limit, until the introduction of Polar Codes.

**Basic principle of Polar Codes:** Erdal Arikan, a professor at Turkey's Bilkent University, proposed the concept of channel polarization in 2007. The theory outlines the first known demonstrable channel coding method to achieve the Shannon limit, which Arikan termed Polar Codes. This discovery was a major breakthrough in coding theory. Polar Codes have clear and simple encoding and decoding algorithms, and the error correction performance currently achievable by Polar Codes is superior to the widely used Turbo and LDPC codes.

To understand Polar Codes, we must first understand the concept of channel polarization. As the term suggests, it involves polarization of the channel and refers to a group of independent symmetric binary-input discrete memoryless channels that use the coding method to enable different sub-channel reliability. When the code length is increased, a ratio of the channels become perfect (error-free), while the rest become pure noise channels.

Continuing with the example of the glass factory, the original packaging method (coding method) makes it impossible to predict the location of products that will break during transport. But with a Polar Codes packaging method, it's possible to guarantee that a certain proportion

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of products in a certain location won't be damaged during transport (perfect channels) no matter how bumpy the road, while the rest in the other locations will certainly break (pure noise channel). This characteristics of channel polarization allows products (information bits) to be placed in the perfect channel and nothing (constant bits) in the pure noise channel location. And because the distribution of the perfect channel is known when the goods are packed, decoding when unpacking them becomes much simpler. In fact, improved Successive Cancellation List (SCL) decoding algorithms for Polar Codes approach the performance of maximum likelihood decoding with acceptable complexity.

The advantages of Polar Codes are: 1) higher gain than Turbo codes: In actual measurements under equivalent error rate, Polar Codes have 0.5-1.2 dB lower SNR requirement than Turbo codes, and higher code efficiency means increased spectral efficiency; 2) Thanks to Hamming distance and strong SC algorithm design, Polar Codes have no error floor and reliability is much better than Turbo codes. (Turbo codes use sub-optimal algorithm, and thus have an error floor). For the ultra-high reliability requirements of 5G service applications (such as remote real-time control and driverless vehicles), Polar Codes support 99.999% reliability, ensuring reliability for vertical industries; 3) Polar Codes use a SC-based decoding scheme that significantly reduces decoding complexity; terminal power consumption is therefore much lower, 20 times lower

in fact than Turbo codes under equivalent complexity. This greatly extends the battery life of IoT sensors, which demand ultra-low power consumption.

Some things bear repeating: F-OFDM is a fundamental waveform technology for supporting a unified air interface that uses flexible numerology to enable air interface slicing. In addition to F-OFDM, SCMA and Polar Codes enhance the number of connections, reliability, and spectral efficiency, meeting ITU's 5G capability requirements. These are the three key technologies underpinning Huawei's new 5G air interface concept.

## Competition drives 5G

The curtain has just been pulled back on 5G and we stand on the cusp of a great era. In each generation of mobile communications, there are competing directions and candidate technologies.

Ultimately, the best directions and technologies survive the filters of theory, practice, and market. Through integration and validation, they are transformed and proliferate, leaving an indelible mark on the world.

When standards are defined, all technologies and directions are worthy of respect and remembrance as the producers of wisdom and for their role in driving 5G advancement. Let's look forward to the new super connected world of 5G. 



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