SparkLink

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Performance Evaluation of SparkLink Basic Radio Access Technology

SparkLink Alliance Release

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Performance Evaluation of SparkLink Basic Radio Access Technology

Keywords: SparkLink Technology; Low Latency; High Reliability; High-accuracy Synchronization; High Concurrency; High Security

Abstract: With the vigorous development of digital society, the circulation of information among people, things and environment are accelerated to a further extent. Connection are becoming an indispensable part in the circulation. As the last hop of information dissemination, short range wireless communication technologies play an enormous role in every aspect of social life. More than 10 billion short range radio devices are launched on the market every year. The number grows year on year. This creates a large number of new applications and valuable scenarios. With more and more applications and services evolve, new requirements challenge the existing short range wireless communication technologies in respect of low latency, high reliability, high synchronization preciseness, high concurrency and information security. New short range wireless communication technology more which is in line with the business requirements and trends is desperately needed by the industry and society. Following the trend, in the communication industry, with joint efforts from partners from the research, the standardization and the development, designed a new-generation short range wireless communication radio access standard technology, i.e. the CCSA YD/T 4007-2022 "Wireless short range communication-Technical requirements and test methods for automotive". An industry promotion alliance - SparkLink Alliance is set up, which aims to promote the commercialization of the new short range wireless communication technology in the fields of intelligent vehicles, smart homes, smart terminals and intelligent manufacturing as well as other scenarios, and further push ahead with continuous evolution of the SparkLink technology. As the first performance evaluation report of SparkLink Basic (SLB) technology in the industry, it comes up with design goal of the SparkLink system from requirements of application scenarios, then introduces system architecture, basic parameters and key technologies of the SparkLink system. It preliminarily evaluates link performance of the key technologies of SLB. Finally, suggestions on the future development route and evolution direction of the SparkLink technology are given.

List of Abbreviations:

AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat Request
BCH	Broadcasting Channel
BLER	Block Error Rate
CB	Code Block
CBG	Code Block Group
CC-HARQ	Chase-Combining HARQ
CDC	Cockpit Domain Controller
CRC	Cyclic Redundancy Check
CSCH	Control Signaling Channel
FEC	Forward Error Correction
G/G-Node	Grant Node
HARQ	Hybrid ARQ
IR-HARQ	Incremental Redundancy HARQ
ICI	Inter sub-Carrier Interference
ISI	Inter-symbol Interference
MCS	Modulation and Coding Scheme
PAS	Phase Adjustment Signal
QoS	Quality of Service
RE	Resource Element
SG	Special G symbol
ST	Special T symbol
SNR	Signal to Noise Ratio
SPS	semi-persistent scheduling
SCL	Successive Cancellation List
T/T-Node	Terminal Node
TDD	Time Division Duplexing
TB	Transmission Block
TBS	Transmission Block Size

1 Introduction

This is an era of Internet of everything. As of 2020, there are around 27 billion devices connected to the Internet worldwide, a number that Statista predicts will grow to 75 billion by 2025. Through the connection, smart devices are becoming increasingly intelligent, and gradually exert a profound influence on people's work, life and entertainment. As a key step to the end-to-end connection, the last tens of meters of short range wireless communication plays a significant role. Statistically, more than 10 billion short range radio connection devices are launched on the market every year. Combing with existing applications, these connections gradually give rise to more updated application scenarios which covers fields of intelligent vehicles, smart homes, smart terminals, intelligent manufacturing as well as others.

The development of new services brings out new application scenarios, and raises new requirements for the communication technologies to carry these applications. Some new applications and corresponding service requirements are illustrated below.

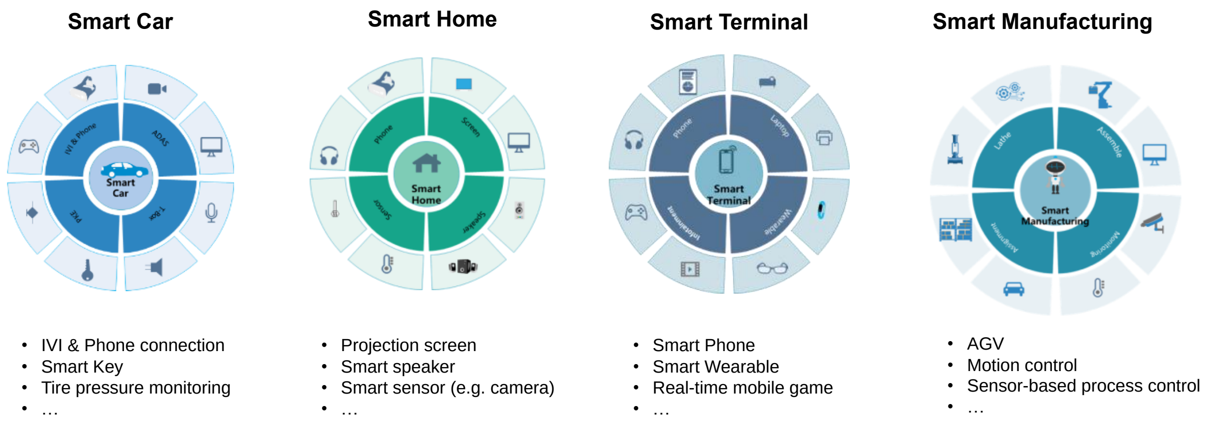


Figure 1-1 Application Scenarios of SparkLink Technology

Because of these application scenarios, different requirements on performance and function for short range wireless communication are brought forward in the application scenarios mentioned above. They are listed in term of fields respectively:

- Intelligent vehicles:
  - To achieve the desired quietness effect in the vehicle, vehicle-mounted active noise reduction service actively cancels engine noise, road noise and wind noise when the vehicle is in motion. It is required that the latency of unidirectional transmission is not more than 20 µs, the reliability is up to the level of wired communication, and the sampling synchronization precision among sensors is less than 1 µs, which supports parallel transmission of dozens of audio signals;
  - To conform to the end-to-end latency requirement of 20~30 ms, the latency of 2~4 ms for unidirectional transmission is required for services such as vehicle-mounted interactive projection screen and rearview mirror of streaming media;
  - Battery management system (BMS) in the electric vehicle requires that sensors to sample signals simultaneously, the synchronization precision is up to µs order of magnitude among the samplings, and more than 200 signals to be transmitted concurrently;
  - End-to-end security protection is required, including authentication, encryption and integrity protection, as well as cross-domain security isolation, etc.
- Smart terminals:
  - To guarantee that the end-to-end latency is less than 20 ms in the interactive game scenarios,

the latency of radio communication is required to be <5 ms;

- Esports game control devices require high refresh rate and low latency. The latency of unidirectional transmission is less than 500 μs, and mouse control, sound and picture are synchronized in real time;
- Esports wireless headphones require support of lossless audio play, at least 48kHz sampling and 24-bit quantitative bit width in mono.

• Smart homes:
  - The communication latency of 4K/8K HD video screen projection is less than 2 ms, the data rate is greater than 10 Gbps;
  - Wireless HiFi-level home theater requires stereo play to support μs order of magnitude high-precision time synchronization as reliable as wireline transmission.

• Intelligent manufacturing:
  - In the closed-loop motion control scenario in an assembly line, the cooperation of sensors and actuators requires that the unidirectional latency is less than 500 μs and the reliability of is around 99.9999% and 99.99999%;
  - End-to-end information security protection is required, including authentication, encryption, integrity protection, etc.

In the above-mentioned typical scenarios, the service requirements, such as low latency of 20 μs, ultra-high reliability of over 99.9999%, microsecond synchronization, hundreds of concurrent transmissions, and end-to-end information security protection have posed enormous challenges to the existing short range wireless communication systems. To cope with the above technical challenges and resolve pain points identified by the industries, the SparkLink technology is designed to target systems in line with the above requirements in term of low latency, high reliability, high-precision synchronization, multiple concurrency and information security. All needs in the typical wireless application scenarios are therefore met.

This document analyzes and assesses the SparkLink Basic (SLB) access technology specified in the CCSA YD/T 4007-2022 “Wireless short range communication - technical requirements and test methods for automotive”, which is one of the air interface of SparkLink Release 1.0 technology. The system architecture, basic parameters, key technologies and performance are introduced. Then it analyzes how much the SLB matches the requirements in the typical application scenarios. Finally, it comes up with suggestions on the future developments and evolution of the SLB technology.

2 Introduction to SLB Technology

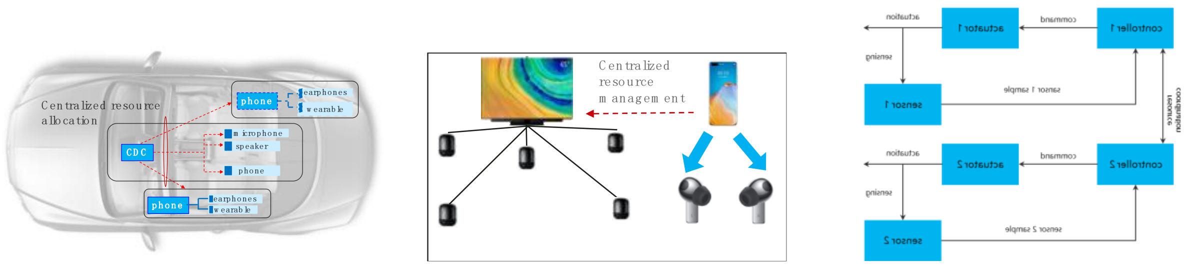
2.1 Architecture of SLB System

2.1.1 Network Architecture

The nodes in the system are classified into managing nodes (G nodes) and managed nodes (T nodes). In an application scenario, a single G node manages multiple T nodes. The G node and T nodes are connected for a specific communication purpose. The G node and the connected T nodes constitute a SparkLink communication domain collectively.

As depicted below in Figure 2-1(a), the scenario of intelligent vehicles, cockpit domain controller (CDC) acts as the G node, and all types of in-vehicle devices, such as microphones and speakers are the T nodes. All of them jointly implements entertainment function in the cockpit. At this time, the CDC and the in-vehicle devices become a SparkLink communication domain. When a mobile phone is connected to the CDC, the mobile phone can be regarded as T node within this communication domain as well.

In other scenarios, there may be multiple communication domains. In the intelligent vehicles, a mobile phone connected with wearable devices is the G node, and then the mobile phone and wearable devices will form another SparkLink communication domain. In the scenario of smart home, a TV set and attached audio devices will form a communication domain, and mobile phone and headphone will produce another communication domain. The two communication domains can be distinguished by an advanced communication domain and a general domain. The former can coexist multiple communication domains by means of resource coordination.



(a) Intelligent vehicle applications (b) Smart home/terminal applications (c) Intelligent manufacturing applications

Figure 2-1 Schematic Diagram of Composition of Communication Domain of SparkLink System

2.1.2 Architecture of Protocol Stack

As displayed in Figure 2-2, the protocol stacks of SparkLink system are classified into three layers, which are Basic Application Layer (5th~7th layers of the OSI model), Basic service Layer (3rd~4th layers of the OSI model) and SparkLink Access Layer (1st~2nd layers of the OSI model).

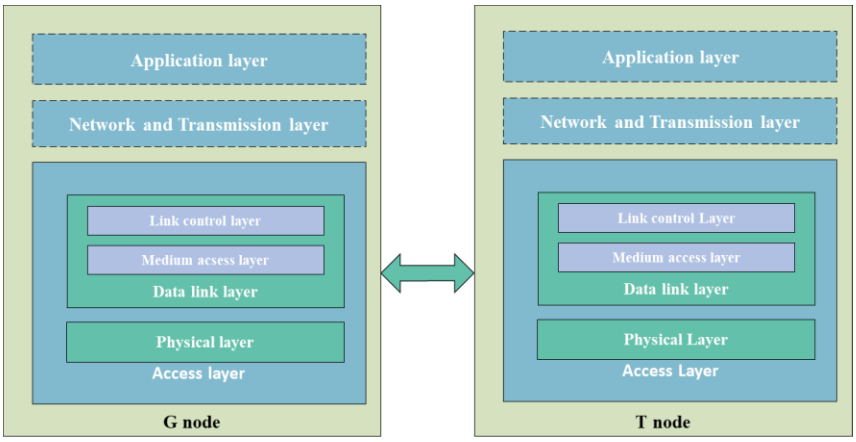


Figure 2-2 Architecture of Protocol Stacks of SparkLink System

Therein, the technical aspects of the SLB air interface involved are as below:

- The data link layer guarantees reliable transmission of data packets, including the link control layer and the media access layer. The former mainly realizes control of transmission mode, encryption and decryption as well as other functions, while the latter mainly implements resource scheduling, data encapsulation, and controls transmission format to satisfy QoS requirements of different services.
- The physical layer realizes transmission functions of bit stream.

The access layer also implements information security and management functions which are used to guarantee security of the protocol stack and carry out necessary management of communications.

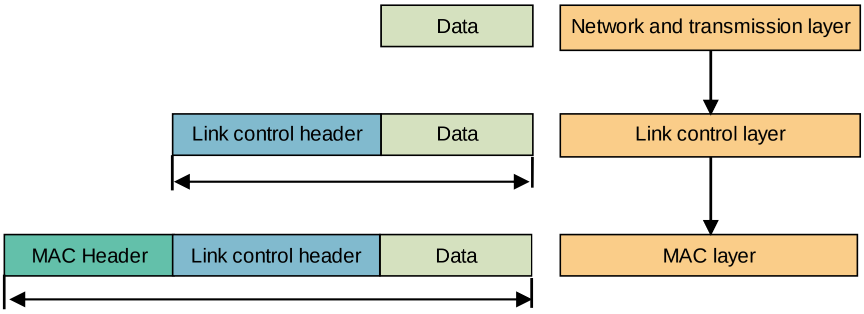


Figure 2-3 Data Encapsulation Process of the SLB System

As displayed in Figure 2-3, in the procedure of data encapsulation at data sending end, packet headers are added to the data layer by layer. On the contrary, at data receiving end, packet headers are removed in reverse order.

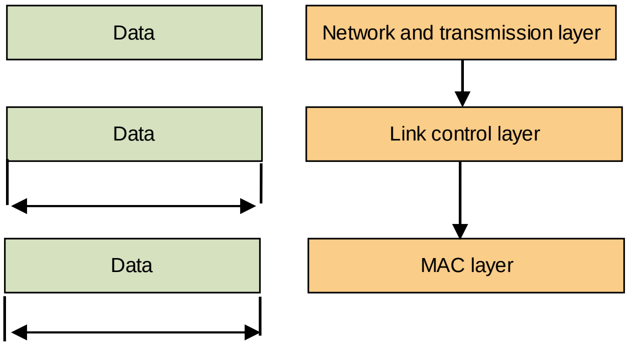


Figure 2-4 Cross-layer Transparent Transmission Mechanism of the SLB System

As displayed in Figure 2-4, the SLB supports cross-layer transparent transmission mechanism for periodic packet data transmission with ultra-low latency, such as audio transmission in active noise reduction service. When the connection is established, it adopts pre-defined service parameters and transmission channels, no packet header is added at each protocol layer. The mechanism cuts down overhead incurred by packet headers, boosts the efficiency of transmission, and decreases the processing time of each layer. So that transmissions with ultra-low latency are obtained.

2.2 Fundamental of Physical Layer of SLB

2.2.1 Transmission Waveform

CP-OFDM waveform transmission is used for the SLB system, in which the time measurement at the physical layer is multiple times of basic time unit Ts, which is defined as Ts=1/fs (fs=30.72 MHz), and sub-carrier spacing Δf=480kHz.

The CP-OFDM symbol contains two parts in the time domain, i.e. effective data and cyclic prefix, the duration of the former is 64Ts, while the duration of the latter includes two types:

$$T_{CP} = \begin{cases} 5 \times T_s, & \text{normal cyclic prefix} \\ 14 \times T_s, & \text{extended cyclic prefix} \end{cases}.$$

Time duration of the CP-OFDM symbol (including cyclic prefix) is:

$$T_{Symb} = \begin{cases} 69 \times T_s, \text{normal cyclic prefix} \\ 78 \times T_s, \text{extended cyclic prefix} \end{cases}.$$

2.2.2 Channel and Sub-carrier Design

The minimum carrier bandwidth of the SLB system is 20MHz, and carrier bandwidths of 40/60/80/100/160/320MHz, which is respectively composed of a plurality of continuous 20MHz carrier aggregation modes, are supported. The 20MHz carrier is made up of 39 continuous sub-carriers with an interval of 480KHz, which are numbered #0, #1, ..., #38 in order of the corresponding frequencies from low to high. Therein, the sub-carrier numbered #19 is DC sub-carrier and does not carry any information. In the 20MHz working bandwidth, the lowest frequency and the highest frequency are reserved for resource protection purpose and are not available for sub-carriers allocation.

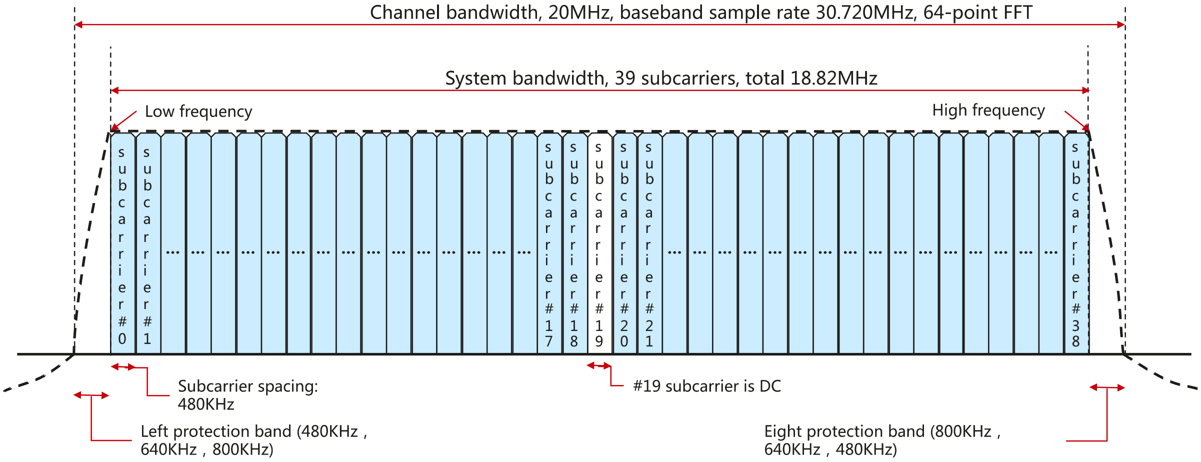


Figure 2-5 Division of Sub-carriers of SparkLink System (20MHz Channel)

2.2.3 Superframe Structure and Radio Frame Structure

The SLB system works in the TDD mode, and format of superframe is shown in Figure 2-6 below. Each superframe consists of 48 radio frames, the duration of each superframe is 1ms while the duration of each radio frame is 20.833 μs. Therein, G symbols are sent by the G node to the T node (G link), and T symbols are sent by the T node to the G node (T link). SG/ST respectively stands for the symbol resources that are used for overhead symbols in G/T symbols. The overhead symbol resources of each radio frame can be flexibly configured as 0, 1 or 2 symbols. GAP is switching interval between G-link symbols and T-link symbols.

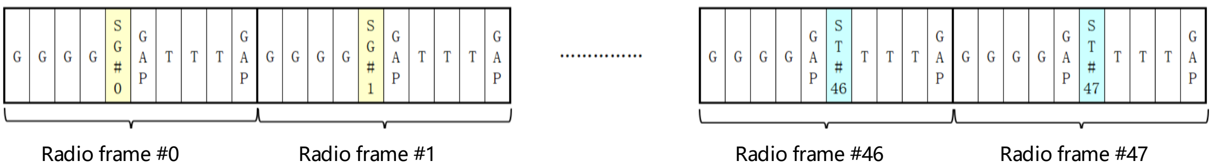


Figure 2-6 Superframe Structure of SparkLink System

If the normal cyclic prefix is used, the radio frame is in support of 14 ratios of G/T symbols; If the extended cyclic prefix is used, the radio frame is in support of 12 ratios of G/T symbols. Flexible ratios of G/T symbols are in line with the requirements of service rates in different link directions under different application scenarios.

Table 2-1 Radio Frame Configuration Based on the Normal Cyclic Prefix

	Symbol configuration

Radio frames configuration	0	1	2	3	4	5	6	7
0	G	T	T	T	T	T	T	T
1	G	G	T	T	T	T	T	T
2	G	G	G	T	T	T	T	T
3	G	G	G	G	T	T	T	T
4	G	G	G	G	G	T	T	T
5	G	G	G	G	G	G	T	T
6	G	G	G	G	G	G	G	T
7	T	G	G	G	G	G	G	G
8	T	T	G	G	G	G	G	G
9	T	T	T	G	G	G	G	G
10	T	T	T	T	G	G	G	G
11	T	T	T	T	T	G	G	G
12	T	T	T	T	T	T	G	G
13	T	T	T	T	T	T	T	G

Table 2-2 Radio Frame Configuration Based on the Extended Cyclic Prefix

Radio frames configuration	**Symbol configuration**						
	0	1	2	3	4	5	6
0	G	T	T	T	T	T	T
1	G	G	T	T	T	T	T
2	G	G	G	T	T	T	T
3	G	G	G	G	T	T	T
4	G	G	G	G	G	T	T
5	G	G	G	G	G	G	T
6	T	G	G	G	G	G	G
7	T	T	G	G	G	G	G
8	T	T	T	G	G	G	G
9	T	T	T	T	G	G	G
10	T	T	T	T	T	G	G
11	T	T	T	T	T	T	G

2.2.4 Working Parameters of the SLB System

The principal working parameters of the SLB system are listed in Table 2-3. In a specific application, reasonable parameters can be configured in line with the requirements for the performance, the cost and the power consumption under different application scenarios.

Table 2-3 Principal Working Parameters of SparkLink System

Parameters	**Specification value**
Working bandwidth	20/40/60/80/100/160/320MHz
Multi-access mode	OFDMA
Duplex mode	TDD
Radio frame configuration	Normal CP: 14 Extended CP: 12
Number of spatial multiplexed data streams	G node is in support of the transmission of maximum 8 streams. T node is in support of the transmission of maximum 4 streams.
Modulation scheme	QPSK/16QAM/64QAM/256QAM/1024QAM
Channel coding	Polar/RS

Length of physical frame	20.833μs
Retransmission mode	HARQ at the physical layer, ARQ at the link layer

3 Key Technologies of SLB System

3.1 Synchronization and Access

3.1.1 System Synchronization

The SLB system is configured with two types of synchronizing signals, i.e. FTS (first training signal) and STS (second training signal). They are placed in two adjacent radio frames and are sent in the superframe periodically. ZC sequence is taken as synchronizing sequence in the SLB system. In comparison with M sequence, the ZC sequence is of higher auto-correlation peak value, lower cross-correlation value and better anti-frequency offset performance, which are beneficial to increase the probability of successful synchronization.

Definition of FTS sequence is

$$d_{FTS}(n) = \begin{cases} exp\left(-j\frac{\pi un(n+1)}{41}\right), n = 0,1,\dots,18 \\ 0 \qquad\qquad\qquad\quad , n = 19 \\ exp\left(-j\frac{\pi un(n+1)}{41}\right), n = 20,21,\dots,38 \end{cases},$$

wherein for the advanced communication domain, $u = 1$, while for the general communication domain, $u = 40$.

Definition of STS sequence is

$$d_{STS}(n) = \begin{cases} \exp\left(-j\frac{\pi u\frac{n}{2}\left(\frac{n}{2}+1\right)}{21}\right), n = 0,2,\dots,38 \\ 0 \qquad\qquad\qquad\qquad , n = 1,3,\dots,37 \end{cases},$$

wherein $u = 1,2,\dots,20$ is synchronization ID of the communication domain. There is a 3dB power boost when the STS sequence is mapped to the subcarriers.

3.1.2 System Access and High Concurrent Transmission

The high concurrent transmission of SLB system mainly includes multi-node concurrency and multi-service concurrency. As shown in Figure 3-1, multi-node concurrency means that a single G node can support stable connection with multiple T nodes simultaneously and can render services to multiple T nodes simultaneously as well. Multi-service concurrency means that different types of services are supported on a single T node simultaneously, so as to provide rich service experience for subscribers.

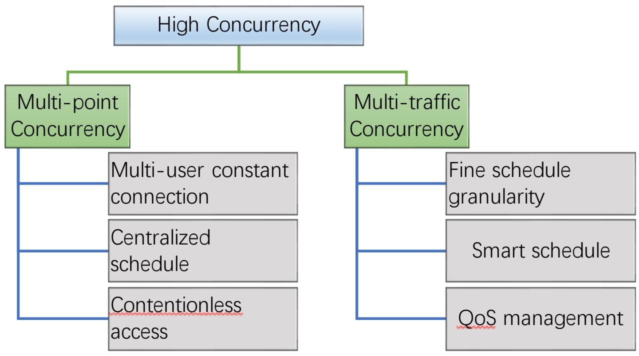


Figure 3-1 Key Technologies to Support High Concurrency

To support high concurrency, some technical schemes are specifically as below:

- Stable connection of a large number of users: In the SLB system, the ID at physical layer used to identify T nodes is 12 bits in length. Theoretically, a single G node can support up to 2^{12}=4096 T nodes.
- Access control mode: centralized scheduling is employed for the SLB system, which avoids link resource conflicts due to distributed resource preemption of a large number of nodes, and increases throughput of the system. The SLB system supports non-competitive access mode, too. That is, a large number of T nodes are able to initiate group access on mutually orthogonal resources simultaneously to achieve millisecond access. As a result, service requirement under the scenario of "work immediately after power on" is achieved.
- Intelligent scheduling based on service features: the T nodes are allowed to report necessary feature information of services to assist the G node in intelligent scheduling in the SLB system. As displayed in Figure 3-2, for the active noise cancellation services, the G node is in support of the T nodes in reporting sampling rate and quantitative bit width. For semi-static scheduling services, the T node can report the semi-static scheduling cycle and packet size to the G node, which is useful for the G node to schedule packet flexibly. In scheduling, the SLB system is in support of the priority mechanism of logical channels. Data encapsulation is performed based on the priority of logical channels. Also, the system is in support of constraining amount of different-priority services in the data encapsulation. This is to balance fairness of scheduling among different services.

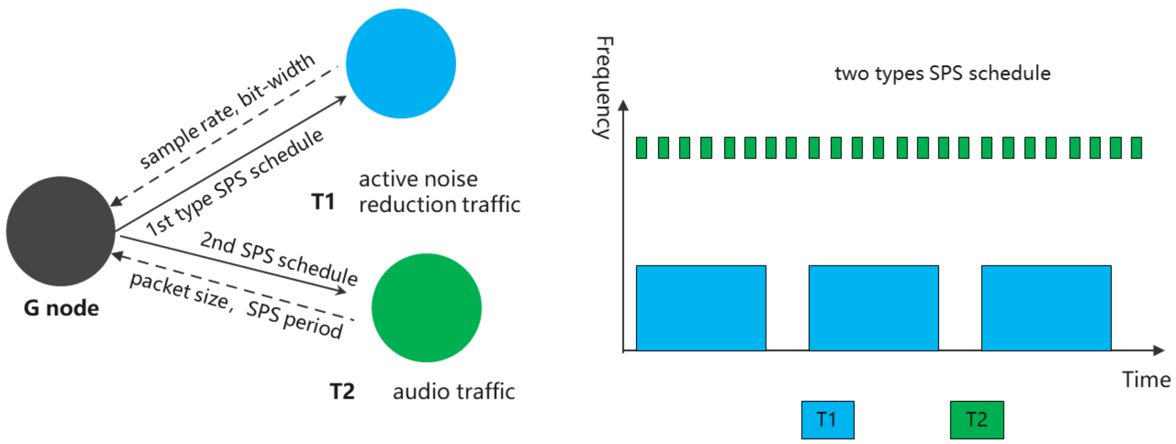


Figure 3-2 Fine Granularity Scheduling and Traffic Intelligent Scheduling of SLB System

3.2 Resource Allocation

3.2.1 Resource Allocation in Frequency Domain

The SLB system is in support of data information transmission with ultra-low latency, which is termed Type I data transmission, and large packet/high traffic information, which is termed Type II data transmission.

The Type I data transmission is in support of services with the requirements for extremely low latency. In this type of data transmission, extremely high transmission reliability needs to be guaranteed in the case that retransmission is not used. For this type of transmission, the scheduling granularity of 1 sub-carrier at the minimum is supported. The G node can schedule different sub-carriers for data transmission based on fading conditions of channels on different sub-carriers of each user on considering that in the same sub-carrier, different frequency domain fading coefficients corresponding to different users. As a result, the purposes to realize scheduling of the optimal sub-carrier combination to the maximum extent and boost the performance of each user as well as the system are achieved. In Figure 3-3, for a single user, the sub-carrier with the best channel conditions can be scheduled for data transmission.

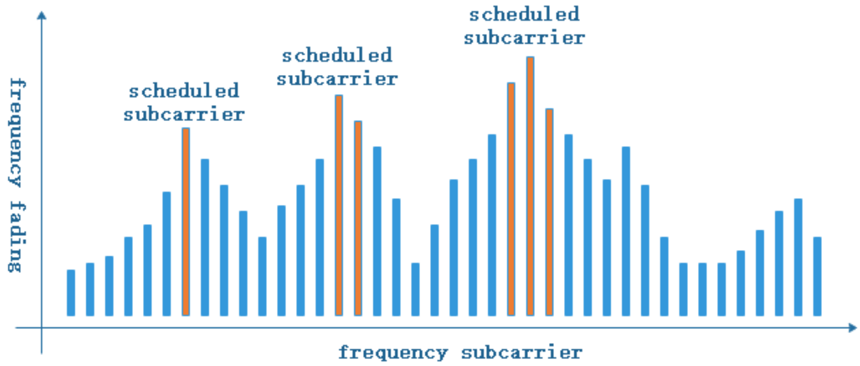


Figure 3-3 Schematic Diagram of Principles for Decentralized Scheduling

For Type II data transmission, the SLB system is in support of the scheduling granularity of 4 or 3 sub-carriers, which can cut down the overhead of signaling indication while reaping enough scheduling gain in frequency domain.

In terms of overhead signals of the system, such as T-link ACK feedback signal and T-node access information, the SLB system is in support of comb transmission of frequency resources, which guarantees that the signals can get enough frequency diversity.

3.2.2 Resource Allocation in Time Domain

With the radio frame of 20.833 μs as the scheduling unit, the SLB system is in support of flexible resource allocation in the time domain, which can fulfill the demand for different latency under different application scenarios. The following key technologies are mainly used for the SLB system with regard to resource allocation in the time domain:

- Short radio frame: Each radio frame is 20.833 μs in length. Since transmission of the G link and the T link are configured in the radio frame simultaneously, the latency of unidirectional transmission at the physical layer is no more than 20.833 μs. Take G link as an example, Figure 3-4 schematically analyzes two types of scenarios with semi-static scheduling. In scenario 1 (case 1) where the 4th symbol of each radio frame is used for data transmission, the data packet is ready in the 1st symbol. Since the latest resources available for transmission are in the 4th symbol, the data packet can be sent only after waiting for 3 symbols, and the transmission latency is less than 20.833 μs. In scenario 2 (case 2), assuming that the data packet is ready after the 3rd symbol of the current radio frame, the data packet is sent at the 4th symbol of the next radio frame. Then the maximum transmission latency of the data packet is only 20.833 µs.

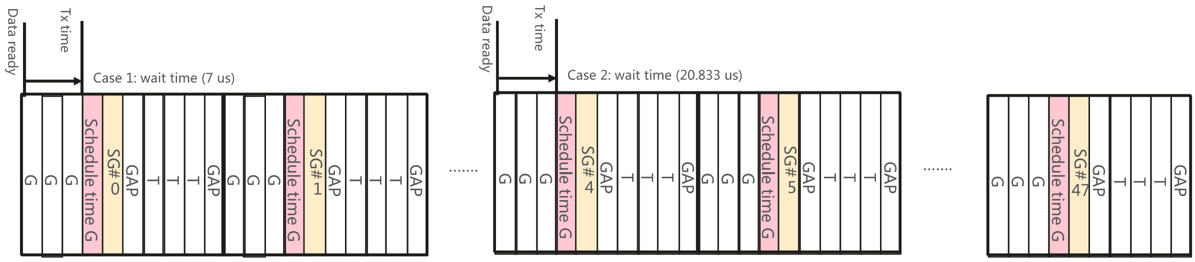


Figure 3-4 Schematic Diagram of Sending Data Packets

- Uniform distribution of overhead signal resources of the system: As demonstrated in Figure 3-4, the resources for the overhead signals of the SLB system (such as synchronizing signals, broadcast information, control information, access information, ACK feedback information of ACK at physical layer, etc.) are scattered in multiple radio frames for transmission. Thereby it is ensured that each radio frame is provided with resources to transmit G-link data packets and T-link data packets.
- Ultra-short flexible scheduling cycle: The SLB system is in support of the configuration of two types of scheduling unit periodically. The shortest scheduling cycle supported by data transmission with ultra-low latency is the length of q radio frame, i.e. 20.833 µs. Each radio frame contains at least one transmission opportunity of the G link and the T link. Thus, the minimum transmission latency is 20.833 µs, one radio frame. Large-packet and high-traffic data transmission is in support of a minimum scheduling cycle of 125 µs, which is the unit of 6 radio frames. It is illustrated in Figure 3-5.

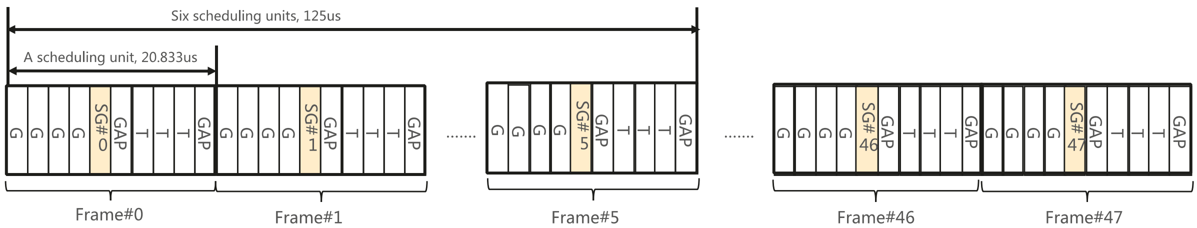


Figure 3-5 Schematic Diagram of Scheduling Unit (periodic) of Data Packet

3.3 Channel Coding and Modulation

3.3.1 Channel Coding for Type I Data Transmission

Polar code is a channel code constructed in light of the channel polarization theory. It can theoretically reach the Shannon limit, and guarantee good performance in the case of random noise. RS code is a linear block code, which is a multi-level channel code built based on the Galois field. Each symbol contain multiple bits, which is used to boast anti-burst interference performance and resist continuous error codes. The SLB system transmits packet services with ultra-low latency (such as in-vehicle active noise cancellation) through the Polar code or the RS code. It guarantees that the system to achieve transmission with high reliability in different application scenarios. The following coded modulation combinations in Table 3-1 are supported.

Table 3-1 Modulation and Coding Mode of Data Transmission with Ultra-low Latency Traffic

Information bit	Length of coding block (including 8-bit CRC)	Scheme of channel coding	Modulation system
16 bits	24 bits	RS (15,11) truncated (10,6) or Polar	QPSK
			16 QAM
			64 QAM
			256 QAM
			1024 QAM
24 bits	32 bits	RS (15,11) truncated (12,8) or Polar	QPSK
			16 QAM
			64 QAM
			256 QAM
			1024 QAM
32 bits	40 bits	RS (15,11) truncated (14,10) or Polar	QPSK
			16 QAM
			64 QAM
			256 QAM
			1024 QAM

3.3.2 Channel Coding for Type II Data Transmission

For the Type II data transmission with large packet and high volume of traffic, the high-performance Polar coding is adopted for the SLB system. It is in support of 32nd-order MCS scheduling, as exhibited in Table 3-2. The SNR gap between the adjacent MCS is largely identical, around 1.0 dB, which is favorable for MCS to match channel characteristics more closely so as to guarantee smooth and stable throughput performance.

Table 3-2 Modulation and Coding Modes of Transmission with Large Packet and High Volume Traffic

MCS index	Modulation	Code rate (R) x 1024	Spectral Efficiency
MCS0	QPSK	148	0.2891
MCS1	QPSK	189	0.3691
MCS2	QPSK	239	0.4668
MCS3	QPSK	297	0.5801
MCS4	QPSK	369	0.7207
MCS5	QPSK	452	0.8828
MCS6	QPSK	542	1.0586
MCS7	QPSK	637	1.2441
MCS8	QPSK	730	1.4258
MCS9	QPSK	820	1.6016
MCS10	16QAM	461	1.8008
MCS11	16QAM	532	2.0781
MCS12	16QAM	615	2.4023
MCS13	16QAM	700	2.7344
MCS14	16QAM	779	3.0430
MCS15	16QAM	853	3.3320
MCS16	16QAM	907	3.5430
MCS17	64QAM	655	3.8379
MCS18	64QAM	719	4.2129
MCS19	64QAM	783	4.5879
MCS20	64QAM	838	4.9102

MCS21	64QAM	896	5.2500
MCS22	64QAM	939	5.5020
MCS23	256QAM	732	5.7188
MCS24	256QAM	791	6.1797
MCS25	256QAM	845	6.6016
MCS26	256QAM	896	7.0000
MCS27	256QAM	937	7.3203
MCS28	1024QAM	768	7.5000
MCS29	1024QAM	812	7.9297
MCS30	1024QAM	856	8.3594
MCS31	1024QAM	945	9.2285

3.3.3 HARQ at Physical Layer

Hybrid automatic repeat request (HARQ) is a technology with FEC and ARQ in combination, which is intended to increase the transmission reliability of a physical link. In terms of traditional ARQ, when the receiving end detects an error in the received packet, the error packet received will be directly discarded and the sending end is requested to retransmit the corresponding data packet. In comparison with ARQ, HARQ enhances ARQ correspondingly. The error packet received is not discarded, but combined with the retransmitted packet to boost the reliability of reception.

Asynchronous HARQ technology based on Polar code is used for the SLB system. It supports up to 4 HARQ processes, CC-HARQ scheme and IR-HARQ scheme. The benefit of the CC-HARQ scheme is from multiple combinations of soft information at the receiving end, which enhances the equivalent SNR of the information at the receiving end and lowers probability of errors. The IR-HARQ scheme, in view of characteristics of the Polar code, further obtains coding gain on the basis of energy gain by extending the mother code length during retransmission or sending the coded bits that were not sent in the first transmission.

The SLB system is in support of three retransmission schemes. They are retransmission based on transmission block (TB), retransmission based on coded block group (CBG), and hybrid transmission of initial transmission and retransmission based on CBG.

The TB retransmission means that when any code block (CB) in one TB is wrong, the data of the whole TB will be retransmitted. During retransmission, the number of CB segments C is the same as that of the first transmission, but the number of channel bits of each CB may be different from that of the first transmission.

For each CB, the implementation process of CBG retransmission is the same as that of the TB retransmission. What is different from the TB retransmission is that the CBG retransmission merely retransmits the CBG where the CB is in error.

The CBG hybrid retransmission refers to each transmission include both the previous TB retransmitted CBG and the new TB initially-transmitted CBG. The number of segments C, is the same as that of the code block contained in the last TB initial transmission associated with the transmission of that time. All initially-transmitted CBGs constitute a new transmission block (TB).

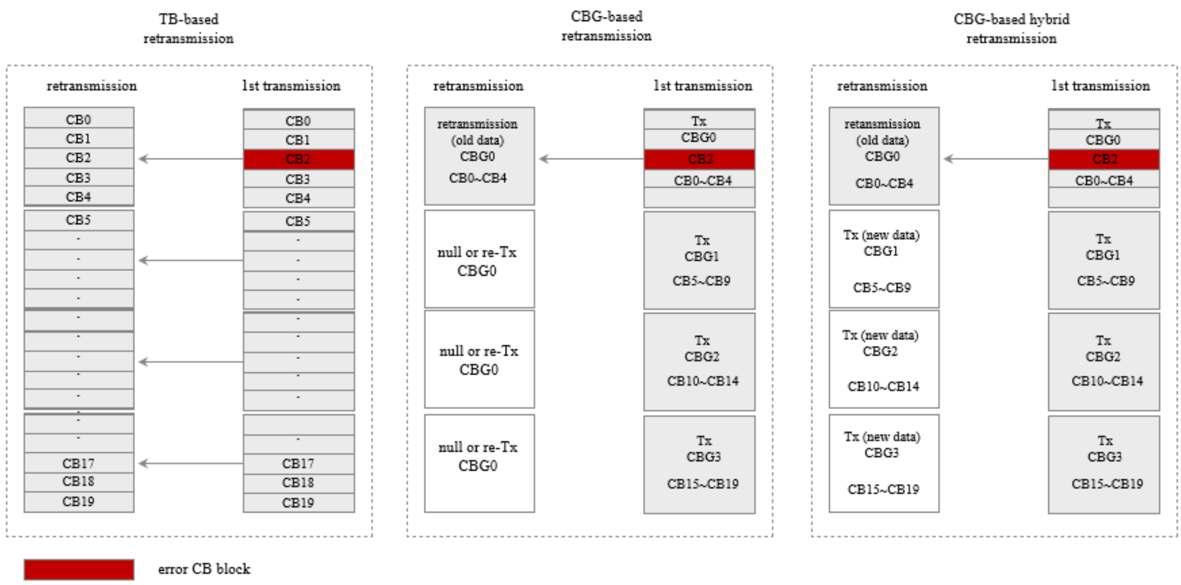


Figure 3-6 Schematic Diagram of HARQ Scheme

3.4 Multi-domain Coordination

3.4.1 Multi-domain Synchronization

The SLB system reduces interference among multiple SparkLink communication domains through time and frequency synchronization among multiple G nodes. The SLB system adopts the OFDM waveform. In scenarios of multiple communication domains, interference among sub-carriers occurs when the frequency difference is not an integer multiple of the 480KHz sub-carrier spacing or the timing difference exceeds CP. This happens even if different frequency band are used in different communication domains. In particular, when the interference comes from multiple communication domains and the interference source is closer to the receiving equipment than the signal source. The interference introduced by time-frequency misalignment among G nodes will decrease the received SINR. Synchronization in time/ frequency domains among G nodes can significantly reduce the interference among multiple SLB communication domains and improve the spectrum efficiency.

For the SLB system, it is necessary to consider the situation that multiple SparkLink communication domains are in the nearby physical space. In a dense deployment scenario, the path loss from the interference source to the receiver may even be substantially smaller than that from the signal source to the receiver. Taking the scenario were two communication domains operate in adjacent carriers as an example, considering that the transmitting power of G nodes in two domains is the same, the path loss from the interference source to the receiver in other domains is, e.g. 20dB smaller than that from the signal source to the receiver. If the two domains are synchronized, the frequency synchronization error is, e.g. 100Hz, then the power leaked from the interference source to the carrier is less than -74dB, and the received SINR is higher than 74-20=54 dB. The interference is small enough to be ignored. If the two SLB domains are asynchronous, the adjacent frequency interference can only be suppressed by filter in general. The power leaked from the interference source to the carrier is about 20dB relative to the power of the interference source, and the received SINR is about 20-20=0 dB. It is not difficult to see that synchronization in time-frequency domain among multiple G nodes can substantially lower the interference among SLB communication domains, especially among the domains located on adjacent carriers.

To achieve the synchronization in time-frequency domain among multi-G nodes, a G node can send synchronization signal to multi-G nodes while other G nodes can monitor the signal. In the figure below, there are five G nodes, and the power-on sequence is order of G1, G5, G4, G2 and G3. The process of implementing time-frequency synchronization among 5 communication domains is as follow.

- Primarily, the G1 and the G5 nodes trigger synchronization signal sending, since no synchronization source can be detected at the time of power-on. As a result, the red synchronization set and the blue synchronization set are set up respectively.
- Then, with power-on of the G2 and the G4 nodes, the number of the red synchronization collection and the blue synchronization collection nodes is gradually increased. They are gradually expanded to cover the G3 nodes.
- In the next step, at the time of power-on, the G3 node detects the existence of red synchronization set and blue synchronization set, and gets aware that each synchronization set consists of two G nodes. The range between the G3 and the G4 nodes is closer, so the blue synchronization set provide better coverage for G3, and the G3 joins the blue synchronization set.
- At last, the G2 node and the G1 node are transferred from the red synchronization set to the blue synchronization set with more nodes in turn, and finally all nodes are in the blue synchronization set. All synchronizations are accomplished.

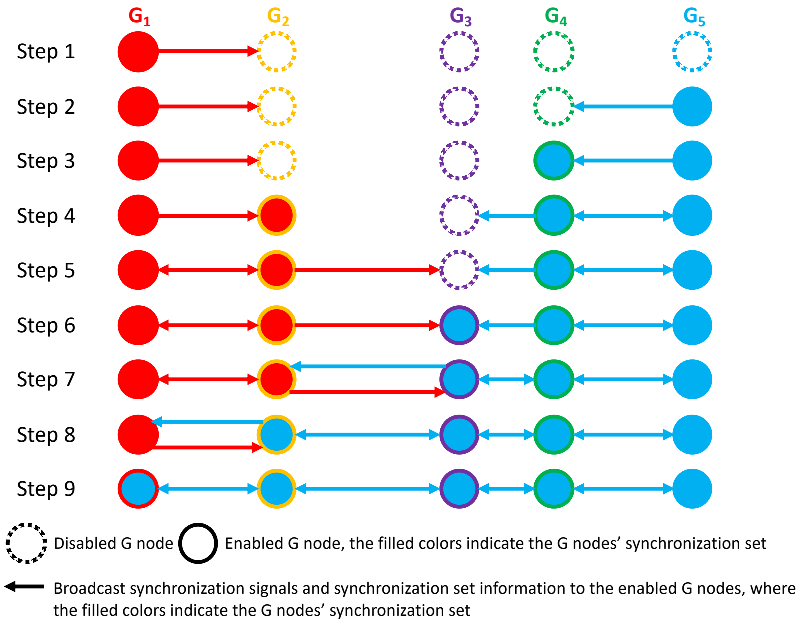


Figure 3-7 Schematic Diagram of Multi-node Synchronization in Time and Frequency Carriers

3.4.2 Multi-domain Resource Coordination

To coordinate the resource among multiple communication domains, the SLB system allows a G node in advanced SparkLink communication domain to allocate resource pools to other communication domains through broadcast. Operating in different carrier channels is a natural choice for the resource pools in different communication domains, while the resource pools in different communication domains on the same carrier resort to different symbols. On the carrier containing an advanced communication domain, the G node in the advanced communication domain indicates the other communication domains to use orthogonal resource pools in the time domain through the system messages. This is to avoid the communication links of the different communication domains from using the same resources.

Figure 3.8 illustrates an example of using resources in the time division manner for two communication domains on the same carrier. In the resource pools of communication domains:

- The resources used for data transmission (G symbol and T symbol in the figure) are allocated at the granularity of symbol, and repeated in the cycle of radio frames;
- The resources used for overhead transmission of the system (S symbol in the figure) are allocated at the granularity of overhead symbol, and are repeated in the cycle of superframe.

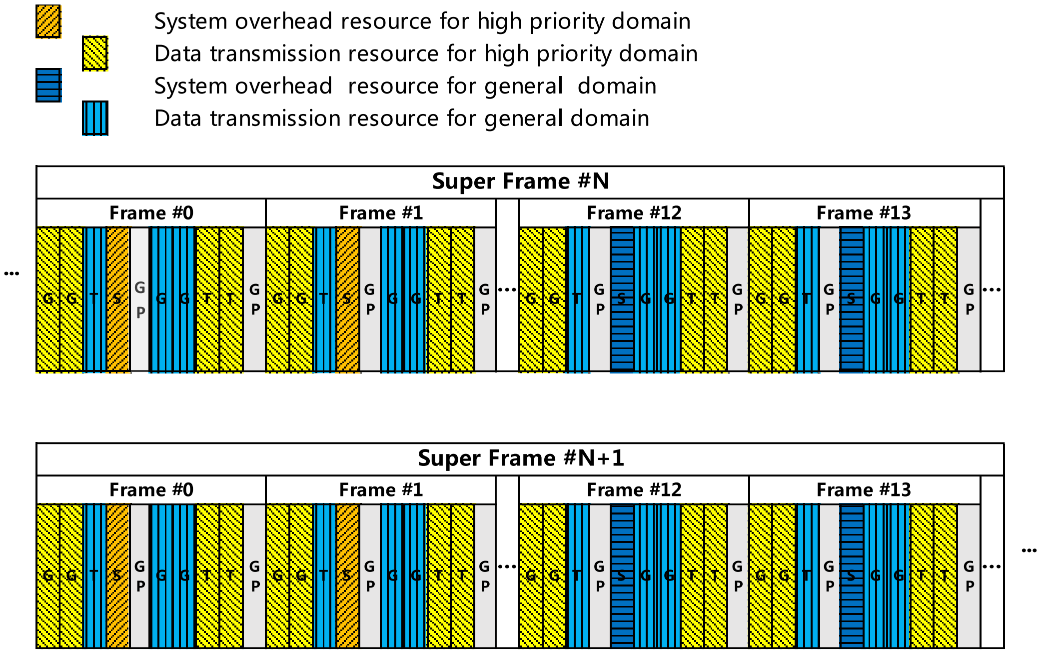


Figure 3-8 Schematic Diagram of Multi-domain Resource Coordination

In the time division manner of the resource pools, the G node in the communication domain sends synchronization signals and transmits data packets in its own resource pool. During the free period of its own communication domain, the G node can implement inter-domain synchronous tracking by receiving synchronization signals from other communication domains in the resource pools. This makes no influence on its service.

3.5 Low-power Design

In the SLB system, the G node can save power consumption of T node by configuring discontinuous transmission (DRX) in view of traffic characteristics. When the T node works in DRX state, it can receive data only on configured radio frames and superframes based on the configured receiving cycle and continuous receiving time of the G node in each cycle. Thereby, the power consumption of the T node is saved.

Besides configuring the DRX of T node through high-level signaling, the G-node can also dynamically indicate the T node to skip current discontinuous transmission cycle through the G-link control information. This mechanism saves the power consumption of the T node to a further extent.

3.6 Information Security

In respect of automobile applications, for example, short range wireless communication is a significant chain of information security system of in-vehicle network. In light of the idea of defense in depth, deploying abundant protective measures in the vehicular device access layer which is the closest to the external environment is beneficial to diminishing the security threats as early as possible.

3.6.1 Information Security Features

The SLB security system is designed in the direction of minimal security signaling and high-level security. Some security features can be found below.

Information security features	Explanation
Minimal security signaling	The information security mechanism is integrated into the association process with a minimal message exchange: • 5 messages in the scenario without context of information security; • 3 messages in the scenario with context of information security.
High strength credentials	The configuration mechanism of authentication credentials provides high-strength authentication credentials. Password complexity requirement is standardized.
Strong certification and authentication	The mandatory bidirectional identity authentication mechanism provides the information security capability of strong certification and authentication. Any unauthenticated devices are forbidden to access.
Double cipher algorithm	• The encryption algorithm is in support of 128-bit encryption algorithms, i.e. ZUC and AES; • All symmetric keys in the key architecture are 256-bit in length; • Double-cipher algorithm furnishes automobiles with double insurances in the whole life cycle. Sequential breakage is avoided.
Independent on/off of encryption and integrity protection	• The algorithm negotiation mechanism is in support of the negotiation of encryption and integrity protection algorithms. This enables introduction of new algorithms in the future; • Encryption and integrity protection are allowed to be turned on or off independently in line with the requirements of business scenarios.

3.6.2 Information Security Mechanism

The information security of SLB system defines the features of information security required for secured communication among SLB devices, such as configuration of authentication credentials, bidirectional authentication, negotiation and update of information security contexts, transmission security protection of data information, privacy protection, etc. All these furnishes transmission security protection with strong certification and authentication, and high-level information security.

3.6.2.1 Configuration of Authentication Credentials

The configuration of authentication credentials is used to configure same 256-bit shared key PSK between the G node and the T node. The SLB system is in support of three configuration schemes. Users enter the same password on the G node and the T node (the password must be in line with requirements for complexity). The password is then converted into 256-bit shared key PSK by means of cryptographic algorithm.

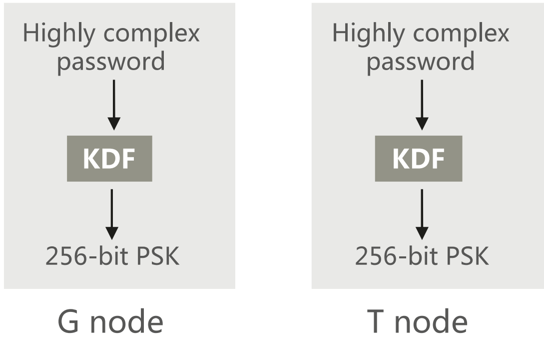


Figure 3-9 Conversion of User Password to PSK

3.6.2.2 Authentication and Negotiation of Security Parameters

Upon completion of the configuration of authentication credentials, when the G node and the T node build association under scenario without security context, it is necessary to perform bidirectional identity authentication based on the configured authentication credentials (256-bit key PSK).

The G node and the T node negotiate the security parameters during the bidirectional identity authentication, such as encryption algorithm, integrity protection algorithm, encryption key and integrity protection key. The negotiations of encryption algorithm and integrity protection algorithm are to negotiate the algorithm with the highest priority premised on the information security capabilities of both parties. The encryption key and the integrity protection key are derived from the master key acquired by the key negotiation algorithm (SM2, ECDH).

The SLB system is in support of privacy protection mechanism. After the G node and the T node establishes an association, the G node will assign a temporary ID to the T node. In the next association, the T node will take this temporary ID as the identity of the T node.

3.6.2.3 Information Security Protection for SLB Communications

Upon the completion of negotiation about the authentication information security parameters, the G node and the T node will protect the information security for SLB wireless communication based on the negotiated security parameters (cryptographic algorithm, key, etc.). The cryptographic algorithm shall support the 128-bit cryptographic algorithms, i.e. ZUC and AES. All symmetric keys in the key architecture are 256-bit in length.

The SLB system is in support of key update mechanism. Prior to expiration of the key or the repetition of the freshness parameters, the G node will trigger a process to update the key between the G node and the T node. This is to prevent the key from being used for too long.

4 Performance Evaluation of SLB System

4.1 Performance of Type I Data Transmission with Ultra-low Latency

Under AWGN channel, when QPSK~1024 QAM modulation are in use, the transmission performance of the Polar code and the RS code is shown in Figure 4-1. The Polar code with the same bit rate is 5~9dB better than the RS code at BLER of 10^{-5}.

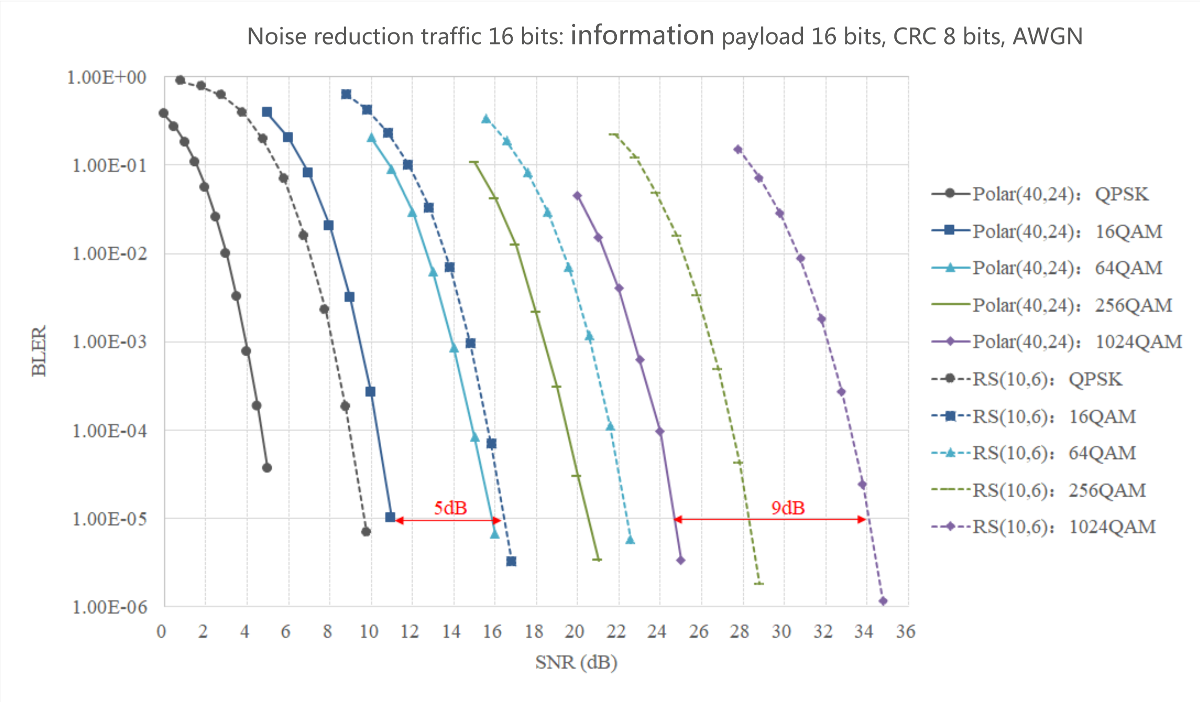


Figure 4-1 Comparison of Performance between Polar Code and RS Code under AWGN Channel (Number of Information Bits is 16-bit)

The Polar code is decoded by soft bit information (referred to as soft decision decoding), while the RS code is decoded by 0 and 1 bits after the decision (referred to as hard decision decoding). Theoretically, the soft decision decoding with the same bit rate is better than the hard decision decoding. In addition to that, the SLB system adopts cascade coding architecture of the CRC and the Polar, and high-performance SCL decoding can be used for the decoder. The CRC can not only assist the SCL decoder in choosing an optimal path, but also increase the Hamming Distance coding spectrum of the Polar code and the decoding performance as a result.

For the QPSK~256 QAM modulation, the RS code is superior to the Polar code by around 5.0~8.0 dB at BLER of 10^{-5} under the scenario that a single transmission symbol is polluted by burst interference. For the 1024 QAM modulation, the RS code is worse than the Polar code in terms of anti-burst capability (beyond the capability of error correction of the RS code limit). The RS code is a multi-level channel coding based on the Galois field. Each symbol of the Galois field is provided with multiple bits, so it can resist block of error codes by virtue of good anti-burst capability.

In view of data services with ultra-low latency, the Polar code and the RS code have their own advantages under conditions of random interference and burst interference. They are selected and configured depending on scenarios of actual application.

For the Type I data transmission, when 24-bit information size and 1024 QAM modulation are adopted, 7 resource elements are needed for the data packet in each channel. A radio frame structure with normal cyclic prefix can support transmission of 35 channels.

4.2 Performance of Type II Data Transmission

As seen in Figure 4-2, the SNR gap between the adjacent MCS in Type II data transmission is basically identical, around 1.0dB. This is favorable for MCS to match channel characteristics more closely and guarantees smoother and more stable throughput performance.

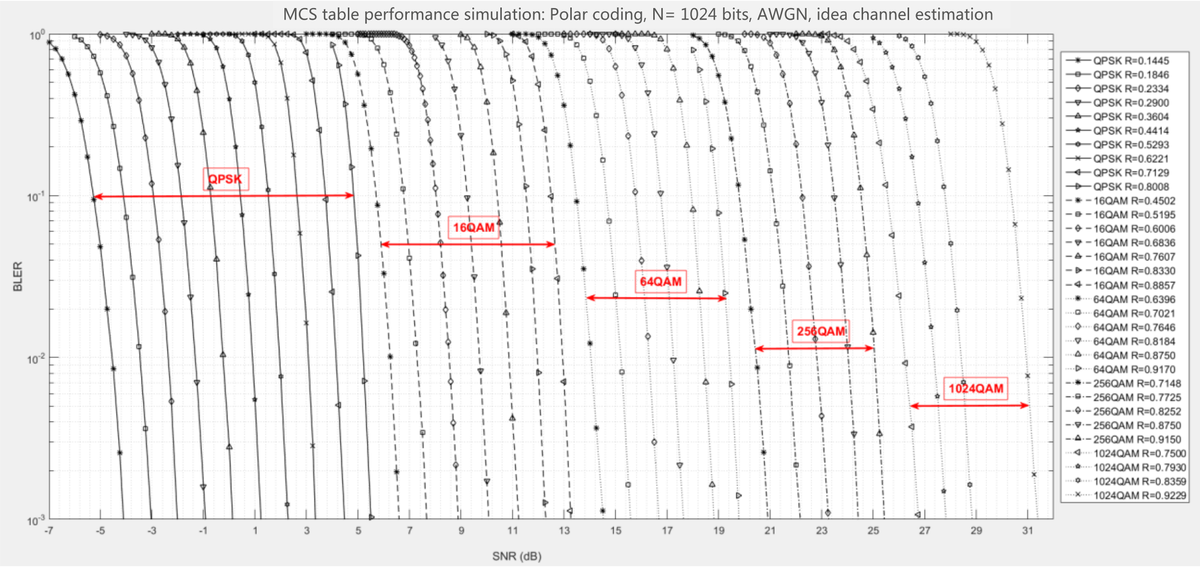


Figure 4-2 MCS Performance of Data Transmission with Large Packet/High Traffic (under AWGN Channel, Ideal Channel Estimation, N=1024-bit MCS0~31)

For the Type II data transmission, the lowest SNR working point supported by the SLB system is -5.0 dB. Under the condition of AWGN channel, in the case of SNR=-5.0 dB, initial transmission of BLER<0.1 can be achieved, while in the case of SNR=31 dB, 1024 QAM, and bit rate R=0.9229, the initial transmission BLER<0.1 can be achieved.

The type II data transmission supports scheduling granularity of 125 μs. Each symbol accommodates a maximum multiplex of data from 10 T nodes. Therefore, 80 channels of data transmissions is supported per superframe, which is 1 ms.

4.3 High Reliability Transmission

4.3.1 Hybrid Automatic Repeat Request

4.3.1.1 Comparison of Performance between CC and IR Retransmission

The following example illustrates comparison of performance between the CC and the IR retransmission on the condition of the Polar (1503,1720), R=7/8, up to 4 times retransmission, and channel bit of each transmission is 1720 in length. The link performance of TB retransmission and that of CBG retransmission is identical. In comparison with the performance pf no-retransmission, the advantage is around 8.0 dB at BLER of 10^{-2}. The IR-HARQ earns of around 2.0 dB advantage at BLER of 10^{-2} relative to CC. Generally, the higher the bit rate, the greater the gain of IR-HARQ in comparison with CC-HARQ; while the lower the bit rate, and the smaller the gain.

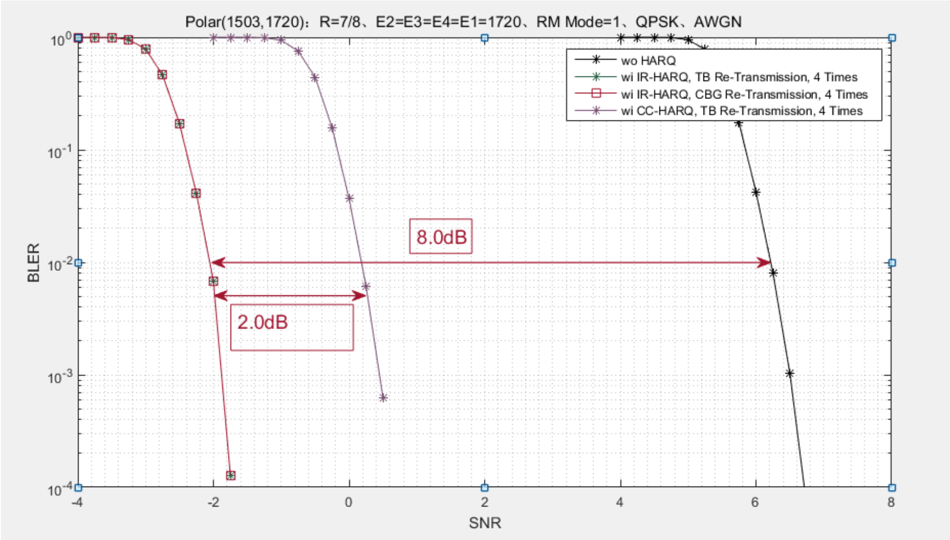


Figure 4-3 Comparison of Performance between CC/IR Retransmissions

4.3.1.2 Comparison of Throughput between ARQ Retransmission and HARQ Retransmission

The HARQ retransmission is used to boost transmission efficiency and throughput of the SLB system. In the case of the initial transmission BLER of the coded block is 10%, the maximum gain of throughput of HARQ relative to that of the ARQ is indicated in the following table.

Table 4-1 Gain of Throughput of HARQ Relative to ARQ

CBs contained in the TB	**TB retransmission**	**Hybrid transmission of CBG**
4	13%	38%
8	48%	110%

4.3.1.3 Feedback Latency of HARQ

The SLB system is in support of ACK feedback with 1 ms latency and retransmission combination with 2 ms latency. This can not only enhance the reliability of transmission, but also conform to the application requirements for low latency.

4.3.1.4 Summary of HARQ Performance

During the TB and the CBG retransmissions, different performance gains can be acquired under different scenarios such as retransmission times, number of retransmitted channel bits, code rate, and so on. In the case of high code rate, such as R=7/8, when the working point is BLER=10^{-2}, IR-HARQ can get the performance gains of more than 2.0 dB in comparison with that of the CC-HARQ. However, the implementation of CC-HARQ is less complex than that of IR-HARQ. In a real applications, it is up to be chosen in line with the requirements for actual performance and complexity.

The HARQ is used for the SLB system. In the case that there are 4 to 8 CBs, the gain of throughput of the HARQ is from 13% to 110% in comparison with that of the ARQ retransmission at the data link layer.

4.3.2 Anti-frequency Selective Fading

4.3.2.1 Frequency Selective Scheduling

In the course of wireless transmission, signals arrive at the receiving end after passing through multiple paths. Superposition of multi-path signals at receiver results in difference in the fading coefficients of different channels which corresponds to different sub-carriers. That is termed frequency selective fading.

Take the fading characteristics in the frequency domain of the in-vehicle channel model as an example, Figure 4-4 shows the fading characteristics in the frequency domain of passenger car (10 ns extended latency), and commercial car (35 ns extended latency), on 64 sub-carriers with a sub-carrier bandwidth of 480kHz. It can be learned that the channel coefficients of different sub-carriers are highly different. The channel is highly frequency selective fading. The frequency selectivity under the scenario of 35 ns extended latency is stronger.

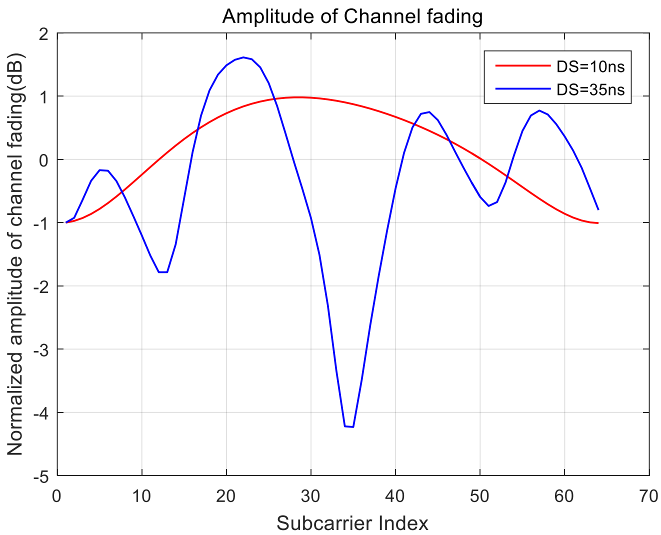


Figure 4-4 Fading Characteristics of Frequency Domain of In-vehicle Channels

4.3.2.2 Performance Evaluation

Under scenarios of wireless transmission with a typical latency spread of 35 ns, the performance gains of decentralized scheduling of discrete sub-carriers in comparison with that of random continuous scheduling of sub-carriers are specifically as below:

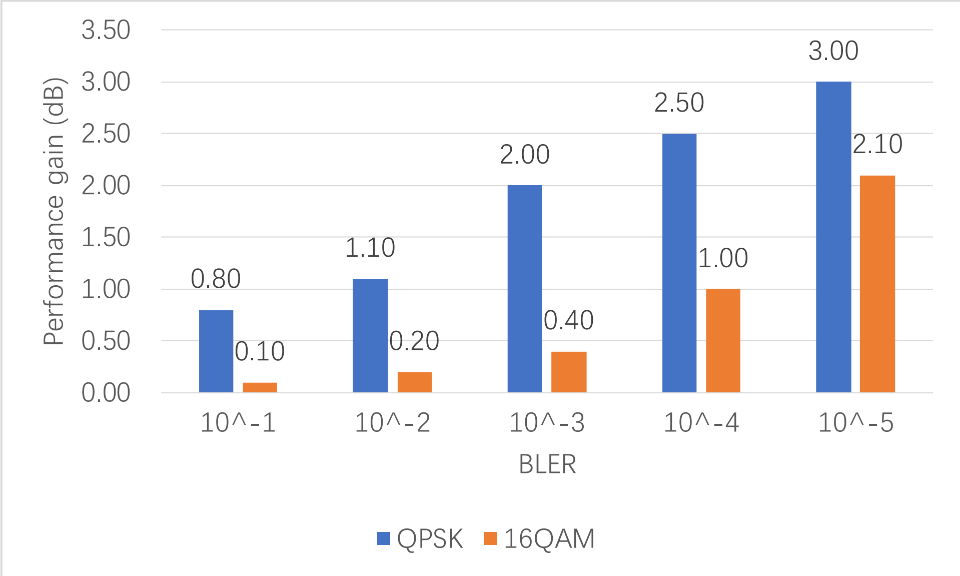


Figure 4-5 Performance Gains of Discrete Scheduling of Sub-carriers in Comparison with Continuous Scheduling of Sub-carriers

When the latency of multipath spread is 35 ns, the performance of discrete scheduling of sub-carriers is superior to that of continuous scheduling of sub-carriers. The lower the BLER, the greater the advantage.

4.4 Summary of Performance Evaluation

The technical performance of the SLB air interface is summarized in Table 4-2 below.

Table 4-2 Summary of Technical Performances of SLB

Item	**Performance**
Peak rate	The peak rate of G link of 20 MHz single carrier is 920 Mbps (8x8MIMO) The peak rate of T link of 20 MHz single carrier is 460 Mbps (4x4MIMO)
Latency	The latency of unidirectional transmission is less than 20 μs.
High reliability	The transmission reliability is greater than 99.999%.
Anti-interference	The RS channel coding and the Polar channel coding, support CBG hybrid retransmission, minimum working SNR of -5 dB.
Synchronization	The precision of synchronization is less than 1 μs.
Multi-service concurrency	35-channel real-time audio streams are concurrent on a single carrier. 80-channel data transmissions are concurrent in 1ms.

5 Summary and Future Direction

In conclusion, the SLB system can meet the requirements for applications with ultra-low latency such as active noise cancellation and industrial manufacturing by defining ultra-short time slot frame structure and ultra-short radio frame scheduling cycle which is 20.833 μs. The high-performance channel coding, HARQ retransmission at physical layer, discrete scheduling of single sub-carriers as well as other technologies are adopted to implement high-reliability transmissions, which meet the requirements for applications with high reliability at the level of over 99.999%. It becomes an alternative to replace wired connection at the terminal device. The multi-domain cooperative technologies boost the resource usage efficiency and alleviate the interference among SparkLink networks. The minimal security signaling and high-level security information features are designed to conform to the requirements of high-security in-vehicle applications. The report evaluates the performance of key technologies of SLB under typical scenarios. The SparkLink alliance will launch further research for performance evaluation in more applications, more scenarios and different channels conditions.

The service development is endless, which will certainly push forward the technology development. Starting with the SLB system, the SparkLink technology will continuously evolve in the direction of higher efficiency, lower power consumption, larger bandwidth, more antennas and so on in the future. More functions such as ranging and networking will be supported. Moreover, an evolution system characterized by higher data rate, lower cost, lower power consumption and higher coverage capability will be introduced. These will be covered in the future version of SparkLink Release 2. The purpose is to enable a variety of applications and scenarios. This makes SparkLink a unique role in the field of short range wireless communications.