Spectral Efficiency Classification Schemes for Future Network Communications(SECS)

Zhongsheng Wang
State and Provincial Joint Engineering Lab. of Advanced Network, Monitoring and Control
Xi'an Technological University
No.2 Xuefu Middle Road, Weiyang district
Xi'an, Shaanxi, China
E-mail: 59483672@qq.com

Qingsong Zhang
State and Provincial Joint Engineering Lab. of Advanced Network, Monitoring and Control
Xi'an Technological University
No.2 Xuefu Middle Road, Weiyang district
Xi'an, Shaanxi, China

***Abstract*—Future Network is an project created and managed by ISO/IEC. The project has produced technical reports in ISO/IEC TR 29181 series and is in the process setting architectures and protocols. The project is known for its distinctive "clean slate design" approach and works on fundamental structural innovations to allow Future Network deliver its promises. Simultaneously, ISO/IEC Future Network should prepare itself for future breakthrough in SE technology and make plans to adapt Future Network to the fast changing "Post Shannon Era" technological revolutions. Using reference to the mechanism of radio frequency band classifications, this standard classifies the spectral efficiencies of the MCS systems, so as to facilitate the classification, discussion, evaluation and comparison of the efficiency of the spectrum of information systems.**

Keywords-Future Network Communications; Spectral Efficiency Classification Schemes（SECE）; International Standardization

I. INTRODUCTION

This paper is the first international standard proposal (draft) of The Ultra Limited Future Network. The development of this proposal (draft) is supported by JTC 1/SC 6/WG 7 working team. The application leader is Dr. Qingsong Zhang (Nanjing Bofeng), and the proposal is proposed by Professor Wang Zhongsheng (Xi 'an Technological University). Itu-r and ICAO acted as the focal points during the development process, while cooperating with ECMA, 3GPP and IEEE.

This standard is prepared in accordance with the provisions of the following three documents :

ISO/IEC TR 29181： Future Network： Problem Statement and Requirements, parts 1-9.

ITU-R SM.856-1：New Spectrally Efficient Techniques and Systems (1992-1997).

ITU-R SM.1046-3：Definition of Spectrum Use Efficiency of a Radio System (2017-09-06).

As an international standard proposal in the field of "industry, Innovation and Infrastructure" , This standard provides classification schemes for MCS Spectral Efficiencies including:

Definition of Modulation and Coding Scheme Spectral Efficiency (MCS SE).

- Method for classification of MCS SE.
- Naming system of MCS SE.

- Examples of the recommended use of SECS.
- Potential impact on Future Network Standardization.
- The differences between SE and Spectral Utilization Efficiency.

II. DEVELOPEMNT BACKGROUND

Spectrum efficiency is a key index to measure the level of development of information and communication systems, which can reflect or affect many key performances, including the efficient use of spectrum resources, higher information transmission rates and greater channel capacity and so on. The higher the spectrum efficiency, higher the utilization rates of resource-constrained spectrum resources, higher transmission rates, and greater the information throughput. Therefore, improving spectrum efficiency is one of the most critical objectives of ICT innovation.

With the development of digital information and computer science and technology, the level of spectrum efficiency of information and communication systems is also improving. 20 years ago at the turn of the century, the spectral efficiency of communication systems was still at a very low level of 1-2 bits. After 20 years of development, some areas of technology are already using 10-bit spectrum efficiency technology. Some areas have incorporated 12-bit spectrum efficiency into next-generation technical standard planning.

Based on historical experience and technical characteristics, the speed of improvement of the spectrum efficiency level of information and communication systems will slow down in the future, reaching 16 bits in 20 years and 20 bits in 45 years, which is the result of the congenital limitations of M-QAM modulation and demodulation technology, a key mechanism for improving spectrum efficiency. However, it cannot be ruled out that the emergence of new theories and new technologies in the basic layer of information and communication physics may lead to rapid improvement of spectrum efficiency. An article published in IEEE Access in 2018 by Chinese scientist Professor Li Daoben shows that information systems with up to 2000 bits spectrum efficiency can be achieved using the overlapping multi-domain multiplexing technology (OVXDM) he invented.

High spectrum efficiency will be the main manifestation of ICT levels in the post-Shannon era. In the next ten to twenty years, the discussion and evaluation criteria on the spectral efficiency of communication technology will exceed 20 bits and enter the category of hundreds of bits or even thousands of bits. Communication products will be increasing spectrum efficiency as the main sign of technical level and service capability.

In the existing ITU international standards, RSM.1046-3 provides for the definition of spectrum utilization efficiency and the evaluation methods for the utilization of various systems spectrum, but does not provide a mechanism for classifying MCS spectrum efficiency. Such a mechanism is necessary to discuss, analyze, evaluate, select and manage the spectrum efficiency of future communication systems.

For example, in some technical or policy documents, the discussion of "low spectrum efficiency" and "high spectrum efficiency" can often be seen, but there are no technical specifications to define and interpret these two concepts. How many bits of spectrum efficiency is "low spectrum efficiency"? How many bits of spectrum efficiency is "high spectrum efficiency"? Some documents refer to a 10-bit system as "high spectrum efficiency", so what category does 16-bit, 20-bit, 32-bit, or even 128-bit spectrum efficiency fall into? Therefore, the two-level classifications of "low spectrum efficiency" and "high spectrum efficiency" cannot meet the future development trend and the need for more accurate spectrum efficiency classification.

In radio spectrum management, there are many classification schemes for spectrum resources. One scheme is dividing frequency resources (RE) into kilohertz, megahertz, gigahertz, and terahertz. Another method is based on wavelength, dividing RE into categories such as Ultra-Long Wave, Long Wave, Medium Wave, Short Wave, Ultra-Short Wave, Microwave, etc. There is also a classification method by frequency, VLF, Low Frequency, Medium Frequency, Medium High Frequency, High Frequency, VHF, UHF, UHF, UHF, UHF and so on. Another band division method marked by the English Alphabet, dividing RE into L-Band, S-Band, C-Band, X-Band, Ku-Band, K-Band, Ka-Band, and so on.

Using reference to the mechanism of radio frequency band classifications, this standard classifies the spectral efficiencies of the MCS systems, so as to facilitate the classification, discussion, evaluation and comparison of the efficiency of the spectrum of information systems.

III. Abbreviations and Terms

A. Abbreviations

TABLE I. ABBREVIATIONS OF TERMS

Abbreviations	Full Name
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
FN	Future Network
OFDM	Orthogonal Frequency Division Multiplexing
OCCS	Over-Capacity Communication Systems
OVXDM	Overlapped X Domain Division Multiplexing
OVTDM	Overlapped Time Domain Division Multiplexing
QAM	Quadrature Amplitude Modulation
RE	Resource Element
RSE	Relative Spectral Efficiency
SE	Spectral Efficiency
SEI	Spectral Efficiency Index
SUE	Spectrum Utilization Efficiency
TSEI	Typical SE Indicator

B. Terms and Definitions

Over-Capacity Communication：Exchange of information that has higher capacity than the Shannon Limit.

OVXDM: An innovative way of modulation and coding that utilizes multiple domains such as time, frequency, spatial and coding overlapping and multiplexing to achieve higher SE, no coding overhead, higher coding gain and low decoding complexity.

MCS Spectral Efficiency：The maximum amount of useful information sent in one second and per Resource Element (RE in Hz) through a communication system based on its modulation and Coding schemes.

Spectral Utilization Efficiency：the product of the frequency bandwidth, the geometric (geographic) space, and the time denied to other potential users: $U = B \cdot S \cdot T$

Shannon Limit: Also known as Shannon Capacity, defined by Claude Shannon in the 1940s setting the limit of theoretically highest rate of information transmission under certain noise levels for a single channel.

Future Network: An International Standard project developed and managed by ISO/IEC for a new network system based on the clean slate design approach. Publications include ISO/IEC TR 29181 and ISO/IEC 21558-21559.

IV. MCS SE Classification Principles

A. Differentiating SE from USE

The SE (Spectral Efficiency) defined in this standard shall not be confused with the Spectrum Efficiency in ITU-RSM.1046-3 (2017). The TABLE II lists these differences:

TABLE II. COMPARISON OF THIS STANDARD WITH ITU STANDARDS

	Comparison Objective	**This Standard**	**ITU**
1	Source	ISO/IEC	ITU-RSM.1046-3
2	Term	Spectral Efficiency	Spectrum Efficiency
3	Abbreviation	MCS SE	USE
4	Factor	bps/Hz	$U = B \cdot S \cdot T$
5	Considering factors	● Capacity ● Resource element (Hz) ● Time (second)	● Bandwidth ● Geometric space (area) ● Time
6	Improvement method	● Modulation ● Channel Coding	● Antenna Directivity ● Geographical Spacing ● Frequency Sharing ● Orthogonal Frequency use ● Time-sharing ● Time division
7	SE Gain potentials	Sky is the limit	Limited potential
8	Perspective	Communication system	User
9	Service	For all	Denying others

The MCS spectrum efficiency defined in this standard refers to the number of bits of valid information transmitted per second per hertz frequency resource through technical means such as modulation and channel coding.

The value of MCS spectrum efficiency is relatively fixed. So long as we know the modulation mechanism and channel coding method used, we can deduct the performance level of the theoretical MCS spectrum efficiency. Because of the small variety of modulation mechanism and channel coding methods, some mainstream technology applications are very broad, such as M-QAM technology in the field of modulation and Turbo code and LDPC code in the field of channel coding. Therefore, MCS spectrum efficiency can be used as a general and important index to assess the performance level of ICT in different fields.

B. Deciding the Range of SE

Currently, communication systems having SE no higher than 10 bps/Hz, some systems may reach 12 bps/Hz in about five years from now. At such a low SE rate, there is no need for a standard classify SE levels.

However, standards are expected to identify future trends, provide directions for technological development, and to have market relevance lasting decades. Since there have been technical trends indicating potential breakthrough in spectral efficiency, this standard takes into account of SE in the hundreds and thousands bps/Hz range.

C. MCS SE Classification Architecture

MCS SE classification system contains three schemes described in TABLE III.

TABLE III. MCS SE CLASSIFICATION SYSTEM DESCRIPTION SCHEME

Scheme	Feature	Format	Purpose
A	Two Letter	#-SE	Indicating specific product SE capabilities
B	Three Letter	VSE	Group SE into category of levels
C	Four letter	DDSE	Provide an alternative and simpler classification of SE
D	Two levels	Lower	Make broader range

V. MCS SPECTRAL EFFICIENCY CLASSIFICATION SCHEMES

A. MCS SE Classification A: Two Letter Scheme

The two letter MCS SE classification system uses only two letters "SE" with numbers indicating specific bps/Hz. It is used not for referring to a level or class, but rather to indicate specific SE performance of a product.

Expression description: number of bits (omitting "s/Hz") with"-"followedby"SE", indicating "spectral efficiency at specific bps/Hz"."

Example:

"56-SE", which means spectral efficiency rate at 56 bps/Hz.

"256-SE", which means spectral efficiency rate at 256 bps/Hz.

"1008-SE", which means spectral efficiency rate at 1008 bps/Hz.

B. MCS SE Classification B: Three Letter Scheme

TABLE IV. THREE LETTER SCHEME IN MCS SE CLASSIFICATION SCHEME

SE Index	Index name	Full Title	SE Range（bps/Hz)	TSEI*（bps/Hz)
SEI 1	BSE	Basic Spectral Efficiency	0.1~2.0	2
SEI 2	LSE	Low Spectral Efficiency	2.1~5.9	5
SEI 3	MSE	Medium Spectral Efficiency	6~10.9	10
SEI 4	HSE	High Spectral Efficiency	11~15	15
SEI 5	VSE	Very-High Spectral Efficiency	16~20	20
SEI 6	USE	Ultra-High Spectral Efficiency	21~32	32
SEI 7	SSE	Super Spectral Efficiency	33~64	64
SEI 8	OSE	One-hundred level spectral efficiency	65~128	128
SEI 9	ESE	Extreme Spectral Efficiency	129~256	256
SEI 10	DSE	500 Spectral Efficiency	257~512	512
SEI 11	JSE	Jump Level spectral efficiency	513~999	768
SEI 12	1-KSE	1K Spectral efficiency	1000~1999	1024
SEI 13	2-KSE	2K Spectral efficiency	2000~2999	2048
SEI 14	3-KSE	3K Spectral efficiency	3000~3999	3072
SEI 15	4-KSE	4K Spectral efficiency	4000~4999	4096
SEI 16	XSE	X Spectral efficiency	5000~6999	6144
*TSEI is the Typical SE indicator for its class.				

As Spectral Efficiency increases, the gaps among the Three Letter Scheme also expand. In SEI 4 and SEI 5, for example, there are only 4 bits differences separating the high from the low. In SEI 9, the gaps are over 200 bits and in SEI 12, the gaps grow to one thousand.

It is anticipated that there will be need for more accurate SE references or comparisons for the upper part of the Three Letter Schemes. In that case and when technological development requires such changes, the Three Letter Scheme may use the following extension Scheme.

Rule 1. No extension needed for indexes SEI 1~6.

Rule 2. The extension in grouped into two index tables, one for SE lower than 1000 bps/Hz（TABLE V） and the other is for SE above 1000 bps/Hz（TABLE VI）.

Rule 3. A single double digit decimal number is added to index name to indicate extension numbers.

Rule 4. For SSE and OSE indexes, 5bps/Hz is used as bases for extension unit.

Rule 5. For ESE and DSE indexes, 10bps/Hz is used as bases for extension unit.

Rule 6. For JSE indexes, 20bps/Hz is used as bases for extension unit.

Rule 7. For KSE indexes, 50bps/Hz is used as bases for extension unit.

Rule 8. For XSE indexes, 100bps/Hz is used as bases for extension unit.

TABLE V. EXTENDED INDEX OF SE LOWER THAN 1000 BPS/HZ

SEI 7 EXT Index	33-64 SE RANGE	SEI 8 EXT Index	65~128 SE RANGE	SEI-9 EXT Index	129-256 SE RANGE	SEI 10 EXT Index	257~512 SE RANGE	SEI 11 EXT Index	513~999 SE RANGE
SSE 1	33-38	OSE 1	65-69	ESE 1	129-139	DSE 1	257-269	JSE 1	513-539
SSE 2	39-43	OSE 2	70-74	ESE 2	140-149	DSE 2	270-279	JSE 2	540-559
SSE 3	44-49	OSE 3	75-79	ESE 3	150-159	DSE 3	280-289	JSE 3	560-579
SSE 4	50-55	OSE 4	80-84	ESE 4	160-169	DSE 4	290-299	JSE 4	580-599
SSE 5	56-60	OSE 5	85-89	ESE 5	170-179	DSE 5	300-319	JSE 5	600-619
SSE 6	61-64	OSE 6	90-94	ESE 6	180-189	DSE 6	320-329	JSE 6	620-639
		OSE 7	95-99	ESE 7	190-199	DSE 7	330-339	JSE 7	640-659
		OSE 8	100-104	ESE 8	200-209	DSE 8	340-349	JSE 8	660-679
		OSE 9	105-109	ESE 9	210-219	DSE 9	350-359	JSE 9	680-699
		OSE 10	110-114	ESE 10	220-229	DSE 10	360-369	JSE 10	700-719
		OSE 11	115-119	ESE 11	230-239	DSE 11	370-379	JSE 11	720-739
		OSE 12	120-124	ESE 12	240-249	DSE 12	380-389	JSE 12	740-759
		OSE 13	125-128	ESE 13	250-256	DSE 13	390-399	JSE 13	760-779
						DSE 14	400-409	JSE 14	780-799
						DSE 15	410-419	JSE 15	800-819
						DSE 16	420-429	JSE 16	820-839
						DSE 17	430-439	JSE 17	840-859
						DSE 18	440-449	JSE 18	860-879
						DSE 19	450-459	JSE 19	880-899

						DSE 20	460-469	JSE 20	900-919
						DSE 21	470-479	JSE 21	920-939
						DSE 22	480-489	JSE 22	940-959
						DSE 23	490-499	JSE 23	960-979
						DSE 24	500-512	JSE 24	980-999

TABLE VI. EXTENDED INDEX OF KSE AND XSE（SE ABOVE 1000 BPS/HZ）

SEI 12 EXT Index	1000-1999 SE RANGE	SEI 13 EXT Index	2000-2999 SE RANGE	SEI 13 EXT Index	3000-3999 SE RANGE	SEI 14 EXT Index	4000-4999 SE RANGE	SEI 15 EXT Index	5000-6999 SE RANGE
1KSE 1	1000-1049	2KSE 1	2000-2049	3KSE 1	3000-3049	4KSE 1	4000-4049	XSE 1	5000-5099
1KSE 2	1050-1099	2KSE 2	2050-2099	3KSE 2	3050-3099	4KSE 2	4050-4099	XSE 2	5100-5199
1KSE 3	1100-1140	2KSE 3	2100-2140	3KSE 3	3100-3140	4KSE 3	4100-4140	XSE 3	5200-5299
1KSE 4	1150-1199	2KSE 4	2150-2199	3KSE 4	3150-3199	4KSE 4	4150-4199	XSE 4	5300-5399
1KSE 5	1200-1249	2KSE 5	2200-2249	3KSE 5	3200-3249	4KSE 5	4200-4249	XSE 5	5400-5499
1KSE 6	1250-1299	2KSE 6	2250-2299	3KSE 6	3250-3299	4KSE 6	4250-4299	XSE 6	5500-5599
1KSE 7	1300-1349	2KSE 7	2300-2349	3KSE 7	3300-3349	4KSE 7	4300-4349	XSE 7	5600-5699
1KSE 8	1350-1399	2KSE 8	2350-2399	3KSE 8	3350-3399	4KSE 8	3350-4399	XSE 8	5700-5799
1KSE 9	1400-1449	2KSE 9	2400-2449	3KSE 9	3400-3449	4KSE 9	4400-4449	XSE 9	5800-5899
1KSE 10	1450-1499	2KSE 10	2450-2499	3KSE 10	3450-3499	4KSE 10	4450-4499	XSE 10	5900-5999
1KSE 11	1500-1549	2KSE 11	2500-2549	3KSE 11	3500-3549	4KSE 11	4500-4549	XSE 11	6000-6099
1KSE 12	1550-1599	2KSE 12	2550-2599	3KSE 12	3550-3599	4KSE 12	4550-4599	XSE 12	6100-6199
1KSE 13	1600-1649	2KSE 13	2600-2649	3KSE 13	3600-3649	4KSE 13	4600-4649	XSE 13	6200-6299
1KSE 14	1650-1699	2KSE 14	2650-2699	3KSE 14	3650-3699	4KSE 14	4650-4699	XSE 14	6300-6399
1KSE 15	1700-1749	2KSE 15	2700-2749	3KSE 15	3700-3749	4KSE 15	4700-4749	XSE 15	6400-6499
1KSE 16	1750-1799	2KSE 16	2750-2799	3KSE 16	3750-3799	4KSE 16	4750-4799	XSE 16	6500-6599
1KSE 17	1800-1849	2KSE 17	2800-2849	3KSE 17	3800-3849	4KSE 17	4800-4849	XSE 17	6600-6699
1KSE 18	1850-1899	2KSE 18	2850-2899	3KSE 18	3850-3899	4KSE 18	4850-4899	XSE 18	6700-6799
1KSE 19	1900-1949	2KSE 19	2900-2949	3KSE 19	3900-3949	4KSE 19	4900-4949	XSE 19	6800-6899
1KSE 20	1950-1999	2KSE 20	2950-2999	3KSE 20	3950-3999	4KSE 20	4950-4999	XSE 20	6900-6999

C. MCS SE Classification C: Four Letter Scheme

TABLE VII. FOUR LETTER SCHEME IN MCS SE CLASSIFICATION SCHEME

	Title	**Whole Title**	**SE (bps/Hz)**	**Relative B categories**
1	SDSE	Single Digits Spectral Efficiency	0-9	BSE，LSE，MSE
2	DDSE	Double Digits Spectral Efficiency	10-99	HSE，VSE，USE，SSE，OSE
3	TDSE	Triple Digits Spectral Efficiency	100-999	ESE，DSE，JSE
4	QDSE	Quadruple Digits Spectral Efficiency	1000-9999	M-KSE，XSE

D. MCS SE Classification D: Comparative Scheme

TABLE VIII. COMPARISON SCHEME OF MCS SE CLASSIFICATION SCHEME

	Title	Whole Title	SE (bps/Hz)	Relation with other categories
1	L	lower	none	All levers below a specific class
2	H	higher	none	All levers above a specific class

VI. SAMPLE OF MAKING REFERENCES

A. Making reference to the standard

This standard is giving the original title “OCC-STD 21001”, established by the developer institution. When adopted into other standard systems such as China’s Industry standard, National Standard, ISO standard and ITU standard, the title and number may be reassigned. Before then, “OCC-STD 21001” is the only source for MCS SE classifications.

In the future, when making references to the classification schemes, it is recommended that a note is included in the document that the SE classifications are defined in “OCC-STD 21001 (2021)” developed by Nanjing Bofeng Communication Technologies Ltd.

B. Examples Referring Specific Classification Levels

- In 2023, the company is expected to deliver communications systems utilizing innovative modulation schemes that can provide VSE level spectral efficiency defined in “OCC-STD 21001”.
- Comparing MCS spectral efficiency, the two products belong to two generations with Sample A is only at the VSE level while Sample B contains USE modulation technology.
- Industry consensus is that the KSE level spectral efficiency technology is only a few years away.
- Some experts anticipate that entering the next decade, communication systems can reach the QDSE level Spectral Efficiency as defined in the Four Letter Classification System in “OCC-STD 21001”.

C. Recommended Use of Comparative Scheme

- When use these two expressions, they shall be accompanied with reference to a specific SE class level.
- Example:
- So far, the most advanced wireless communication system have MCS spectral efficiencies lower than the VSE level as defined in “OCC-STD 21001”.
- It is expected that products with higher spectral efficiency than the VSE level will enter service by 2025.
- The new system has backward compatibility design providing continuous support to MCS SE levels of.

D. Referring Specific SE Rate

When referring specific SE rate, the following statement are examples:

- “Bofeng.com offers two radio systems that operate at SSE level spectral efficiency as defined in “OCC-STD 21001”. Radio A system has 48-SE modulation scheme and Radio B system has 64-SE capabilities.
- Product specification: MCS SE: 32-SE, 48-SE and 64-SE. This description

indicates the system contains three types of MCS supporting three SE rates.

VII. Potential Impact on Future Network Standardization

Future Network is an International Standardization project created and managed by ISO/IEC. The project has produced technical reports in ISO/IEC TR 29181 series and is in the process setting architectures and protocols. The project is known for its distinctive "clean slate design" approach and works on fundamental structural innovations to allow Future Network deliver its promises.

Making MCS-SE classification system a Future Network standardization item can benefit the project in many ways. Firstly, ISO/IEC Future Network will become the first international standards adopting a MCS SE classification system; Secondly, Other standardization bodies may adopt this system or make normative reference to this standard; Thirdly, ISO/IEC Future Network becomes the first standard indicating future trends in MCS SE development; Fourthly, the inclusion of three digits and four digits MCS SE in Future Network standards will reflect the huge potential of network performance and capabilities; and finally, the successful adoption of this standard will open the door of ISO/IEC Future Network standards to future technologies that achieve higher and higher MCS SE.

ISO/IEC Future Network should prepare itself for future breakthrough in SE technology and make plans to adapt Future Network to the fast changing "Post Shannon Era" technological revolutions.

References

[1] T. M. Cover and J. A. Thomas, Elements of Information Theory. Hoboken, NJ, USA: Wiley, 2006.

[2] L. Daoben, Waveform Coding Theory of High Spectral Efficiency-OVTDM and Its Application. Beijing, China: Scientific, 2013.

[3] L. Daoben, ''A novel high spectral efficiency waveform coding–OVFDM,'' China Commun., vol. 12, no. 2, pp. 61–73, Feb. 2015.

[4] S. G. Wilson, Digital Modulation and Coding. Englewood Cliffs, NJ, USA: Prentice-Hall, 1996.

[5] L. Daoben, ''A novel high spectral efficiency waveform coding-OVTDM,'' Int. J. Wireless Commun. Mobile Comput., vol. 2, nos. 1–4, pp. 11–26, Dec. 2014.

[6] L. Daoben, Statistical Theory of Signal Detection and Estimation, 2nd ed. Beijing, China: Scientific, 2005

[7] J. G. Proakis, Digital Communications. New York, NY, USA: McGraw-Hill, 2001.

[8] G. J. Foschini, ''Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas,'' Bell Labs Tech. J., vol. 1, no. 2, pp. 41–59, 1996.

[9] G. J. Foschini and M. J. Gans, ''On limits of wireless communications in a fading environment when using multiple antennas,'' Wireless Pers. Commun., vol. 6, no. 3, pp. 311–335, Mar. 1998

[10] S. Wu, L. Kuang, Z. Ni, J. Lu, D. D. Huang, and Q. Guo, ''Low-complexity iterative detection for large-scale multiuser MIMO-OFDM systems using approximate message passing,'' IEEE J. Sel. Topics Signal Process., vol. 8, no. 5, pp. 902–915, Oct. 2014.

[11] N. Wu, W. Yuan, H. Wang, Q. Shi, and J. Kuang, ''Frequency-domain iterative message passing receiver for faster-than-Nyquist signaling in doubly selective channels,'' IEEE Wireless Commun. Lett., vol. 5, no. 6, pp. 584–587, Dec. 2016.

[12] J. CØspedes, P. M. Olmos, M. SÆnchez-FernÆndez, and F. Perez-Cruz, ''Expectation propagation detection for high-order high-dimensional MIMO systems,'' IEEE Trans. Commun., vol. 62, no. 8, pp. 2840–2849, Aug. 2014.

[13] A. L. Swindlehurst, E. Ayanoglu, P. Heydari, and F. Capolino, ''Millimeterwave massive MIMO: The next wireless revolution?'' IEEE Commun. Mag., vol. 52, no. 9, pp. 56–62, Sep. 2014.

[14] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, ''Energy and spectral efficiency of very large multiuser MIMO systems,'' IEEE Trans. Commun., vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

[15] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, MIMO-OFDM Wireless Communication Technology With MATLAB. Beijing, China: PublishingHouse of Electronics Industry, 2013.

[16] Y. D. Zhang, M. G. Amin, and B. Himed, ''Altitude estimation of maneuvering targets in MIMO over-the-horizon radar,'' in Proc. IEEE 7th IEEE Sensor Array Multichannel Signal Process. Workshop (SAM), Jun. 2012, pp. 257–260

[17] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, ''Massive MIMO for next generation wireless systems,'' IEEE Commun. Mag., vol. 52, no. 2, pp. 186–195, Feb. 2014.

[18] U. Gustavsson et al., ''On the impact of hardware impairments on massive MIMO,'' in Proc. IEEE Global Telecommun. Conf. Workshops (GC Wkshps), Austin, TX, USA, Dec. 2014, pp. 294–300.

[19] E. Björnson, M. Matthaiou, and M. Debbah, ''Massive MIMO with nonideal arbitrary arrays: Hardware scaling laws and circuit-aware design,'' IEEE Trans.

Wireless Commun., vol. 14, no. 8, pp. 4353–4368, Aug. 2015.

[20] J. E. Mazo and H. J. Landau, ‘‘On the minimum distance problem for faster-than-Nyquist signaling,’’ IEEE Trans. Inf. Theory, vol. 34, no. 6, pp. 1420–1427, Nov. 1988.

[21] F. Rusek and J. B. Anderson, ‘‘CTH04-1: On information rates for faster than Nyquist signaling,’’ in Proc. IEEE GLOBECOM, Nov./Dec. 2006, pp. 1–5.

[22] F. Rusek and J. B. Anderson, ‘‘Multistream faster than Nyquist signaling,’’ IEEE Trans. Commun., vol. 57, no. 5, pp. 1329–1340, May 2009.

[23] J. B. Anderson, F. Rusek, and V. Öwall, ‘‘Faster-than-Nyquist signaling,’’ Proc. IEEE, vol. 101, no. 8, pp. 1817–1830, Aug. 2013.

[24] A. Prlja and J. B. Anderson, ‘‘Reduced-complexity receivers for strongly narrowband intersymbol interference introduced by faster-than-Nyquist signaling,’’ IEEE Trans. Commun., vol. 60, no. 9, pp. 2591–2601, Sep. 2012.

[25] S. Sugiura, ‘‘Frequency-domain equalization of faster-than-Nyquist signaling,’’ IEEE Wireless Commun. Lett., vol. 2, no. 5, pp. 555–558, Oct. 2013.

[26] J. Fan, S. Guo, X. Zhou, Y. Ren, G. Y. Li, and X. Chen, ‘‘Faster-thanNyquist signaling: An overview,’’ IEEE Access, vol. 5, pp. 1925–1940,2017.

[27] K. Takeuchi, M. Vehkapera, T. Tanaka, and R. R. Muller, ‘‘Large-system analysis of joint channel and data estimation for MIMO DS-CDMA systems,’’ IEEE Trans. Inf. Theory, vol. 58, no. 3, pp. 1385–1412, Mar. 2012.

[28] D. Dasalukunte, V. Öwall, F. Rusek, and J. B. Anderson, Faster than Nyquist Signaling: Algorithms to Silicon. Dordrecht, The Netherlands: Springer, 2014.

[29] E. Bedeer, M. H. Ahmed, and H. Yanikomeroglu, ‘‘A very low complexity successive symbol-by-symbol sequence estimator for faster-than-Nyquist signaling,’’ IEEE Access, vol. 5, pp. 7414–7422, 2017.

[30] A. D. Liveris and C. N. Georghiades, ‘‘Exploiting faster-than-Nyquist signaling,’’ IEEE Trans. Commun., vol. 51, no. 9, pp. 1502–1511, Sep. 2003.

[31] Y. J. D. Kim and J. Bajcsy, ‘‘Iterative receiver for faster-than-Nyquist broadcasting,’’ Electron. Lett., vol. 48, no. 24, pp. 1561–1562, Nov. 2012.

[32] Y. J. D. Kim, J. Bajcsy, and D. Vargas, ‘‘Faster-than-Nyquist broadcasting in Gaussian channels: Achievable rate regions and coding,’’ IEEE Trans. Commun., vol. 64, no. 3, pp. 1016–1030, Mar. 2016.

未来网络通讯的频谱效率分类方案

王中生
新型网络与检测控制国家实验室
西安工业大学
中国陕西省西安市未央区学府中路 No.2 号

张庆松
新型网络与检测控制国家实验室
西安工业大学
中国陕西省西安市未央区学府中路 No.2 号

摘要：**作为一个由 ISO/IEC 创建和管理的国际标准化项目，未来网络已产生了 ISO/IEC TR 29181 系列的技术报告，并正处于设置体系架构和协议的阶段。该项目以其独特的“全新设计”方式而闻名，并致力于基本的结构创新，以使得未来网络实现其所承诺的目标。同时，未来网络的标准化工作将为 SE 技术的未来突破做好准备，并制定计划，使未来网络适应快速变化的“后香农时代”技术革命。本标准参考射频频带分类机制，对 MCS 系统的频谱效率进行分类，便于对信息系统的频谱效率进行分类、讨论、评价和比较。**

关键词：未来网络通讯； 频谱效率分类方案； 国际标准

1. 介绍

本文是超限未来网络的第一项国际标准提案（草案），该提案（草案）的开发，依托于 JTC 1/SC 6/WG 7 工作团队，申请负责人是张庆松博士（南京博峰），提案的提议人是王中生教授（西安工业大学），开发过程中作为联络人的团队是 ITU-R 和 ICAO，同时联合 ECMA、3GPP 和 IEEE 三个组织进行合作开发。

本文按照以下三份文件的规定进行拟定：

ISO/IEC TR 29181：未来网络：问题陈述和要求，第 1-9 部分；

ITU-R SM.856-1：新频谱效率技术和系统（1992-1997）；

ITU-R SM.1046-3：无线电系统频谱使用效率的定义(2017-09-06)。

本文作为一份“工业、创新和基础建设”领域的国际标准提案（草案），提供了调制编码方案频谱效率 MCS SE（Modulation and Coding Scheme Spectral Efficiency）的分类方案，包括以下六个方面：

MCS SE 的定义；

MCS SE 的分类方法；

MCS SE 的命名体系；

SECS 推荐使用的示例；

对未来网络标准化的潜在影响；

频谱效率 SE 和频谱利用效率之间的不同点。

2. 开发背景

频谱效率是衡量信息通信系统发展水平的一个关键指标，它可以反应甚至影响诸多关键性能指标，包括频谱资源的有效利用率、信息传输率、信道容量等等。频谱效率越高，资源受限频谱的资源利用率就越高，同时传输速率越高，那么信息吞吐量也就越大。因此，提高频谱效率是信息通信技术（ICT）创新最关键的目标之一。

随着数字信息和计算机科学技术的发展，信息通信系统的频谱效率水平也在不断提高。20 年前的通信系统频谱效率还处于很低的水平，仅有 1 到 2 个比特。经过 20 年的发展，部分技术领域已经采用了 10 比特的频谱效率技术，更有一些领域已经将 12 比特频谱效率纳入下一代技术标准规划中。

但是，上述这一发展速度并不是直线上升的。根据历史经验和技术特点分析，由于多进制正交调幅（M-QAM）调制和反调制技术的先天限制，未来的信息和通讯系统的频谱效率水平的发展速度将放缓，预计在 20 年内达到 16 比特，45 年内达到 20 比特，而突破这一限制也是提高频谱效率的关键机制。与此同时，也不能排除由于信息通信物理基础层新理论和新技术的出现，而导致频谱效率的快速提高的可能性。

在后香农时代，高频谱效率将会成为信息通讯技术（ICT）水平的主要表现形式。在接下来的十到二十年内，对通信技术频谱效率的讨论和评价标准将超过 20 比特，达到几百比特甚至几千比特。通讯产品也将会促进频谱效率作为主要技术水平及服务能力的标志。

在现有的国际电信联盟（ITU）标准 RSM.1046-3 中规定了频谱利用效率的定义和使用各种系统频谱的评估方法，但没有提供调制编码方案（MCS）频谱效率的分类机制。而这种机制，对未来通信系统频谱效率的讨论、分析、评估、选择和管理是必需的。

例如，在一些技术或政策文件中，经常可以看到对“低频谱效率”和“高频谱效率”的讨论，但没有技术规范来定义和解释这两个概念。多少比特的频谱效率是“低频谱效率”？多少位的频谱效率是“高频谱效率”？相当一部分的划分方式中，将 10 比特系统称为“高频谱效率”，那么 16 比特、20 比特、32 比特甚至 128 比特的频谱效率如何归类呢？因此，仅仅只有“低频谱效率”和“高频谱效率”这两级分类标准是不能满足未来发展趋势和更精确的频谱效率分类的需要的。

在无线电频谱管理中，对频谱资源有多种分类方案，这里我们列举其中四种方案：①将频率资源(RE)划分为千赫兹、兆赫、千兆赫兹和太赫兹；②基于波长，将频率资源（RE）分为超长波、长波、中波、短波、超短波、微波等类别；③按频率分类的方法，即超低频（VLF）、低频、中频、中高频、高频、极高频（VHF）、超高频（UHF）等；④以英文字母为标志，将频谱资源 RE 分为 L-波段、S-波段、C-波段、X-波段、Ku-波段、K-波段、Ka-波段等。

本标准参考射频频带分类机制，对 MCS 系统的频谱效率进行分类，便于对信息系统的频谱效率进行分类、讨论、评价和比较。

3. 术语规定

3.1 缩写

表 1 术语缩写示例

缩写	全称	中文名称
MCS	Modulation and Coding Scheme	调制编码方案
MIMO	Multiple Input Multiple Output	多入多出技术
FN	Future Network	未来网络
OFDM	Orthogonal Frequency Division Multiplexing	正交频分复用
OCCS	Over-Capacity Communication Systems	超容量通讯系统
OVXDM	Overlapped X Domain Division Multiplexing	重叠 X 分域复用系统
OVTDM	Overlapped Time Domain Division Multiplexing	重叠时分域复用系统
QAM	Quadrature Amplitude Modulation	正交调幅
RE	Resource Element	资源元素
RSE	Relative Spectral Efficiency	相对频谱效率
SE	Spectral Efficiency	频谱效率
SEI	Spectral Efficiency Index	频谱效率指标
SUE	Spectrum Utilization Efficiency	频谱使用效率
TSEI	Typical SE Indicator	经典频谱效率指示器

3.2 术语定义

超容量通讯：信息交换的容量超过香农限制。

OVXDM：一种创新的调制编码方式，利用时间、频率、空间等多个域以及编码的重叠和多路复用，以达到更高的频谱效率，无编码开销，更高的编码增益和解码的低复杂度。

调制编码方案的频谱效率：根据通信系统的调制和编码方案，每一资源单元（RE 以 H 为单位）每秒发送的最大有用信息量。

频谱使用率：频率带宽、几何（地理）空间和时间的乘积，不包含其他潜在因子：$U = B \cdot S \cdot T$

香农限制：又称香农容量，在十九世纪四十年代由 Claude Shannon 定义，为单一信道在一定噪声水平下设定理论上最高的信息传输速率的极限。

未来网络：一个由 ISO/IEC 开发和管理的国际标准项目，它是基于全新的网络系统设计方法。出版物包括 ISO/IEC TR 29181 和 ISO/IEC 21558-21559。

4. MCS SE 分类原则

4.1 频谱效率（SE）和超高频谱效率（USE）的区分

本标准中定义的 SE（频谱效率）不应该与 ITU-RSM.1046-3 (2017)中的频谱效率混淆。下面的表格所列的是它们之间的区别：

表 2 本标准与 ITU 标准对比

	比较对象	本标准	ITU
1	来源	ISO/IEC	ITU-RSM.1046-3
2	术语	Spectral Efficiency	Spectrum Efficiency
3	缩写词	MCS SE	USE
4	因子	波特率 bps/Hz	U=B·S·T
5	考虑因素	● 容量 ● 资源元素（赫兹 Hz） ● 时间（秒）	● 带宽 ● 几何空间（空间） ● 时间
6	改进方法	● 调制 ● 通道编码	● 天线指向性 ● 地理空间 ● 频率公用 ● 正交频率使用 ● 分时技术 ● 时间划分
7	SE 增益潜力	空域限制了 SE 增益	SE 增益是有限的
8	视角	通讯系统	用户
9	服务	对所有开放	拒绝其他的使用

本标准定义的 MCS 频谱效率是指通过调制和信道编码等技术手段，而获得的每赫兹频率资源每秒传输的有效信息位数。

MCS 的频谱效率值是相对固定的，只要知道所使用的调制机制和信道编码方法，就可以推导出 MCS 频谱效率在理论上的性能水平。由于调制机制和信道编码方法种类较少，于是一些

主流技术的应用非常广泛，如调制领域中的 M-QAM 技术以及信道编码领域中的 Turbo 码和 LDPC 码。因此，MCS 频谱效率可以作为衡量 ICT 在不同领域性能水平的一个通用且重要的指标。

4.2 确定 SE 的范围

目前，通信系统的 SE 不高于 10bps/Hz，一些系统可能在大约 5 年后达到 12bps/Hz。在如此低的 SE 比率下，没有必要对 SE 水平进行标准分类。

然而，人们期望这样的一个标准能够指向未来的趋势，为技术发展提供方向，并具有持续数十年的市场相关性。由于有技术趋势表明在频谱效率方面有潜在的突破，本标准考虑了在数百和数千 bps/Hz 范围内的频谱效率。

4.3 MCS SE 分类架构

MCS SE 分类系统包括下表中描述的三种方案：

表 3 MCS SE 分类系统描述方案

方案	特征	版本	目的
A	两个字母	#-SE	表示特定产品 SE 能力
B	三个字母	VSE	将 SE 按级别类别分组
C	四个字母	DDSE	提供一个可替代的、更简单的 SE 分类
D	二级	Lower	更广泛的级别

5. MCS 频谱效率分类方案

5.1 MCS SE 类 A：两个字母方案

两个字母的 MCS SE 分类系统只使用两个字母“SE”和数字显示特定的 bps/Hz. 它不是用于引用级别或类，而是用于指示产品的特定 SE 性能。

表达式描述:带“-”后跟“SE”的比特数(省略“s/Hz”)，表示“特定 bps/Hz 下的频谱效率”。

例如：

“56-SE”表示 56bps/Hz 的频谱效率。

“256-SE”表示 256bps/Hz 的频谱效率。

“1008-SE”表示 1008bps/Hz 的频谱效率。

5.2 MCS SE 类 B：三字母名称方案

表 4 MCS SE 分类方案中的三字母方案

SE 索引	索引名	全称	SE 范围（bps/Hz)	TSEI* (bps/Hz)
SEI 1	BSE	Basic Spectral Efficiency 基本频谱效率	0.1~2.0	2
SEI 2	LSE	Low Spectral Efficiency 低频谱效率	2.1~5.9	5
SEI 3	MSE	Medium Spectral Efficiency 中频谱效率	6~10.9	10
SEI 4	HSE	High Spectral Efficiency 高频谱效率	11~15	15
SEI 5	VSE	Very-High Spectral Efficiency	16~20	20

		极高频谱效率		
SEI 6	USE	Ultra-High Spectral Efficiency 超高频谱效率	21~32	32
SEI 7	SSE	Super Spectral Efficiency 超级频谱效率	33~64	64
SEI 8	OSE	One-hundred level spectral efficiency 100 级频谱效率	65~128	128
SEI 9	ESE	Extreme Spectral Efficiency 极大频谱效率	129~256	256
SEI 10	DSE	500 Spectral Efficiency 500 频谱效率	257~512	512
SEI 11	JSE	Jump Level spectral efficiency 跃迁能级频谱效率	513~999	768
SEI 12	1-KSE	1K Spectral efficiency 1000 频谱效率	1000~1999	1024
SEI 13	2-KSE	2K Spectral efficiency 2000 频谱效率	2000~2999	2048
SEI 14	3-KSE	3K Spectral efficiency 3000 频谱效率	3000~3999	3072
SEI 15	4-KSE	4K Spectral efficiency 4000 频谱效率	4000~4999	4096
SEI 16	XSE	X Spectral efficiency X 频谱效率	5000~6999	6144
*TSEI 该等级下的典型 SE 指标 .				

随着频谱效率的提高，三字母方案之间的差距也随之扩大。例如，在 SEI4 和 SEI5 中，只有 4 字节差将高电平和低电平分开。在 SEI9 中，间隙超过 200 字节，而在 SEI12 中，间隙增加到 1000 字节。

对于三个字母方案的上部，预计需要更加准确的 SE 参考资料或是比较方式。在这种情况下，当技术发展需要这样的改变时，三字母方案可以使用下列八条规则进行拓展：

规则 1. SEI1～6 不需要拓展；

规则 2. 拓展的分组被分为两张索引表，一张是如表 5 所示的 SE 低于 1000bps/Hz 的情况，另一张是如表 6 所示的 SE 高于 1000bps/Hz 的情况；

规则 3. 一个简单的两位十进制数被添加到索引名字中来表示拓展数字；

规则 4. 对于 SSE 和 OSE 索引，5bps/Hz 作为扩展单元的基础；

规则 5. 对于 ESE 和 DSE 索引，10bps/Hz 作为扩展单元的基础；

规则 6. 对于 JSE 索引，20bps/Hz 作为扩展单元的基础；

规则 7. 对于 KSE 索引，50bps/Hz 作为扩展单元的基础；

规则 8. 对于 XSE 索引，100bps/Hz 作为扩展单元的基础。

表 5 低于 1000SE 的拓展

SEI 7	33-64	SEI 8	65~128	SEI-9	129-256	SEI 10	257~512	SEI 11	513~999
EXT	SE	EXT	SE	EXT	SE	EXT	SE	EXT	SE
Index	RANGE	Index	RANGE	Index	RANGE	Index	RANGE	Index	RANGE
SSE 1	33-38	OSE 1	65-69	ESE 1	129-139	DSE 1	257-269	JSE 1	513-539
SSE 2	39-43	OSE 2	70-74	ESE 2	140-149	DSE 2	270-279	JSE 2	540-559
SSE 3	44-49	OSE 3	75-79	ESE 3	150-159	DSE 3	280-289	JSE 3	560-579
SSE 4	50-55	OSE 4	80-84	ESE 4	160-169	DSE 4	290-299	JSE 4	580-599
SSE 5	56-60	OSE 5	85-89	ESE 5	170-179	DSE 5	300-319	JSE 5	600-619
SSE 6	61-64	OSE 6	90-94	ESE 6	180-189	DSE 6	320-329	JSE 6	620-639
		OSE 7	95-99	ESE 7	190-199	DSE 7	330-339	JSE 7	640-659
		OSE 8	100-104	ESE 8	200-209	DSE 8	340-349	JSE 8	660-679
		OSE 9	105-109	ESE 9	210-219	DSE 9	350-359	JSE 9	680-699
		OSE 10	110-114	ESE 10	220-229	DSE 10	360-369	JSE 10	700-719
		OSE 11	115-119	ESE 11	230-239	DSE 11	370-379	JSE 11	720-739
		OSE 12	120-124	ESE 12	240-249	DSE 12	380-389	JSE 12	740-759
		OSE 13	125-128	ESE 13	250-256	DSE 13	390-399	JSE 13	760-779
						DSE 14	400-409	JSE 14	780-799
						DSE 15	410-419	JSE 15	800-819
						DSE 16	420-429	JSE 16	820-839
						DSE 17	430-439	JSE 17	840-859
						DSE 18	440-449	JSE 18	860-879
						DSE 19	450-459	JSE 19	880-899
						DSE 20	460-469	JSE 20	900-919
						DSE 21	470-479	JSE 21	920-939
						DSE 22	480-489	JSE 22	940-959
						DSE 23	490-499	JSE 23	960-979
						DSE 24	500-512	JSE 24	980-999

表 6 KSE 和 XSE 拓展索引

SEI 12	1000-1999	SEI 13	2000-2999	SEI 13	3000-3999	SEI 14	4000-4999	SEI 15	5000-6999
EXT	SE	EXT	SE	EXT	SE	EXT	SE	EXT	SE
Index	RANGE	Index	RANGE	Index	RANGE	Index	RANGE	Index	RANGE
1KSE 1	1000-1049	**2KSE 1**	2000-2049	**3KSE 1**	3000-3049	**4KSE 1**	4000-4049	**XSE 1**	5000-5099
1KSE 2	1050-1099	**2KSE 2**	2050-2099	**3KSE 2**	3050-3099	**4KSE 2**	4050-4099	**XSE 2**	5100-5199
1KSE 3	1100-1140	**2KSE 3**	2100-2140	**3KSE 3**	3100-3140	**4KSE 3**	4100-4140	**XSE 3**	5200-5299
1KSE 4	1150-1199	**2KSE 4**	2150-2199	**3KSE 4**	3150-3199	**4KSE 4**	4150-4199	**XSE 4**	5300-5399
1KSE 5	1200-1249	**2KSE 5**	2200-2249	**3KSE 5**	3200-3249	**4KSE 5**	4200-4249	**XSE 5**	5400-5499
1KSE 6	1250-1299	**2KSE 6**	2250-2299	**3KSE 6**	3250-3299	**4KSE 6**	4250-4299	**XSE 6**	5500-5599
1KSE 7	1300-1349	**2KSE 7**	2300-2349	**3KSE 7**	3300-3349	**4KSE 7**	4300-4349	**XSE 7**	5600-5699

1KSE 8	1350-1399	**2KSE 8**	2350-2399	**3KSE 8**	3350-3399	**4KSE 8**	3350-4399	**XSE 8**	5700-5799
1KSE 9	1400-1449	**2KSE 9**	2400-2449	**3KSE 9**	3400-3449	**4KSE 9**	4400-4449	**XSE 9**	5800-5899
1KSE 10	1450-1499	**2KSE 10**	2450-2499	**3KSE 10**	3450-3499	**4KSE 10**	4450-4499	**XSE 10**	5900-5999
1KSE 11	1500-1549	**2KSE 11**	2500-2549	**3KSE 11**	3500-3549	**4KSE 11**	4500-4549	**XSE 11**	6000-6099
1KSE 12	1550-1599	**2KSE 12**	2550-2599	**3KSE 12**	3550-3599	**4KSE 12**	4550-4599	**XSE 12**	6100-6199
1KSE 13	1600-1649	**2KSE 13**	2600-2649	**3KSE 13**	3600-3649	**4KSE 13**	4600-4649	**XSE 13**	6200-6299
1KSE 14	1650-1699	**2KSE 14**	2650-2699	**3KSE 14**	3650-3699	**4KSE 14**	4650-4699	**XSE 14**	6300-6399
1KSE 15	1700-1749	**2KSE 15**	2700-2749	**3KSE 15**	3700-3749	**4KSE 15**	4700-4749	**XSE 15**	6400-6499
1KSE 16	1750-1799	**2KSE 16**	2750-2799	**3KSE 16**	3750-3799	**4KSE 16**	4750-4799	**XSE 16**	6500-6599
1KSE 17	1800-1849	**2KSE 17**	2800-2849	**3KSE 17**	3800-3849	**4KSE 17**	4800-4849	**XSE 17**	6600-6699
1KSE 18	1850-1899	**2KSE 18**	2850-2899	**3KSE 18**	3850-3899	**4KSE 18**	4850-4899	**XSE 18**	6700-6799
1KSE 19	1900-1949	**2KSE 19**	2900-2949	**3KSE 19**	3900-3949	**4KSE 19**	4900-4949	**XSE 19**	6800-6899
1KSE 20	1950-1999	**2KSE 20**	2950-2999	**3KSE 20**	3950-3999	**4KSE 20**	4950-4999	**XSE 20**	6900-6999

5.3 MCS SE 类 C：四个字母方案

表 7 MCS SE 分类方案中的四字母方案

	标题	完整标题	SE (bps/Hz)	相对与 B 类
1	SDSE	Single Digits Spectral Efficiency 单字节频谱效率	0-9	BSE，LSE，MSE
2	DDSE	Double Digits Spectral Efficiency 双字节频谱效率	10-99	HSE，VSE，USE，SSE，OSE
3	TDSE	Triple Digits Spectral Efficiency 三字节频谱效率	100-999	ESE，DSE，JSE
4	QDSE	Quadruple Digits Spectral Efficiency 四字节频谱效率	1000-9999	M-KSE，XSE

5.4 MCS SE 类 D：比较方案

表 8 MCS SE 分类方案中的比较方案

	标题	完整标题	SE (bps/Hz)	与其他范畴的关系
1	L	低	无	所有低于特定类别的等级
2	H	高	无	所有高于特定类别的等级

6. 对本标准的描述

对本项标准内容的引用描述，可以参考以下形式。

6.1 参考标准

本标准的原名是“OCC-STD 21001”，由开发机构制定。在纳入中国行业标准、国家标准、ISO 标准、国际电联标准等其他标准体系时，

可对标题和编号进行重新分配。在此之前，“OCC-STD 21001”是 MCS SE 分类的唯一来源。

今后在参考分类方案时，建议在文件中注明 SE 分类在南京博丰通信技术有限公司开发的“OCC-STD 21001(2021)”中进行定义。

6.2 参考特定分类级别的示例

（1）在 2023 年，该公司有望交付使用创新调制方案的通信系统，可以提供“OCC-STD 21001”中定义的 VSE 级频谱效率。

（2）比较 MCS 的频谱效率，两个产品属于两代，A 样本仅在 VSE 水平，B 样本包含 USE 调制技术。

（3）行业共识是，KSE 级的频谱效率技术只需要几年的时间。

（4）一些专家预计，进入下一个十年，通信系统可以达到“OCC-STD 21001”四字母分类系统中定义的 QDSE 级频谱效率。

6.3 推荐使用的比较方案

当使用这两个表达方式时，它们应该伴随着一个具体的 SE 分类水平，以便于比较。

（1）到目前为止，最先进的无线通信系统的 MCS 频谱效率低于“OCC-STD 21001”中定义的 VSE 水平。

（2）预计到 2025 年，频谱效率高于 VSE 水平的产品将投入使用。

（3）新系统具有向后兼容设计，提供对 MCS SE 级的持续支持。

6.4 用以参考的专用 SE 比率

当参考专用 SE 比率时，下面两种情况为例：

（1）“Bofeng.com”提供两个无线电系统，按照“OCC-STD 21001”中定义的 SSE 级频谱效率运行。射频 A 系统具有 48-SE 调制方案，射频 B 系统具有 64-SE 调制能力

（2）产品规格:MCS SE:32-SE、48-SE 和 64-SE。说明系统包含三种类型的 MCS，支持三种 SE 速率。

7. 对未来网络标准化的潜在影响

未来网络是一个由 ISO/IEC 创建和管理的国际标准化项目。该项目已经产生了 ISO/IEC TR 29181 系列的技术报告，并正处于设置体系架构和协议的阶段。该项目以其独特的“全新设计”方式而闻名，并致力于基本的结构创新，以使得未来网络实现其所承诺的目标。

将 MCS-SE 分类系统作为未来网络标准化项目，对项目的建设有多方面的好处。首先，ISO/IEC 未来网络将成为第一个采用 MCS SE 分类系统的国际标准；第二，其他标准化机构可以采用该体系或对本标准进行规范引用；第三，ISO/IEC 未来网络成为第一个预示 MCS SE 未来发展趋势的标准；第四，未来网络标准中包含三比特和四比特的 MCS SE 将反映出网络表现和容量的巨大潜力；最后，该标准的成功采用将打开 ISO/IEC 未来网络标准的大门，以实现越来越高的 MCS SE 的未来技术。

ISO/IEC 未来网络应该为 SE 技术的未来突破做好准备，并制定计划，使未来网络适应快速变化的“后香农时代”技术革命。

参考文献

[1] T. M. Cover and J. A. Thomas, Elements of Information Theory. Hoboken, NJ, USA: Wiley, 2006.

[2] L. Daoben, Waveform Coding Theory of High Spectral Efficiency-OVTDM and Its Application. Beijing, China: Scientific, 2013.

[3] L. Daoben, ‘‘A novel high spectral efficiency waveform coding–OVFDM,’’ China Commun., vol. 12, no. 2, pp. 61–73, Feb. 2015.

[4] S. G. Wilson, Digital Modulation and Coding. Englewood Cliffs, NJ, USA: Prentice-Hall, 1996.

[5] L. Daoben, ‘‘A novel high spectral efficiency waveform coding-OVTDM,’’ Int. J. Wireless Commun. Mobile Comput., vol. 2, nos. 1–4, pp. 11–26, Dec. 2014.

[6] L. Daoben, Statistical Theory of Signal Detection and Estimation, 2nd ed. Beijing, China: Scientific, 2005

[7] J. G. Proakis, Digital Communications. New York, NY, USA: McGraw-Hill, 2001.

[8] G. J. Foschini, ‘‘Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas,’’ Bell Labs Tech. J., vol. 1, no. 2, pp. 41–59, 1996.

[9] G. J. Foschini and M. J. Gans, ‘‘On limits of wireless communications in a fading environment when using multiple antennas,’’ Wireless Pers. Commun., vol. 6, no. 3, pp. 311–335, Mar. 1998

[10] S. Wu, L. Kuang, Z. Ni, J. Lu, D. D. Huang, and Q. Guo, ''Low-complexity iterative detection for large-scale multiuser MIMO-OFDM systems using approximate message passing,'' IEEE J. Sel. Topics Signal Process., vol. 8, no. 5, pp. 902–915, Oct. 2014.

[11] N. Wu, W. Yuan, H. Wang, Q. Shi, and J. Kuang, ''Frequency-domain iterative message passing receiver for faster-than-Nyquist signaling in doubly selective channels,'' IEEE Wireless Commun. Lett., vol. 5, no. 6, pp. 584–587, Dec. 2016.

[12] J. CØspedes, P. M. Olmos, M. SÆnchez-FernÆndez, and F. Perez-Cruz, ''Expectation propagation detection for high-order high-dimensional MIMO systems,'' IEEE Trans. Commun., vol. 62, no. 8, pp. 2840–2849, Aug. 2014.

[13] A. L. Swindlehurst, E. Ayanoglu, P. Heydari, and F. Capolino, ''Millimeterwave massive MIMO: The next wireless revolution?'' IEEE Commun. Mag., vol. 52, no. 9, pp. 56–62, Sep. 2014.

[14] [14] H. Q. Ngo, E. G. Larsson, and T. L. Marzetta, ''Energy and spectral efficiency of very large multiuser MIMO systems,'' IEEE Trans. Commun., vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

[15] Y. S. Cho, J. Kim, W. Y. Yang, and C. G. Kang, MIMO-OFDM Wireless Communication Technology With MATLAB. Beijing, China: PublishingHouse of Electronics Industry, 2013.

[16] Y. D. Zhang, M. G. Amin, and B. Himed, ''Altitude estimation of maneuvering targets in MIMO over-the-horizon radar,'' in Proc. IEEE 7th IEEE Sensor Array Multichannel Signal Process. Workshop (SAM), Jun. 2012, pp. 257–260

[17] E. G. Larsson, O. Edfors, F. Tufvesson, and T. L. Marzetta, ''Massive MIMO for next generation wireless systems,'' IEEE Commun. Mag., vol. 52, no. 2, pp. 186–195, Feb. 2014.

[18] U. Gustavsson et al., ''On the impact of hardware impairments on massive MIMO,'' in Proc. IEEE Global Telecommun. Conf. Workshops (GC Wkshps), Austin, TX, USA, Dec. 2014, pp. 294–300.

[19] E. Björnson, M. Matthaiou, and M. Debbah, ''Massive MIMO with nonideal arbitrary arrays: Hardware scaling laws and circuit-aware design,'' IEEE Trans. Wireless Commun., vol. 14, no. 8, pp. 4353–4368, Aug. 2015.

[20] J. E. Mazo and H. J. Landau, ''On the minimum distance problem for faster-than-Nyquist signaling,'' IEEE Trans. Inf. Theory, vol. 34, no. 6, pp. 1420–1427, Nov. 1988.

[21] F. Rusek and J. B. Anderson, ''CTH04-1: On information rates for faster than Nyquist signaling,'' in Proc. IEEE GLOBECOM, Nov./Dec. 2006, pp. 1–5.

[22] F. Rusek and J. B. Anderson, ''Multistream faster than Nyquist signaling,'' IEEE Trans. Commun., vol. 57, no. 5, pp. 1329–1340, May 2009.

[23] J. B. Anderson, F. Rusek, and V. Öwall, ''Faster-than-Nyquist signaling,'' Proc. IEEE, vol. 101, no. 8, pp. 1817–1830, Aug. 2013.

[24] A. Prlja and J. B. Anderson, ''Reduced-complexity receivers for strongly narrowband intersymbol interference introduced by faster-than-Nyquist signaling,'' IEEE Trans. Commun., vol. 60, no. 9, pp. 2591–2601, Sep. 2012.

[25] S. Sugiura, ''Frequency-domain equalization of faster-than-Nyquist signaling,'' IEEE Wireless Commun. Lett., vol. 2, no. 5, pp. 555–558, Oct. 2013.

[26] J. Fan, S. Guo, X. Zhou, Y. Ren, G. Y. Li, and X. Chen, ''Faster-thanNyquist signaling: An overview,'' IEEE Access, vol. 5, pp. 1925–1940,2017.

[27] K. Takeuchi, M. Vehkapera, T. Tanaka, and R. R. Muller, ''Large-system analysis of joint channel and data estimation for MIMO DS-CDMA systems,'' IEEE Trans. Inf. Theory, vol. 58, no. 3, pp. 1385–1412, Mar. 2012.

[28] D. Dasalukunte, V. Öwall, F. Rusek, and J. B. Anderson, Faster than Nyquist Signaling: Algorithms to Silicon. Dordrecht, The Netherlands: Springer, 2014.

[29] E. Bedeer, M. H. Ahmed, and H. Yanikomeroglu, ''A very low complexity successive symbol-by-symbol sequence estimator for faster-than-Nyquist signaling,'' IEEE Access, vol. 5, pp. 7414–7422, 2017.

[30] A. D. Liveris and C. N. Georghiades, ''Exploiting faster-than-Nyquist signaling,'' IEEE Trans. Commun., vol. 51, no. 9, pp. 1502–1511, Sep. 2003.

[31] Y. J. D. Kim and J. Bajcsy, ''Iterative receiver for faster-than-Nyquist broadcasting,'' Electron. Lett., vol. 48, no. 24, pp. 1561–1562, Nov. 2012.

[32] Y. J. D. Kim, J. Bajcsy, and D. Vargas, ''Faster-than-Nyquist broadcasting in Gaussian channels: Achievable rate regions and coding,'' IEEE Trans. Commun., vol. 64, no. 3, pp. 1016–1030, Mar. 2016.