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• PERSPECTIVE •

Special Topic: Spectrum, Coverage, and Enabling Technologies for Intelligent 6G

6G extreme connectivity via exploring spatiotemporal exchangeability

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MIMO channel capacity collapse effect. The blocklength of channel coding is a critical factor that affects the communication latency over wireless channels. In the fifth-generation (5G) wireless communication network, a new structure of mini-slot has been introduced to support the requirement of communication latency no larger than 1 ms. Towards the next-generation wireless communication network, i.e., the sixth-generation (6G) network, extreme connectivity is a newly emerging feature of the development of 6G. The extreme connectivity puts forward more stringent demands on the key performance indicators (KPIs) of 6G including communication latency, data rate, and transmission reliability [1, 2]1). It is envisioned that the 6G network will enable both channel coding with short blocklength and time-slot with reduced duration in order to meet these KPIs for extreme connectivity.

Multiple-input multiple-output (MIMO) is an effective technique to improve the capacity of wireless communication systems. It has played an essential role in the development of both the fourth-generation (4G) and 5G wireless networks, and its importance will certainly remain in the development of future 6G networks. Under the assumption of independent and identically distributed (i.i.d.) fading channels and the exploration of an infinitely long channel-coding blocklength, e.g., much longer than 100 bits, the capacity of a MIMO channel is concisely characterized as $m\log_2(1+\mathrm{SNR})$, which is proportional to the spatial degree of freedom (DoF), m, of the MIMO channel.

However, this capacity bound is unable to reflect the impact of a finite channel-coding blocklength in practice. Specifically, the achievable rate of a MIMO channel deteriorates rapidly from this channel capacity bound when the blocklength reduces down to, e.g., 100 bits or even less, resulting in a phenomenon known as the channel capacity collapse effect. Note that in theory there does not exist nonzero channel capacity when a finite blocklength is used, if we stick to the conventional definition of channel capacity with a vanishing error probability. In this perspective, we deliberately abuse the term of channel capacity for consistency and redefine the channel capacity as the maximum achievable rate of the channel under a given target of error probability.

Polyanskiy et al. [3] derived a tight channel capacity bound under the consideration of a finite blocklength. Based on this result, Ref. [4] successfully characterized a capacity bound with finite blocklength for MIMO channels, which gives the closed-form bound as

$$\frac{\bar{R}}{m} \leqslant \log_2\left(1+\mathrm{SNR}\right) - \sqrt{\frac{1}{nm}}\,\Phi^{-1}\left(\epsilon\right), \tag{1}$$

where $\bar{R}$ is the mean value of the maximum achievable rate of the MIMO channel, n is the blocklength, ϵ is the block error rate, and Φ^{-1} is the inverse of the Gaussian Q-function. From (1), the second term on the right hand side of this inequality becomes ignorable when nm grows sufficiently large, tending to the classical MIMO channel capacity. On the contrary, the average maximum achievable rate per unit spatial DoF, $\bar{R}/m$, degrades severely when nm is so small that this second term is non-ignorable, that is, the channel capacity collapse effect occurs.

A typical result is exemplified in Figure 1(a). It shows that the maximum achievable rate of the MIMO channel degrades sharply when nm is small and the target block error rate is high, e.g., $\epsilon = 10^{-7}$. Note that small nm implies that we use not only short blocklength for low latency communication but also a small antenna array with limited spatial DoFs. Therefore, this channel capacity collapse effect can be effectively mitigated by increasing the spatial DoF m, if the other system parameters remain invariant.

Spatiotemporal 2-D channel coding. In [3, 4], the deterioration of MIMO channel capacity is characterized with respect to finite blocklength, and the deficiency of conventional channel coding schemes in the time domain is revealed. An innovative manner to tackle this issue is to apply the spatiotemporal 2-D channel coding in [5], as depicted in Figure 1(c). In particular, this can be realized by performing channel coding like polar coding first in the time domain and subsequently in the spatial domain across mul-

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1) Project Hexa-X. Accessed date: Jul. 10, 2022. https://hexa-x.eu/.

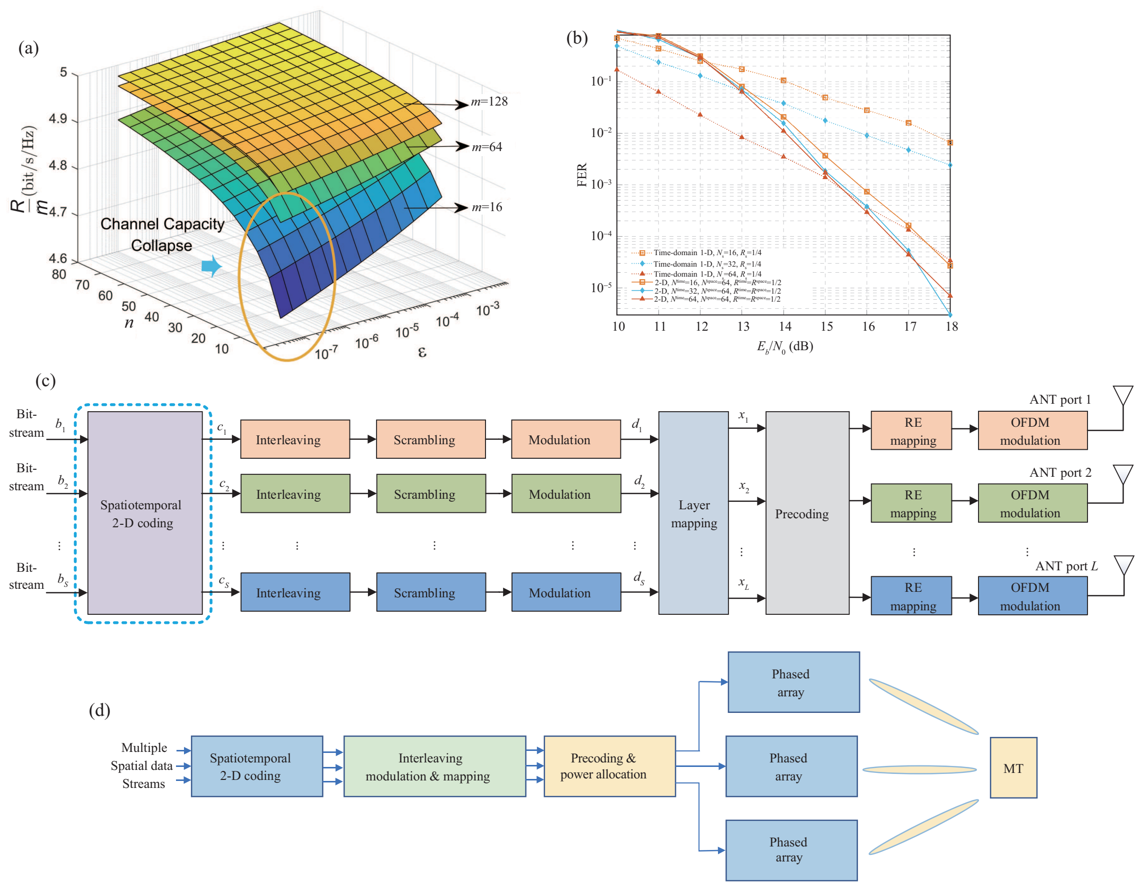

Figure 1 (Color online) (a) MIMO channel capacity collapse effect; (b) spatiotemporal 2-D channel coding performance simulation; (c) spatiotemporal 2-D rich scattering channel coding MIMO wireless transmission; (d) spatiotemporal 2-D sparsely-scattering channel coding MIMO wireless transmission.

tiple data streams. Figure 1(b) exhibits typical performance comparisons of the spatiotemporal 2-D channel coding with a conventional time-domain channel coding under an i.i.d. Rayleigh MIMO channel of size 64×128. It verifies that the proposed 2-D channel coding scheme achieves a 3 dB gain in terms of the frame error rate (FER) when the framelength is as short as 16 symbols and when the equivalent transmission rate remains constant for fair comparison.

It is worth noting that Ref. [5] initialized a preliminary design of the spatiotemporal 2-D channel coding scheme. To tightly approach the channel capacity bound discovered in (1), it is still an open problem to explore and develop new near-optimal and even the optimal spatiotemporal 2-D channel coding methods.

6G extreme connectivity via spatiotemporal exchangeability. Another observation from (1) is that the channel capacity degradation due to finite blocklength can be constantly upper bounded if the product, mn, remains invariant. Interestingly, it implies that the low-latency communication with a significantly decreasing n in 6G can be effectively supported by increasing the spatial DoF m to ensure an unchanging mn. We refer to this interesting principle as spatiotemporal exchangeability. Briefly in other words, lower latency communications can be enabled by exploiting a larger antenna array, or equivalently the use of less antennas results in prolonged communication latency in order to guarantee the average maximum achievable rate $\bar{R}/m$.

Specifically, under rich scattering environments, it is reasonable to assume that the MIMO channel roughly follows an i.i.d. Rayleigh distribution. As stated in the above section, a corresponding design with the spatiotemporal 2-D channel coding can be exploited for the MIMO channel, as depicted in Figure 1(c). This is to apply the spatiotemporal 2-D channel coding with a growing number of antennas, which enables the 6G extreme connectivity with an extremely short blocklength as well as ultra-high reliability and data rate.

On the other hand, under sparsely-scattering environments like millimeter-wave and Tera-Hertz (THz) wireless propagations, the MIMO channel dominantly follows the beam-domain channel model [6, 7]. Figure 1(d) illustrates a methodology to realize the 6G extreme connectivity with ultra-high reliability, low latency, and ultra-high data rate by distributed multi-beamforming. Analogous to the methodology in Figure 1(c), the spatiotemporal 2-D channel coding here is firstly performed across multiple code streams before the other signal processing procedures, except that the precoding applied for inter-stream interference cancelation is no longer needed because we use orthogonal beamforming.

Conclusion. MIMO communication is an indispensable key technology for the 6G wireless network. Under the requirement of extremely low-latency communication in 6G, the MIMO capacity exhibits the channel capacity collapse effect. The spatiotemporal exchangeability theory of MIMO channel and the spatiotemporal 2-D channel coding are promising approaches to combat this effect and to enable extreme connectivity for 6G. Fundamental researches in this area are still in its beginnings. Comprehensive simulation validations and constructing experimental systems in practical scenarios are necessary to further validate relevant theories and technologies. They are helpful to promote research in this area towards maturity.

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References

1 You X H, Wang C X, Huang J, et al. Towards 6G wireless communication networks: vision, enabling technologies, and new paradigm shifts. Sci China Inf Sci, 2021, 64: 110301

2 IMT-2030 (6G) Promotion Group. White Paper on 6G Overall Vision and Potential Key Technologies. White Paper, 2021, http://www.caict.ac.cn/kxyj/qwfb/ztbg/202106/P020210604552573543918.pdf

3 Polyanskiy Y, Poor H V, Verdu S. Channel coding rate in the finite blocklength regime. IEEE Trans Inform Theor, 2010, 56: 2307–2359

4 You X H, Sheng B, Huang Y, et al. Closed-form approximation for performance bound of finite blocklength massive MIMO transmission. 2022. ArXiv:2206.07243

5 You X H, Zhang C, Sheng B, et al. Spatiotemporal 2-D channel coding for very low latency reliable MIMO transmission. In: Proceedings of IEEE Global Communications Conference (GLOBECOM), 2022

6 Brady J, Behdad N, Sayeed A M. Beamspace MIMO for millimeter-wave communications: system architecture, modeling, analysis, and measurements. IEEE Trans Antennas Propagat, 2013, 61: 3814–3827

7 Yang X, Li X, Zhang S L, et al. On the ergodic capacity of mmWave systems under finite-dimensional channels. IEEE Trans Wireless Commun, 2019, 18: 5440–5453