JETIR.ORG | ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A Comprehensive Survey on Modulation Techniques for 5G and 6G Wireless Networks: From OFDM to OTFS and AFDM

Seema Paliwal, Gajanan Pakhare , Archana Nandkishor Shewale , Rohan Pardeshi, Amrita Singh , Komal Wankhede

Assistant Professor, Assistant Professor, HOD at Electronics and Comp Engineering., Assistant Professor, Assistant Professor, Assistant Professor

KCES College of Engineering & Management Jalgaon (Maharashtra)(1 to 5), Smt. Sharchchandrika Suresh Patil Institute of Technology (Engineering & Polytechnic), Chopda (6th author)

Abstract

The transition from fifth-generation (5G) to sixth-generation (6G) wireless networks is driving a fundamental rethink of physical-layer modulation and waveform design. While orthogonal frequency division multiplexing (OFDM) remains the workhorse of 4G and 5G New Radio, its sensitivity to high-mobility, doubly dispersive channels and its high peak-to-average power ratio (PAPR) limit its suitability for emerging 6G use cases such as terahertz (THz) communication, integrated sensing and communication (ISAC), and ultra-high-mobility non-terrestrial networks. This paper presents a comprehensive survey of modulation and waveform techniques spanning 5G and 6G systems. We review multicarrier alternatives to OFDM including filter bank multicarrier (FBMC), universal filtered multicarrier (UFMC), and generalized frequency division multiplexing (GFDM) before examining the delay-Doppler domain paradigm introduced by orthogonal time frequency space (OTFS) modulation and its index-modulation extensions. We further discuss the recently proposed affine frequency division multiplexing (AFDM) waveform, which uses chirp-based signalling in the discrete affine Fourier domain to achieve full diversity in doubly dispersive channels. Index modulation, non-orthogonal multiple access (NOMA)-aided modulation, and AI/ML-assisted waveform design are reviewed as cross-cutting enablers of spectral and energy efficiency. A comparative analysis of spectral efficiency, PAPR, complexity, and Doppler resilience is provided, followed by a discussion of open research challenges including receiver complexity, channel estimation overhead, and standardization and future directions for 6G modulation design.

Index Terms: 5G, 6G, modulation, OFDM, FBMC, GFDM, UFMC, OTFS, AFDM, index modulation, NOMA, waveform design, ISAC.

1. Introduction

The evolution of cellular networks from the fourth generation (4G) through fifth generation (5G) and toward sixth generation (6G) has been shaped as much by advances in physical-layer waveform design as by increases in bandwidth or antenna count. 5G New Radio adopted cyclic-prefix OFDM (CP-OFDM) as its primary waveform because of its robustness to multipath, simple frequency-domain equalization, and compatibility with MIMO precoding. However, OFDM's rectangular pulse shaping produces high out-of-band emission (OOBE), its cyclic prefix reduces spectral efficiency, and its orthogonality collapses under the large Doppler spreads expected in 6G scenarios such as low-Earth-orbit satellite access, high-speed rail, and unmanned aerial vehicle (UAV) links.

6G is further expected to operate at millimetre-wave and terahertz frequencies, support integrated sensing and communication (ISAC), and provide extreme connectivity for massive machine-type communication. These requirements motivate a re-examination of modulation and waveform design beyond incremental OFDM variants, toward two-dimensional and chirp-based formats such as orthogonal time frequency space (OTFS) modulation and affine frequency division multiplexing (AFDM), as well as resource-efficient paradigms such as index modulation (IM).

This survey organizes the modulation landscape for 5G and 6G into four broad families: (i) OFDM and its filtered/block variants used in 5G (FBMC, UFMC, GFDM); (ii) the delay-Doppler paradigm led by OTFS; (iii) the emerging affine/chirp domain paradigm led by AFDM; and (iv) cross-cutting techniques index modulation and NOMA-aided modulation — that can be layered onto any of the above waveforms to improve spectral and energy efficiency. Section 2 summarizes the key performance requirements driving 6G waveform design. Sections 3–5 review 5G waveforms, OTFS-based techniques, and AFDM, respectively. Section 6 covers index modulation and NOMA-aided schemes. Section 7 presents a comparative analysis, Section 8 discusses open challenges, and Section 9 concludes the paper.

2. 5G/6G Requirements Driving Modulation Design

6G research has articulated requirement sets that go well beyond the enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC), and massive machine-type communication (mMTC) triad defined for 5G. Chafii et al. frame twelve scientific challenges for 6G that touch directly on waveform and modulation theory, including robustness to doubly dispersive channels, integration of sensing and communication, and new information-theoretic limits for non-stationary channels [18]. Broader 6G surveys catalogue requirements such as sub-millisecond latency, terabit-per-second peak rates, ultra-massive connectivity, and native support for THz and non-terrestrial links [19], and outline candidate key technologies and testbeds that are shaping the 6G research roadmap [20].

From a modulation design perspective, four metrics recur across the literature: (1) spectral efficiency, (2) peak-to-average power ratio (PAPR), which affects power-amplifier efficiency and coverage, (3) robustness to time-varying, doubly dispersive channels (delay and Doppler spread), and (4) receiver/transmitter computational complexity. No single existing waveform dominates on all four axes, which is precisely why the field has diversified beyond OFDM.

3. Modulation and Waveform Techniques for 5G

3.1 OFDM and Its Limitations

CP-OFDM converts a frequency-selective channel into a set of parallel flat-fading subchannels via the cyclic prefix, enabling low-complexity single-tap equalization. This simplicity made it the default 5G NR waveform. However, rectangular time-domain pulses give OFDM high out-of-band leakage, and its two-dimensional (time-frequency) representation does not adequately capture the delay-Doppler spreading that occurs in high-mobility channels, leading to inter-carrier interference (ICI) and performance degradation as user velocity increases.

3.2 Filter Bank Multicarrier (FBMC)

FBMC applies a well-localized prototype filter to each subcarrier instead of relying on a rectangular pulse and cyclic prefix, which sharply improves frequency localization and reduces OOBE relative to OFDM. Comparative studies confirm that FBMC achieves the best spectral containment among 5G waveform candidates and offers improved bit-error-rate and spectral-density performance relative to conventional OFDM [25], though this comes at the cost of longer filter tails, loss of strict time-frequency orthogonality (typically resolved with offset-QAM), and higher receiver complexity, especially when combined with MIMO.

3.3 Universal Filtered Multicarrier (UFMC)

UFMC filters groups of subcarriers (sub-bands) rather than individual subcarriers, striking a balance between OFDM's simplicity and FBMC's spectral containment. Comparative analyses of OFDM, FBMC, and UFMC show that UFMC achieves competitive PAPR performance and can be an attractive choice for short-burst transmissions typical of machine-type traffic, with PAPR further reducible through optimization techniques [20].

3.4 Generalized Frequency Division Multiplexing (GFDM)

GFDM organizes data into a two-dimensional time-frequency block in which each subcarrier is independently pulse-shaped and a single cyclic prefix covers the entire block, reducing overhead relative to per-symbol CP-OFDM. A systematic overview of 5G waveform candidates positions GFDM, together with OFDM, FBMC, and UFMC, as one of the main options evaluated during the 5G air-interface discussions, comparing their essential advantages and disadvantages [12]. GFDM was an early candidate for the 5G air interface owing to its flexible spectrum shaping and comparatively low PAPR; however, its non-orthogonal filter design introduces self-interference that must be mitigated by successive interference cancellation or advanced detection, and a fair comparison shows that GFDM's PAPR and out-of-band emission characteristics closely track OFDM's unless additional windowing or waveform redesign is applied [21], [23]. Comparative studies of the 5G waveform candidates (OFDM, UFMC, FBMC, and GFDM) under a common spectral-efficiency and PAPR framework are provided in the waveform-race literature, which is a standard reference point for 5G physical-layer benchmarking [23].

4. Delay-Doppler Modulation: OTFS

4.1 Principle of OTFS

Orthogonal time frequency space (OTFS) modulation, introduced by Hadani et al., maps information symbols into the two-dimensional delay-Doppler (DD) domain rather than the conventional time-frequency domain [1]. Through the inverse symplectic finite Fourier transform, each DD-domain symbol spreads over the entire time-frequency grid, so that all symbols experience the same channel gain and full diversity is extracted from a time-varying multipath channel. This design converts a fast time-varying channel in the time-frequency domain into an approximately time-invariant, sparse channel in the delay-Doppler domain, which is the key property that makes OTFS attractive for 6G high-mobility scenarios.

4.2 Performance versus OFDM

A recent comprehensive evaluation across TDL and extended channel models (TDLA, TDLB, EVA, EPA, ETU) and multiple modulation orders (QPSK through 256-QAM) shows that OTFS achieves superior bit-error-rate performance relative to OFDM, particularly under high mobility and multipath, while OFDM retains a computational-complexity advantage [2]. Related studies confirm that the block-error-rate advantage of OTFS over OFDM grows with mobility speed across QPSK, 16-QAM, and 64-QAM formats, and that this advantage persists as the number of subcarriers is varied. A fair comparison under sparsity assumptions similarly demonstrates that the relative advantage of OTFS depends on channel sparsity and equalizer design, underscoring that OTFS's gains are context-dependent rather than universal [21]. Iterative message-passing detectors have been developed to keep OTFS receiver complexity tractable despite the dense effective channel matrix induced by DD-domain spreading [22].

4.3 OTFS Beyond Terrestrial Links

Because of its Doppler resilience, OTFS has been investigated for space-air-ground integrated networks (SAGINs), where satellites, UAVs, and terrestrial nodes coexist and produce severe Doppler spreads that conventional OFDM struggles to tolerate; simulation studies over extreme mobility scenarios (hundreds to thousands of km/h) confirm OTFS's BER advantage in such regimes.

4.4 OTFS-Based Index Modulation

Index modulation has been combined with OTFS to further improve spectral and energy efficiency by encoding additional information bits in the indices of active delay-Doppler resources. Recent schemes include OTFS-based code index modulation [3], joint delay-Doppler index modulation [4], OTFS-aided media-based modulation exploiting reconfigurable antennas [5], dual-mode index modulation, and blockwise index modulation designed for high-mobility OTFS communication. A dedicated survey systematically categorizes these OTFS-IM schemes by system architecture, detection method, and performance trade-off, concluding that OTFS-IM variants can improve spectral or energy efficiency relative to plain OTFS at the cost of additional index-detection complexity [6].

5. Affine Frequency Division Multiplexing (AFDM)

Affine frequency division multiplexing (AFDM) is a chirp-based waveform proposed by Bemani, Ksairi, and Kountouris that modulates information symbols in the discrete affine Fourier transform (DAFT) domain using chirp basis functions parameterized by two tunable chirp rates [13]. By tuning these chirp parameters to the channel's delay-Doppler profile, AFDM can achieve full diversity in doubly dispersive channels, a property that neither OFDM nor, in general, OTFS guarantees without additional precoding. A comparative study positions AFDM alongside OTFS as next-generation waveform candidates for ISAC in doubly dispersive channels, noting that AFDM retains an OFDM-like single-carrier-per-chirp structure that simplifies implementation relative to OTFS's two-dimensional symplectic transform [14].

AFDM has attracted particular attention for integrated sensing and communication: because chirp signals are naturally suited to radar-style delay-Doppler estimation, AFDM-based ISAC systems have been proposed that jointly estimate channel, data, and radar parameters from the same affine-domain waveform [15]. Practical enablers such as diagonally reconstructed channel estimation for MIMO-AFDM under inter-Doppler interference [16] and AFDM combined with sparse code multiple access (AFDM-SCMA) for massive connectivity over high-mobility channels [17] have extended AFDM from a point-to-point waveform toward a multi-user, multi-antenna candidate for 6G access networks. Index-modulation variants of AFDM, including pre-chirp-domain index modulation for full diversity, and chirp-permutation index modulation, mirror the OTFS-IM trend of layering resource-index encoding onto the base waveform to further raise spectral efficiency.

6. Index Modulation and NOMA-Aided Modulation

Index modulation (IM) is a general modulation paradigm in which information is conveyed not only by conventional constellation symbols but also by the on/off pattern or identity of active transmission resources — subcarriers, antennas, time slots, or delay-Doppler bins. Basar's foundational treatment of index modulation for 5G networks and the subsequent OFDM-IM framework of Başar et al. established the core subcarrier-activation approach [7]; Cheng et al. review how activating a subset of building blocks such as antennas, subcarriers, and time slots allows IM schemes to trade constellation size for resource-index information, improving energy and spectral efficiency simultaneously [8]. Ishikawa, Sugiura, and Hanzo's survey traces five decades of permutation, spatial, and index modulation research, spanning classic RF systems through visible light communication and data storage, and situates 5G/6G index modulation within this broader historical arc [9]. More recently, Li et al. formalize index modulation multiple access (IMMA) as a unifying framework for 6G, discussing its principles, application scenarios, and open implementation challenges [10].

IM has also been combined with non-orthogonal multiple access (NOMA) to boost connectivity: uplink index-modulated NOMA schemes have been analyzed for 6G, showing spectral-efficiency gains over conventional NOMA when index and power-domain multiplexing are jointly optimized [23]. Pattern division multiple access (PDMA), which exploits pattern-domain resource allocation, represents a related non-orthogonal multiple access technique originally proposed for 5G that shares design philosophy with IM-NOMA [24]. Multiple-input multiple-output OFDM with index modulation has additionally been shown to extract spatial-domain gains for next-generation wireless networks by activating a subset of transmit antennas jointly with subcarrier indices.

7. Comparative Analysis

Table 1 summarizes the qualitative trade-offs among the waveform and modulation families reviewed above. OFDM remains attractive for its low complexity but is the weakest performer under high Doppler. FBMC offers the best spectral containment at the price of complexity and loss of strict orthogonality. GFDM and UFMC occupy an intermediate position, trading flexibility for moderate implementation overhead. OTFS and AFDM both target doubly dispersive 6G channels from different mathematical domains — delay-Doppler versus affine/chirp — with OTFS offering more mature detector and channel-estimation literature and AFDM offering lower structural complexity and a more natural fit for ISAC. Index modulation is best understood as an orthogonal design axis that can be layered onto any of the above waveforms to improve spectral or energy efficiency at the cost of index-detection complexity.

Table 1. Qualitative Comparison of 5G and 6G Modulation / Waveform Candidates

Technique	Domain	PAPR	Doppler Robustness	Complexity	Primary Target
OFDM	Time-Frequency	High	Poor (high mobility)	Low	4G / 5G eMBB
FBMC	Time-Frequency (filtered)	Moderate–High	Moderate	Moderate–High	5G fragmented spectrum
UFMC	Time-Frequency (sub-band filtered)	Moderate	Moderate	Moderate	5G short-burst mMTC
GFDM	Time-Frequency (block filtered)	Moderate	Moderate	Moderate	5G flexible numerology
OTFS	Delay-Doppler	Moderate–High	Excellent	High	6G high-mobility, NTN
AFDM	Affine (chirp) domain	Moderate	Excellent (full diversity)	Moderate–High	6G ISAC, doubly dispersive
Index Modulation (OFDM-IM/OTFS-IM)	Resource-index augmented	Low–Moderate	Good (variant-dependent)	Moderate	6G energy/spectral efficiency

8. Open Challenges and Future Directions

8.1 Receiver Complexity and Channel Estimation

Both OTFS and AFDM trade OFDM's simple single-tap equalization for denser effective channel matrices, requiring iterative or message-passing detectors [22] and specialized channel-estimation procedures under inter-Doppler interference [16]. Reducing this complexity gap while retaining Doppler robustness remains an open problem, particularly for low-cost mMTC devices.

8.2 Standardization and 3GPP/6G Waveform Selection

AFDM has already entered early 3GPP 6G waveform discussions, reflecting industry interest in chirp-based alternatives to OFDM. Whether OTFS, AFDM, an IM-augmented variant, or a hybrid waveform is ultimately standardized for 6G remains an open question that will depend on complexity-performance trade-offs validated in realistic deployment testbeds [20].

8.3 Integration with ISAC

Because both OTFS and AFDM naturally represent delay and Doppler, they are strong candidates for unifying communication and radar sensing in a single waveform [14], [15]. Open challenges include ambiguity-function optimization for joint sensing accuracy and communication throughput, and low-complexity joint parameter estimation for multi-target, multi-user scenarios.

8.4 AI/ML-Assisted Waveform Design

Machine-learning-assisted receivers and adaptive waveform selection — for example, ML-assisted schemes that dynamically choose between OTFS and OFDM based on channel and mobility conditions — represent a promising direction for reducing the complexity burden of next-generation waveforms while retaining their performance benefits.

8.5 PAPR and Energy Efficiency

PAPR reduction remains relevant across all candidate waveforms, since chirp-based and delay-Doppler waveforms do not automatically solve the power-amplifier efficiency problem inherited from multicarrier transmission. Adaptive chirp-parameter selection approaches for AFDM illustrate an emerging class of solutions that jointly target PAPR and channel adaptivity.

9. Conclusion

This survey has reviewed the modulation and waveform landscape spanning 5G and 6G wireless networks, from OFDM and its filtered/block variants (FBMC, UFMC, GFDM) to the delay-Doppler paradigm of OTFS and the emerging affine/chirp-domain paradigm of AFDM, alongside cross-cutting index-modulation and NOMA-aided techniques. No single waveform dominates across spectral efficiency, PAPR, Doppler robustness, and complexity simultaneously; rather, the choice of modulation is increasingly application-dependent, favoring OFDM for low-mobility eMBB, OTFS or AFDM for high-mobility and ISAC scenarios, and index-modulation variants where energy and spectral efficiency are paramount. Continued research on low-complexity detection, standardization, ISAC integration, and AI-assisted adaptive waveform selection will shape which of these techniques ultimately underpins commercial 6G systems.

References

[1] R. Hadani, S. Rakib, M. Tsatsanis, A. Monk, A. J. Goldsmith, A. F. Molisch, and R. Calderbank, “Orthogonal Time Frequency Space Modulation,” in Proc. IEEE Wireless Commun. Netw. Conf. (WCNC), 2017, pp. 1–6.

[2] A. Mohammadi et al., “Performance Study of OTFS Modulation in Mobility and Noisy Scenarios for 6G Communication Networks,” Int. J. Commun. Syst., Wiley, 2025.

[3] B. A. Ozden, E. Aydin, E. Aslandogan, H. Ilhan, E. Basar, M. Wen, and M. D. Renzo, “A New OTFS-Based Index Modulation System for 6G and Beyond: OTFS-Based Code Index Modulation,” in Proc. IEEE 36th Int. Symp. Personal, Indoor, Mobile Radio Commun. (PIMRC), 2025, pp. 1–6.

[4] Y. I. Tek and E. Basar, “Joint Delay-Doppler Index Modulation for Orthogonal Time Frequency Space Modulation,” IEEE Trans. Commun., vol. 72, no. 7, pp. 3985–3993, 2024.

[5] B. A. Ozden, M. Kaymaz, E. Aydin, E. Aslandogan, H. Ilhan, E. Basar, M. Wen, and M. D. Renzo, “Orthogonal Time-Frequency Space (OTFS) Aided Media-Based Modulation System for 6G and Beyond Wireless Communications Networks,” in Proc. IEEE 36th Int. Symp. Personal, Indoor, Mobile Radio Commun. (PIMRC), 2025, pp. 1–6.

[6] B. A. Ozden et al., “A Survey of OTFS-Based Index Modulation Techniques: Challenges, Benefits, and Future Directions for 6G and Beyond,” arXiv:2510.20265, 2025.

[7] E. Basar, “Index Modulation Techniques for 5G Wireless Networks,” IEEE Commun. Mag., vol. 54, no. 7, pp. 168–175, 2016.

[8] X. Cheng, M. Zhang, M. Wen, and L. Yang, “Index Modulation for 5G: Striving to Do More with Less,” IEEE Wireless Commun., vol. 25, no. 2, pp. 126–132, 2018.

[9] N. Ishikawa, S. Sugiura, and L. Hanzo, “50 Years of Permutation, Spatial and Index Modulation: From Classic RF to Visible Light Communications and Data Storage,” IEEE Commun. Surveys Tuts., vol. 20, no. 3, pp. 1905–1938, 2018.

[10] J. Li, S. Dang, M. Wen, Q. Li, Y. Chen, Y. Huang, and W. Shang, “Index Modulation Multiple Access for 6G Communications: Principles, Applications, and Challenges,” IEEE Network, vol. 37, no. 1, pp. 52–60, 2023.

[11] F. Conceição, M. Gomes, V. Silva, R. Dinis, A. Silva, and D. Castanheira, “A Survey of Candidate Waveforms for Beyond 5G Systems,” Electronics, vol. 10, no. 1, 2020.

[12] A. F. Demir, M. Elkourdi, M. Ibrahim, and H. Arslan, “Waveform Design for 5G and Beyond,” in 5G Networks: Fundamental Requirements, Enabling Technologies, and Operations Management, Wiley-IEEE Press, 2019, ch. 2, pp. 51–76.

[13] A. Bemani, N. Ksairi, and M. Kountouris, “Affine Frequency Division Multiplexing for Next Generation Wireless Communications,” IEEE Trans. Wireless Commun., vol. 22, no. 11, pp. 8214–8229, Nov. 2023.

[14] H. S. Rou, G. T. F. de Abreu, J. Choi, D. Gonzalez G., M. Kountouris, Y. L. Guan, and O. Gonsa, “From Orthogonal Time Frequency Space to Affine Frequency-Division Multiplexing: A Comparative Study of Next-Generation Waveforms for Integrated Sensing and Communications in Doubly Dispersive Channels,” IEEE Signal Process. Mag., vol. 41, no. 5, pp. 71–86, Sept. 2024.

[15] Y. H. Ni, P. Yuan, Q. Huang, F. Liu, and Z. L. Wang, “An Integrated Sensing and Communications System Based on Affine Frequency Division Multiplexing,” IEEE Trans. Wireless Commun., vol. 24, no. 5, pp. 3763–3779, 2025.

[16] H. Yin, X. Wei, Y. Tang, and K. Yang, “Diagonally Reconstructed Channel Estimation for MIMO-AFDM with Inter-Doppler Interference in Doubly Selective Channels,” IEEE Trans. Wireless Commun., vol. 23, no. 10, pp. 14066–14079, Oct. 2024.

[17] Q. Luo, P. Xiao, Z. Liu, Z. Wan, and N. Ding et al., “AFDM-SCMA: A Promising Waveform for Massive Connectivity over High Mobility Channels,” IEEE Trans. Wireless Commun., vol. 23, no. 10, pp. 14421–14436, Oct. 2024.

[18] M. Chafii, L. Bariah, S. Muhaidat, and M. Debbah, “Twelve Scientific Challenges for 6G: Rethinking the Foundations of Communications Theory,” IEEE Commun. Surveys Tuts., vol. 25, no. 2, pp. 868–904, 2nd Quarter 2023.

[19] M. Alsabah, M. A. Naser, B. M. Mahmmod, S. H. Abdulhussain, M. R. Eissa, A. Al-Baidhani, N. K. Noordin, S. M. Sait, K. A. Al-Utaibi, and F. Hashim, “6G Wireless Communications Networks: A

Comprehensive Survey," IEEE Access, vol. 9, pp. 148191–148243, 2021.

[20] C.-X. Wang et al., "On the Road to 6G: Visions, Requirements, Key Technologies, and Testbeds," IEEE Commun. Surveys Tuts., vol. 25, no. 2, pp. 905–974, 2nd Quarter 2023.

[21] L. Gaudio, G. Colavolpe, and G. Caire, "OTFS vs. OFDM in the Presence of Sparsity: A Fair Comparison," IEEE Trans. Wireless Commun., vol. 21, no. 6, pp. 4410–4423, June 2022.

[22] P. Raviteja, K. T. Phan, Y. Hong, and E. Viterbo, "Interference Cancellation and Iterative Detection for Orthogonal Time Frequency Space Modulation," IEEE Trans. Wireless Commun., vol. 17, no. 10, pp. 6501–6515, 2018.

[23] Y.-K. Bae, J. S. Yeom, and B. C. Jung, "Performance Analysis of Uplink Index-Modulated NOMA for 6G Wireless Communications," IEEE Wireless Commun. Lett., vol. 12, no. 8, pp. 1404–1408, 2023.

[24] X. Dai, Z. Zhang, B. Bai, S. Chen, and S. Sun, "Pattern Division Multiple Access: A New Multiple Access Technology for 5G," IEEE Wireless Commun., vol. 25, no. 2, pp. 54–60, 2018.

[25] E. Başar, Ü. Aygölü, E. Panayırcı, and H. V. Poor, "Orthogonal Frequency Division Multiplexing with Index Modulation," IEEE Trans. Signal Process., vol. 61, no. 22, pp. 5536–5549, 2013.

[26] E. Basar, "On Multiple-Input Multiple-Output OFDM with Index Modulation for Next Generation Wireless Networks," IEEE Trans. Signal Process., vol. 64, no. 15, pp. 3868–3878, 2016.