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Research Article

Quantum-Inspired FBMC Transceivers for 6G: Potential Applications, Fundamentals, Opportunities, Advantages, Challenges, Future Trends

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ABSTRACT

The forthcoming sixth-generation (6G) networks require transformative improvements in spectral efficiency, latency, and energy performance. This review highlights the novelty of integrating quantum-inspired approaches with Filter Bank Multicarrier (FBMC) transceivers, offering a new paradigm for 6G communication. The fusion of quantum-inspired algorithms with FBMC enables advanced interference management, improved robustness, and adaptability for diverse applications such as intelligent transportation, immersive extended reality, and ultra-reliable low-latency communication. Key challenges, including hardware complexity, scalability, and algorithmic optimization, are critically examined. The article further outlines future research directions, emphasizing how this integration can shape efficient, intelligent, and resilient 6G transceivers.

1. INTRODUCTION

The rapid evolution of wireless communication systems has led to significant breakthroughs in mobile networks, transitioning from 1G analog systems to the highly sophisticated 5G networks that offer enhanced data rates, low latency, and massive connectivity. As we look toward the sixth generation (6G) of wireless communication, new paradigms must be explored to meet the unprecedented demands of future applications such as holographic communication, pervasive intelligent environments, extended reality (XR), and ultra-reliable low-latency communication (URLLC) [1-2]. These next-generation applications require not only higher spectral and energy efficiency but also robust transceiver architectures capable of operating in dynamic and heterogeneous environments. In this context, Filter Bank Multicarrier (FBMC) modulation has emerged as a prominent candidate for future wireless systems due to its improved spectral efficiency, reduced out-of-band (OoB) emissions, and the ability to function without the need for cyclic prefix, which is a limitation in traditional Orthogonal Frequency Division Multiplexing (OFDM). FBMC offers a strong advantage in highly fragmented and interference-prone spectral environments, making it particularly suitable for 6G use cases such as device-to-device (D2D) communication, machine-type communication (MTC), and non-terrestrial networks (NTN). Its ability to provide better frequency localization through the use of prototype filters enhances its performance in asynchronous and dynamic multiuser scenarios. Despite these strengths, challenges in FBMC transceiver design, such as increased computational complexity, synchronization issues, and channel estimation difficulties, remain a barrier to widespread adoption. To overcome these limitations and further enhance the capabilities of FBMC systems, researchers are turning toward quantum-inspired methodologies, which draw on the mathematical frameworks and computational concepts of quantum mechanics without requiring quantum hardware. Quantum-inspired computing (QIC) techniques, such as quantum-inspired optimization, entanglement-based signal processing, and amplitude amplification strategies, offer novel solutions to long-standing problems in wireless communication. When applied to FBMC transceivers, these approaches can potentially improve signal processing efficiency, optimize resource allocation, and enhance channel estimation accuracy. Quantum-inspired models also exhibit potential in improving the resilience of FBMC systems against noise and interference, thereby addressing some of the inherent design challenges faced by conventional transceivers.

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Figure 1 shows evolution of Mobile Communication from 1G to 6G [3]. The intersection of FBMC and quantum-inspired methodologies is particularly timely, as 6G will operate in an environment characterized by ultra-dense network deployments, high-mobility users, and diverse service requirements. In such scenarios, classical signal processing and optimization techniques may fall short in meeting the growing complexity and real-time requirements. By adopting quantum-inspired methods, FBMC transceivers can achieve adaptive and intelligent behavior, paving the way for more efficient modulation, coding, and resource management strategies.

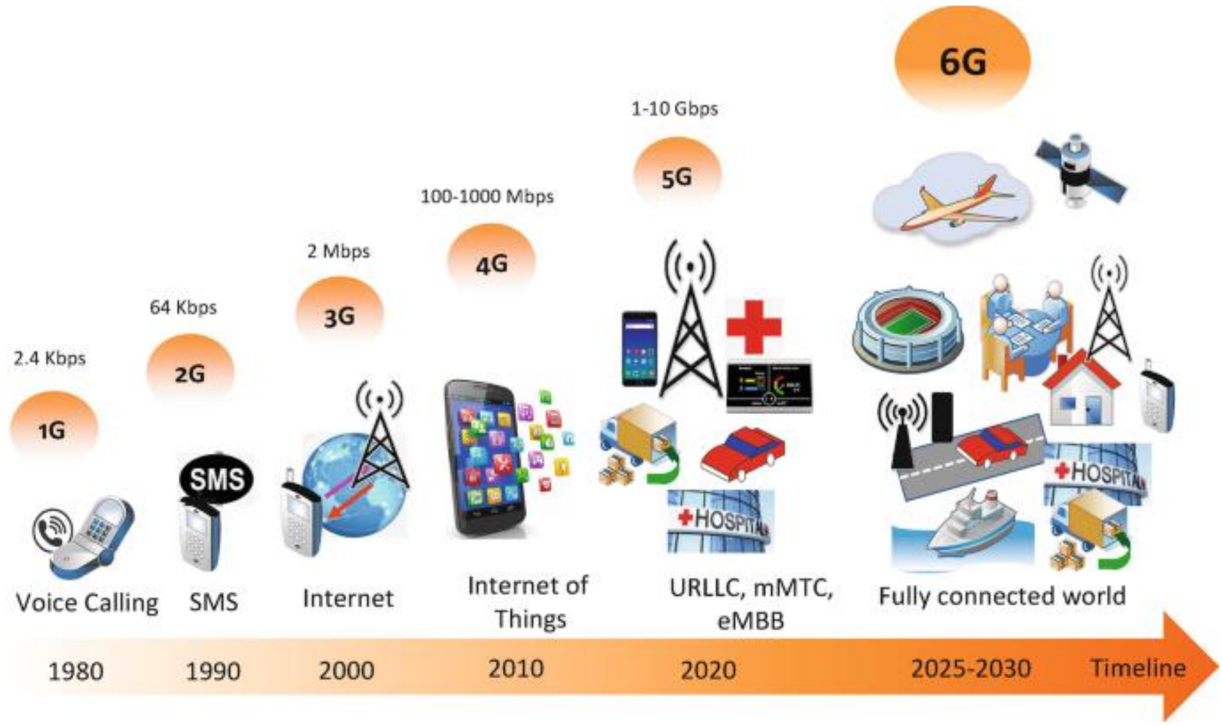

Fig. 1. 1G to 6G [3]

Traditional solutions such as OFDM and classical optimization techniques face several limitations when addressing the stringent requirements of 6G systems. OFDM suffers from poor spectral containment and high out-of-band leakage due to its cyclic prefix and rectangular pulse shaping, making it less efficient in fragmented spectrum environments. Moreover, classical metaheuristic and deterministic optimization methods often struggle with the high dimensionality and nonlinearity of 6G problems, frequently getting trapped in local optima. In contrast, FBMC offers superior spectral efficiency and reduced interference by eliminating the cyclic prefix and employing well-localized filters, making it more suitable for heterogeneous 6G scenarios. When combined with quantum-inspired optimization methods, which leverage principles such as superposition and parallelism to achieve better global search capability, the framework becomes highly effective in addressing challenges like PAPR reduction, resource allocation, and adaptive signal design. This integration provides a robust and scalable solution that overcomes the shortcomings of traditional approaches and aligns with the performance expectations of future 6G networks. This review provides an overview of integrating quantum-inspired techniques into FBMC transceiver design for 6G networks. It first outlines the fundamentals of FBMC, including its structure, filtering strategies, and performance advantages over other multicarrier systems. It then introduces the principles of quantum-inspired computing and explains their relevance to practical transceiver architectures. The review highlights opportunities from this convergence, such as improved spectral utilization, enhanced interference mitigation, and efficient multiuser support. It also discusses the advantages of quantum-inspired FBMC in meeting 6G requirements, along with key challenges like hardware constraints, algorithmic complexity, and scalability. Finally, it examines recent research, experimental efforts, and future trends shaping this field. By combining FBMC modulation with quantum-inspired optimization, this emerging approach offers robust and efficient transceiver solutions for next-generation communication systems.

2. 6G COMMUNICATIONS

The 6G wireless communication system is envisioned as the successor of the current 5G technology, aiming to revolutionize connectivity by enabling ultra-high-speed, low-latency, and intelligent communication systems. While 5G has laid the foundation for enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type communications, 6G seeks to push these boundaries significantly further. It is expected to support data rates in the order of terabits per second (Tbps), sub-millisecond latency, ubiquitous connectivity, and real-time responsiveness across a highly diversified range of applications and environments [4-7]. Figure 2 illustrates the 6G communication paradigm.

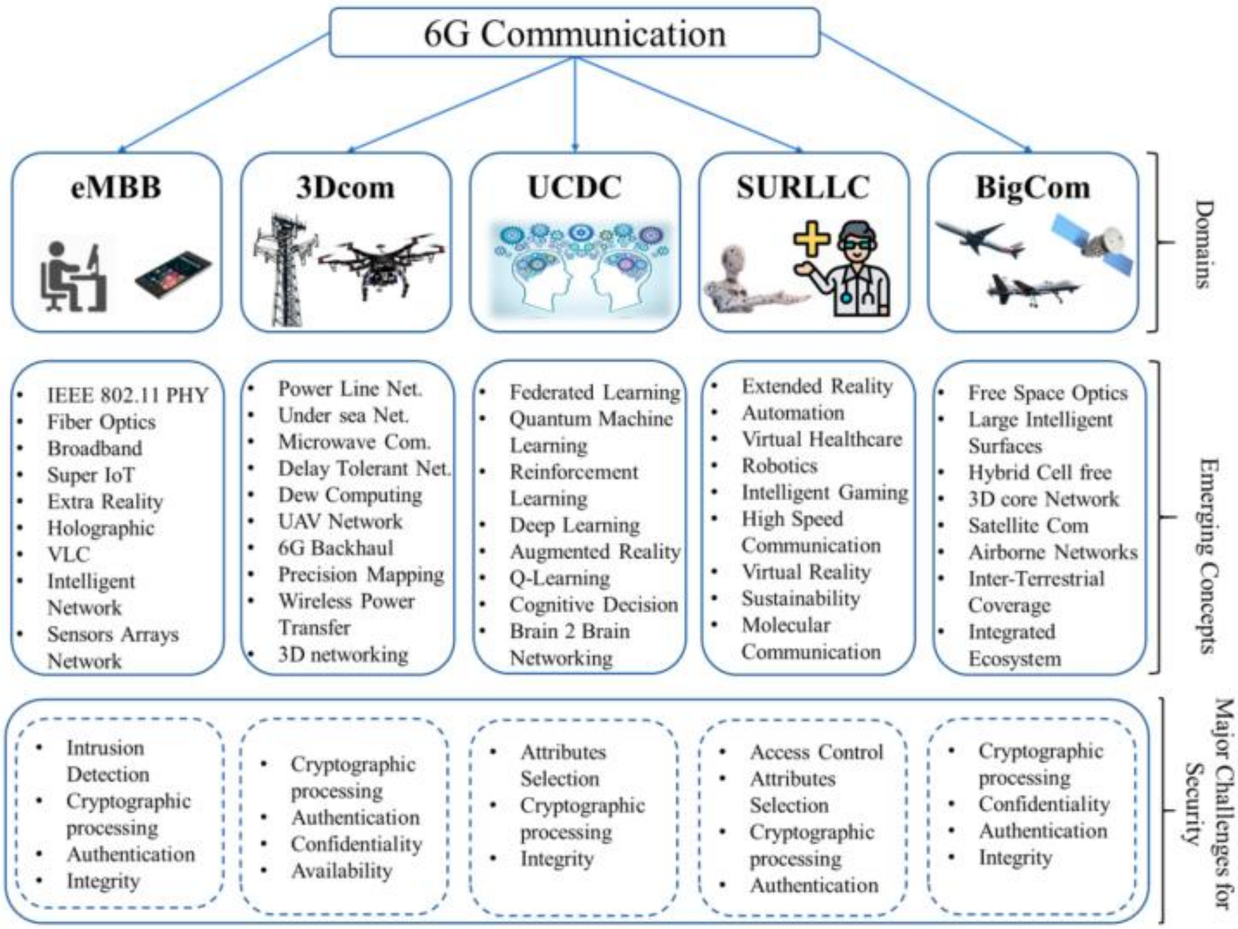

Fig. 2. 6G communication paradigm [8]

2.1 Fundamentals of 6G Communication

At the core of 6G technology lies the ambition to seamlessly integrate the physical and digital worlds through advanced wireless networks. Building upon existing cellular architectures, 6G is expected to introduce new paradigms such as integrated sensing and communication, joint communication and computation, reconfigurable intelligent surfaces, and three-dimensional (3D) network architectures [9]. The key principles driving this vision include achieving high spectral efficiency with ultra-low latency, enabling massive connectivity to support the dynamic and mobile Internet of Everything (IoE), and ensuring smooth integration with non-terrestrial networks (NTNs) such as satellites and high-altitude platforms. Additionally, 6G will rely on advanced coding, modulation, and multiple-access techniques to enhance performance, while network virtualization and slicing will allow customized service delivery tailored to the diverse requirements of future industries.

2.2 Frequency Bands for 6G

6G communication is expected to utilize a broad spectrum of frequency ranges, with a particular expansion into the sub-terahertz (sub-THz) and terahertz (THz) bands above 100 GHz. These higher frequency ranges promise extremely high data rates and wide bandwidth availability, but they also introduce significant challenges such as signal attenuation, high path loss, and limited propagation distance [10]. To ensure both backward compatibility and future scalability, 6G will operate across multiple bands, including sub-6 GHz for broad coverage, millimeter-wave (mmWave) frequencies between 30 GHz and 100 GHz to extend 5G capabilities, and THz bands ranging from 100 GHz to 10 THz for ultra-wideband channels supporting terabit-per-second communication. Additionally, visible light communication (VLC) and infrared bands are being explored for specialized high-speed indoor connectivity, further diversifying the frequency resources available to 6G systems. Innovative antenna technologies, such as massive multiple-input multiple-output (MIMO), ultra-massive MIMO, and beamforming techniques, will be essential to effectively utilize these high-frequency bands and to ensure reliable communication. Figure 3 presents the EM spectrum and its potential application.

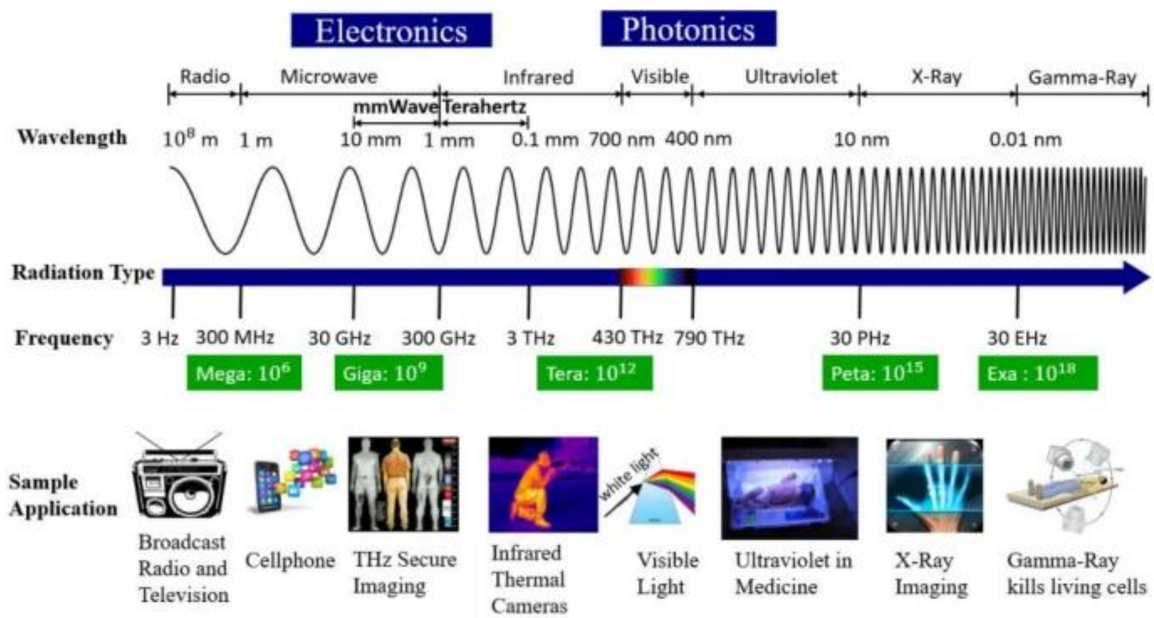

Fig. 3. EM spectrum and possible Applications [11]

2.3 Potential Applications

6G is expected to support a wide range of applications that go beyond enhancing mobile broadband, enabling entirely new services across industries. Among the most prominent use cases are holographic telepresence and immersive extended reality (XR), which demand ultra-high throughput and ultra-low latency to deliver seamless user experiences. Autonomous transportation systems, including self-driving vehicles, drones, and maritime vessels, will rely on real-time sensor communication to ensure safety and efficiency. In the healthcare sector, 6G will facilitate smart healthcare solutions such as remote surgeries, body-area networks, and continuous health monitoring. Industrial domains will benefit from digital twins and advanced automation, where precise synchronization and reliable data exchange are essential. Additionally, space-air-ground integrated networks will provide uninterrupted global connectivity, while remote education and telemedicine will be transformed through haptic communication and high-fidelity interactive video. Figure 4 depicts key 6G-based applications.

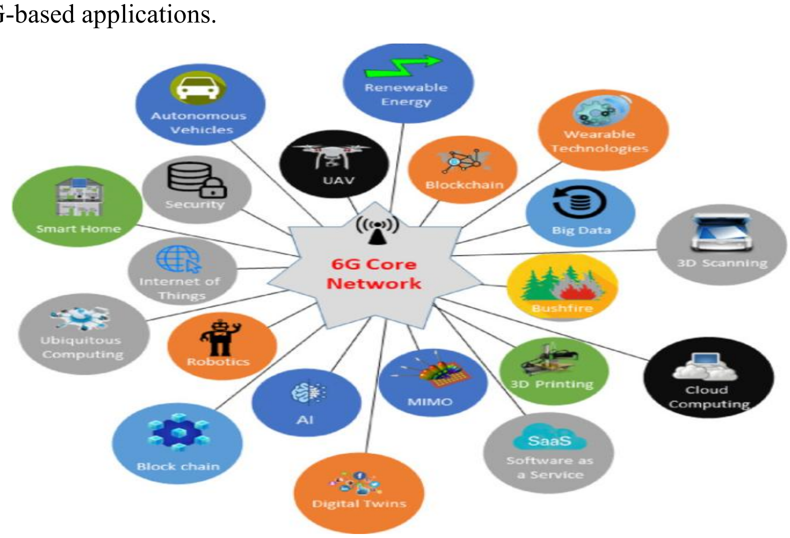

Fig. 4. 6G based Applications [12]

2.4 Opportunities

6G presents numerous technological and societal opportunities [13], ranging from bridging the digital divide through satellite–terrestrial convergence to empowering future industries such as Industry 5.0 with intelligent connectivity and automation. It will also enhance disaster response by enabling rapidly deployable and adaptable communication platforms, while promoting sustainability through energy-efficient designs and green communication protocols. Furthermore, 6G will facilitate the convergence of communication, sensing, and control, supporting the development of intelligent urban systems and advanced environmental monitoring.

2.5 Advantages

The transition to 6G is expected to deliver several advantages over previous generations, most notably unprecedented data rates that could exceed 1 Tbps, enabling real-time transmission of ultra-high-definition content. It will also achieve sub-millisecond latency, which is vital for mission-critical applications and high-speed automation. Beyond performance gains, 6G will support massive connectivity, with the capacity to handle tens of millions of devices per square kilometer, while offering hyper-reliable and secure communication essential for sensitive domains such as finance, defense, and healthcare. Additionally, integrated intelligence will be embedded into the network, allowing it to adapt dynamically and self-optimize in response to diverse and evolving service requirements.

2.6 Challenges

Despite its vast potential, the development and deployment of 6G face several critical challenges. One major issue is spectrum availability and regulation, particularly for terahertz (THz) and visible light communication (VLC) bands, which are not yet fully allocated for commercial use. Hardware limitations also pose difficulties, as designing energy-efficient transceivers and antennas capable of operating in the THz range remains complex. Additionally, high propagation loss and susceptibility to signal blockage at THz frequencies demand the dense deployment of supporting infrastructure, raising cost and feasibility concerns. Security and privacy risks are another pressing challenge, given the massive data collection and sharing envisioned in 6G-enabled systems. Furthermore, achieving standardization and interoperability will require extensive global coordination, research, and testing to ensure seamless integration across devices and networks. Finally, environmental and health considerations related to exposure to new frequency ranges must be thoroughly investigated to ensure safe and sustainable adoption of 6G technologies. Figure 5 illustrates the main challenges of 6G.

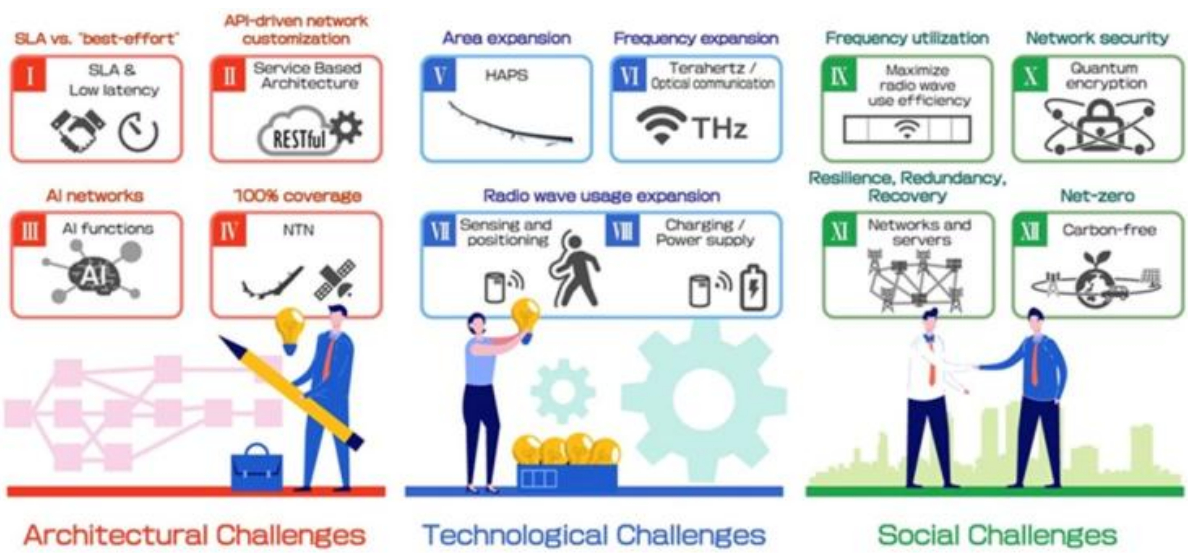

Fig. 5. Challenges of 6G

2.7 Future Trends

The development of 6G is expected to be shaped by several key trends that will define its capabilities and applications. One major direction is the integration of communication and sensing, where networks will not only transmit information but also actively perceive and interpret the surrounding environment. Energy-aware network design will also play a crucial role, with a strong focus on sustainability, efficiency, and achieving carbon neutrality. Moreover, 6G will increasingly adopt distributed architectures, leveraging edge computing and device-to-device (D2D) communication to enable localized and real-time data processing. Another significant trend is the incorporation of quantum communication and advanced security mechanisms, ensuring future-proof data integrity and confidentiality against evolving threats. The rise of software-defined everything (SDx), including programmable hardware and intelligent network control, will further enhance adaptability and performance. Finally, global spectrum harmonization will be essential to make 6G truly universal, ensuring seamless connectivity and accessibility across different regions of the world. In the context of 6G, the direct link to FBMC and quantum-inspired transceivers lies in addressing the key challenges of next-generation wireless systems. 6G is envisioned to support ultra-high data rates, sub-millisecond latency, and massive device connectivity, which require more advanced and efficient waveform designs than conventional OFDM. FBMC emerges as a strong candidate due to its high spectral efficiency, minimal out-of-band leakage, and robustness in asynchronous and high-mobility environments, making it well-suited for dense 6G networks. At the same time, the complexity of real-time optimization in 6G, including adaptive resource allocation, interference management, and enhanced security, necessitates the use of advanced computational approaches. Quantum-inspired transceivers offer promising solutions by leveraging quantum-inspired algorithms to improve signal processing, reduce PAPR, enhance error performance, and ensure secure communications. Together, FBMC's efficient waveform structure and quantum-inspired transceiver designs directly align with the goals of 6G, providing a pathway to achieve the required performance, efficiency, and adaptability. 6G communication envisions a hyper-connected world, where people, machines, and environments are seamlessly linked by intelligent, fast, and reliable networks. As research, development, and standardization efforts progress over the next decade, 6G is set to be a cornerstone of future digital society, enabling unprecedented applications, services, and economic growth.

3. QUANTUM COMMUNICATION

Quantum communication is an emerging field that leverages the fundamental principles of quantum mechanics to transmit information in a secure and efficient manner. Unlike classical communication, which encodes data using bits (0s and 1s), quantum communication utilizes quantum bits, or qubits, which can exist in a superposition of states. This allows quantum systems to process and transfer information in fundamentally different ways, offering unique advantages such as unbreakable security and the potential for entanglement-based connectivity. As the world moves toward 6G networks, quantum communication is expected to play a critical role in enabling secure, high-speed, and intelligent communication infrastructures [14]. Figure 6 illustrates the role of quantum computing in 6G.

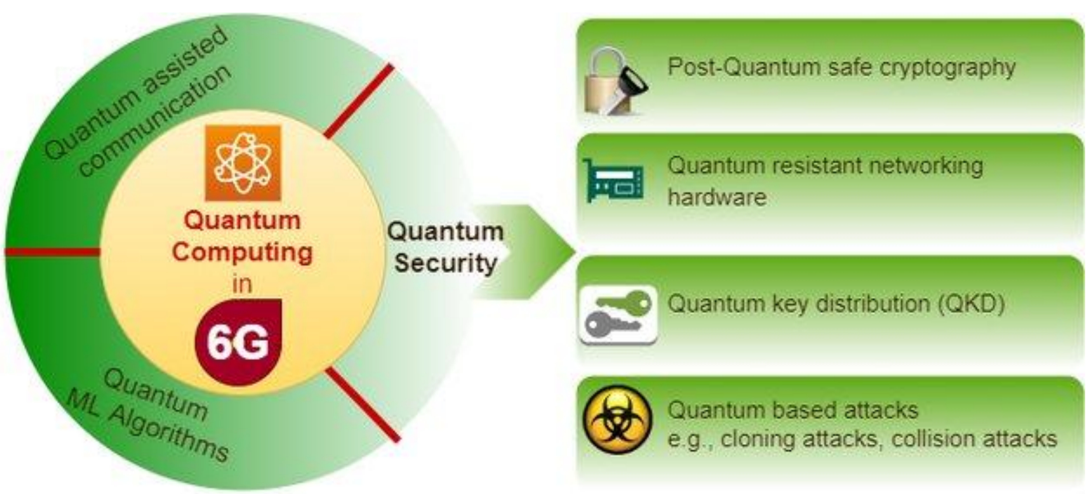

Fig. 6. Role of quantum computing in 6G [15]

3.1 Basics of Quantum Communication

At its core, quantum communication leverages the unique properties of quantum particles, particularly photons, to enable highly secure data transmission. The two foundational principles are **superposition**, where a qubit can exist in multiple states simultaneously unlike a classical bit, and **entanglement**, where particles remain correlated in such a way that the state of one instantly influences the other, regardless of distance. These properties form the basis for novel communication protocols, the most notable being Quantum Key Distribution (QKD). QKD allows two parties to share encryption keys with the ability to detect any eavesdropping attempt, thereby ensuring unmatched security. This capability holds significant importance for future 6G networks and FBMC-based transceivers, where massive data exchange and ultra-reliable security will be critical to maintaining privacy and trust.

3.2 Enabling Quantum Technologies in 6G

Integrating quantum communication into the 6G ecosystem requires the seamless convergence of classical and quantum technologies across multiple communication layers. Within the 6G architecture, quantum communication is expected to serve as a foundational pillar by enabling secure communication links for critical infrastructure, ensuring resilience against advanced cyber threats. It will also support the development of quantum networks that interconnect quantum computers, sensors, and communication devices, thereby creating an integrated quantum-classical environment. Furthermore, distributed quantum computing will become feasible, allowing quantum processors to collaborate efficiently over long distances. In addition, quantum-enhanced mechanisms will play a vital role in strengthening data integrity and privacy within massive IoT environments, making them more reliable and secure. When aligned with FBMC-based transceivers, these capabilities can help achieve robust, efficient, and future-proof communication systems in the 6G era. To support this integration, advancements in both hardware and protocols are essential. Photonic technologies such as single-photon detectors, sources, and quantum-compatible transceivers must become scalable and compatible with current fiber and free-space communication systems. Moreover, hybrid classical-quantum interfaces need to be developed for seamless communication between conventional and quantum devices. Quantum communication in 6G also opens the door to ultra-precise sensing and timing applications. Quantum sensors embedded within the 6G framework could offer real-time environmental monitoring, precise location tracking, and high-resolution imaging capabilities. Figure 7 illustrates the enabling quantum technologies in 6G.

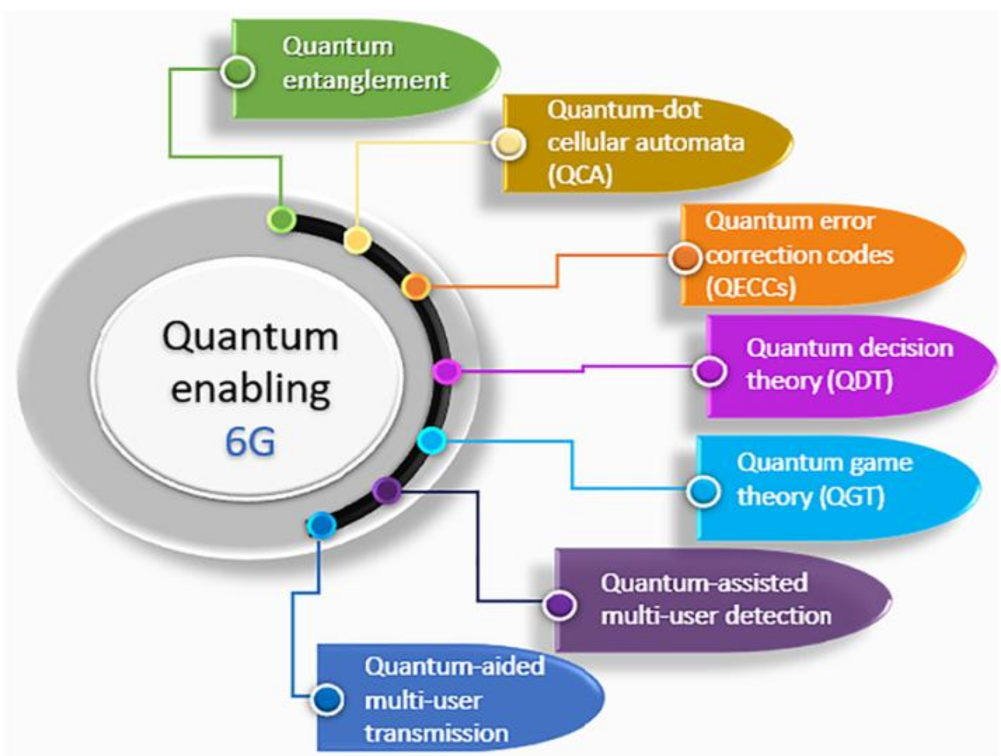

Fig. 7. Enabling quantum technologies in 6G [18]

3.3 Quantum Security

Security is one of the most compelling reasons for incorporating quantum communication into future networks. As classical encryption methods become vulnerable to quantum computing attacks, quantum security solutions offer a future-proof alternative [19]. QKD is a leading technique in quantum security. It allows two parties to generate a shared, secret random key, which can then be used for classical encryption. The security of QKD does not rely on the complexity of mathematical problems (as in RSA or ECC), but on the laws of physics. Any eavesdropping attempt will disturb the quantum states being transmitted and thus be detectable. Quantum security can also be extended to network-wide encryption, authentication, and integrity checks. In a 6G context, this means highly secure end-to-end communication for applications ranging from autonomous vehicles and smart grids to military communications and financial systems. Moreover, post-quantum cryptography (PQC), though a classical technique, may be combined with quantum security protocols to ensure robust defenses against both current and future threats.

3.4 Quantum Repeaters

One of the key limitations of quantum communication lies in the distance problem, as quantum signals particularly those based on photons cannot be amplified through classical methods due to the no-cloning theorem, which prevents the duplication of unknown quantum states. To overcome this challenge, quantum repeaters are employed, enabling long-distance quantum communication by dividing the transmission path into shorter segments. Within each segment, entanglement is generated and stored until it can be extended across the entire link through a chain of entanglement connections. A quantum repeater typically comprises three critical components: quantum memory for temporary storage of quantum states, entanglement swapping mechanisms to connect distant qubits, and error correction techniques to preserve transmission fidelity. By leveraging these functions, quantum repeaters make global-scale quantum communication feasible, enabling secure links across cities, countries, and continents. In the context of 6G, the deployment of quantum repeaters will be vital for establishing wide-area quantum communication networks that deliver both high reliability and enhanced security, particularly when integrated with FBMC-based transceiver architectures.

3.5 Quantum Interconnects

Quantum interconnects play a crucial role in linking diverse quantum devices such as processors, sensors, and communication modules, thereby enabling interoperability and scalability within emerging quantum networks. These interconnects allow the seamless transfer of quantum information across different components by performing essential functions such as converting quantum states between various physical mediums (e.g., photons to ions), maintaining entanglement between distant nodes, and synchronizing operations between quantum and classical systems. Despite being a major research challenge due to the need for high efficiency and minimal signal loss, the development of robust quantum interconnects is fundamental for realizing advanced applications like quantum data centers, distributed quantum computing, and cross-layer quantum communication in 6G networks. Overall, quantum communication is expected to serve as a cornerstone of future 6G systems by delivering secure, efficient, and intelligent connectivity far beyond the capabilities of classical technologies. Through the integration of enabling elements such as quantum repeaters and interconnects, alongside fundamental principles like superposition and entanglement, 6G can overcome challenges related to security, latency, and long-distance communication. Nonetheless, large-scale realization will require significant advancements in hardware design, network integration, and protocol standardization. As research progresses, quantum communication is poised not only to secure digital infrastructures but also to redefine the boundaries of global communication and computation, particularly when aligned with FBMC-based transceivers for next-generation networks.

4. FILTER BANK MULTICARRIER (FBMC) SYSTEM IN ADVANCED COMMUNICATION SYSTEMS

FBMC is a spectrally efficient multicarrier modulation technique that offers enhanced time-frequency localization and reduced OoB emissions compared to OFDM. As advanced communication systems, including 5G and beyond, require increased spectral efficiency, low latency, and improved energy efficiency, FBMC emerges as a strong candidate due to its inherent properties such as the absence of CP, high spectral confinement, and better resistance to synchronization errors. The operation of a FBMC system is based on dividing the available bandwidth into multiple narrow subcarriers, each modulated with real-valued data symbols and filtered using a carefully designed prototype filter. Unlike OFDM, which uses a rectangular pulse and CP, FBMC avoids the use of a CP by employing well-localized filtering per subcarrier, significantly reducing spectral leakage and improving spectral efficiency. At the transmitter, the input data stream is first mapped to complex-valued symbols, typically using modulation schemes like QAM. These complex symbols are then separated into real and imaginary parts and staggered in time using Offset QAM (OQAM). This staggering ensures that only real parts overlap in time and frequency, preserving orthogonality in the real domain [22-24]. Each real-valued symbol is then modulated onto a specific subcarrier frequency and passed through a prototype filter. This filter shapes the signal in both time and frequency domains, improving spectral confinement. The filtered subcarrier signals are summed to form the overall FBMC transmitted signal. At the receiver, the incoming signal is passed through a bank of matched filters, each tuned to a particular subcarrier. After demodulation and recombination of the real and imaginary parts (using OQAM post-processing), the original complex data symbols are recovered. This process ensures minimal inter-symbol and inter-carrier interference without requiring a cyclic prefix, thus improving bandwidth usage and performance in advanced communication systems. Figure 8 depicts the block diagram of FBMC system.

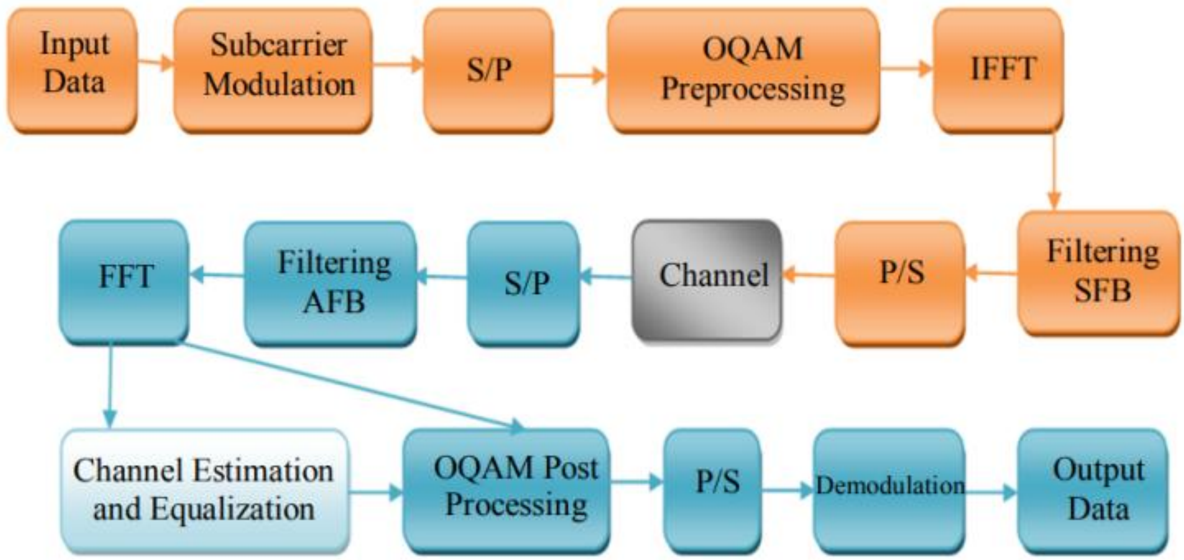

Fig. 8. FBMC System [21]

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4.1 Fundamentals of FBMC System

FBMC is a multicarrier scheme in which each subcarrier is filtered individually using a prototype filter, leading to excellent frequency localization. Unlike OFDM, which employs rectangular pulse shaping and requires a cyclic prefix to mitigate inter-symbol interference (ISI), FBMC uses well-designed prototype filters, thereby avoiding the need for CP and enhancing spectral efficiency [25]. In FBMC, the transmitted signal is composed of a set of time-frequency localized pulses, generated through filtering and modulation operations. The modulation scheme commonly associated with FBMC is OQAM, which helps in maintaining orthogonality in the real domain.

4.2 Transmitter Model

The baseband transmitted signal in an FBMC-OQAM system is represented as:

$$s(t)=\sum_{n=-\infty}^{\infty}\sum_{k=0}^{K-1}a_{k,n}.g\left(t-\frac{nT}{2}\right).e^{j2\pi kFt}$$

Where $a_{k,n}$ represents the real-valued OQAM symbols, g(t) is the prototype filter, T is the symbol duration, F is the subcarrier spacing, k is the subcarrier index, and n is the time index. OQAM modulation involves the transmission of real-valued symbols with a half-symbol offset in time between the in-phase and quadrature components, thereby enabling the system to maintain orthogonality without CP [26]. The OQAM symbols $a_{k,n}$ are derived from the complex-valued QAM data symbols dk,n as follows:

$$a_{k,n} = \begin{cases} R\{d_{k,n}\}, \ if \ k+n \ is \ even \\ I\{d_{k,n}\}, \ if \ k+n \ is \ odd \end{cases}$$

This offset scheme leads to a time-frequency tiling where adjacent symbols in time or frequency are shifted by half a symbol period, ensuring minimal interference.

4.3 Prototype Filter Design

A well-designed prototype filter g(t) is central to the performance of FBMC. One of the most commonly used filters is the PHYDYAS filter, which satisfies the orthogonality and time-frequency localization conditions [27]. The prototype filter is designed to meet the following orthogonality condition:

$$\int_{-\infty}^{\infty} g(t).g(t-mT).e^{-j2\pi kFt}dt = 0; \ for \ m \neq k \neq 0$$

This ensures that different subcarriers and symbol intervals do not interfere with each other.

4.4 Polyphase Network Implementation

The implementation of FBMC systems is efficiently realized using a Polyphase Network (PPN) structure in combination with an Inverse Fast Fourier Transform (IFFT). At the transmitter, the process begins with OQAM preprocessing, where QAM symbols are converted into Offset-QAM (OQAM) symbols to ensure orthogonality in the real domain. These symbols are then passed through polyphase filtering, where the prototype filter is applied using polyphase decomposition to minimize complexity. The IFFT block follows, converting the signal from the frequency domain to the time domain, after which the outputs of all subcarriers are summed to generate the final FBMC signal. The polyphase implementation is particularly advantageous as it significantly reduces computational complexity by exploiting the inherent structure of the filter bank. Mathematically, the filtering operation can be expressed as:

$$x[n] = \sum_{m=0}^{M-1} h_m[n] * d_m[n]$$

Where $h_m[n]$ is the polyphase component of the filter and $dm[n]$ is the data stream on the m^{th} subcarrier.

4.5 Receiver Model

At the receiver, the inverse operations are carried out to recover the transmitted data symbols. The received signal is first passed through a matched filter, which ensures optimal detection by maximizing the signal-to-noise ratio while suppressing interference. The filtered signal is then processed by an FFT block, which extracts the frequency-domain subcarrier components. Finally, OQAM post-processing is applied to recombine the real-valued offset symbols into the original complex QAM symbols, thereby reconstructing the transmitted data. Mathematically, the demodulated signal can be expressed as:

$$\hat{a}_{k,n} = \int_{-\infty}^{\infty} r(t).g\left(t - \frac{nT}{2}\right).e^{-j2\pi kFt}dt$$

The orthogonality and filtering ensure that $\hat{a}_{k,n} \approx a_{k,n}$ in the absence of noise and channel distortions.

4.6 Advantages of FBMC in Advanced Communication Systems

FBMC offers several advantages that make it highly suitable for advanced communication systems such as 5G and 6G. One of the key benefits is high spectral efficiency, as FBMC eliminates the need for a cyclic prefix (CP) and employs narrow subcarrier filtering, thereby utilizing available bandwidth more effectively than OFDM. Additionally, the use of well-designed prototype filters provides improved time-frequency localization, which enhances robustness against synchronization errors and narrowband interference. Another important advantage is the reduction of out-of-band (OoB) emissions, a feature that makes FBMC particularly attractive for dynamic spectrum access and cognitive radio applications, both of which are central to 6G networks. Furthermore, FBMC's superior localization properties enable support for asynchronous transmissions, making it highly effective for uplink scenarios in heterogeneous networks with diverse user requirements. Finally, FBMC is well-suited for massive MIMO systems, as its reduced interference and enhanced channel estimation capabilities allow efficient integration with large-scale antenna deployments. Collectively, these advantages position FBMC as a promising candidate waveform for future wireless systems.

4.7 Challenges of FBMC

Despite its significant advantages, FBMC also faces several challenges that limit its widespread adoption. One of the major issues is increased system complexity, since the absence of a cyclic prefix (CP) and the reliance on OQAM modulation demand more sophisticated equalization and synchronization techniques. Additionally, MIMO integration with FBMC is more challenging compared to CP-OFDM, as FBMC does not exhibit circular convolution properties, making the design of spatial multiplexing and channel estimation schemes more complex. Another drawback is higher latency, as the long tails of prototype filters can introduce delays, which may hinder applications requiring ultra-low latency. These challenges highlight the need for further research and optimization to fully realize FBMC's potential in advanced communication systems. FBMC modulation stands out as a promising waveform for future communication systems beyond 5G, such as 6G. Its ability to provide better spectral efficiency, robustness to interference, and excellent time-frequency localization make it suitable for advanced wireless environments. The mathematical formulation of FBMC reveals its strong theoretical foundation and its potential for flexible and efficient communication. However, practical challenges related to complexity, latency, and MIMO compatibility must be addressed to make FBMC a mainstream solution in advanced wireless networks.

5. QUANTUM-INSPIRED COMPUTING (QIC)

QIC is a rapidly evolving computational paradigm that draws upon the foundational principles of quantum mechanics, such as superposition, entanglement, and quantum probability amplitudes, to develop algorithms that run on classical computing platforms. Unlike quantum computing, which relies on physical qubits and quantum gates, quantum-inspired algorithms do not require quantum hardware but instead use quantum-inspired representations and dynamics to improve algorithmic efficiency and performance [28]. These algorithms have shown considerable promise in solving complex optimization, classification, and search problems across a variety of fields including telecommunications, signal processing, and network design. In the context of 6G wireless communication, where the demands for low latency, high throughput, and adaptability are extremely high, QIC techniques offer novel and efficient solutions to enhance the performance of FBMC transceivers. The integration of QIC into FBMC design and optimization enables smarter, more adaptive, and computationally efficient transceiver architectures that can meet the stringent requirements of future communication environments. This section delves into three prominent quantum-inspired approaches that are particularly relevant for FBMC-based 6G systems: Quantum-Inspired Evolutionary Algorithms (QIEA), Quantum-Inspired Particle Swarm Optimization (QPSO), and Quantum-Inspired Neural Networks (QINN).

5.1 Quantum-Inspired Evolutionary Algorithm (QIEA)

QIEAs extend classical evolutionary techniques by incorporating quantum principles into their search and representation mechanisms. In QIEA, each candidate solution is modeled as a quantum individual using qubits represented by probability amplitudes, which enhances diversity and exploration. This approach improves convergence speed and helps avoid local optima, making it highly effective for optimizing multicarrier systems like FBMC. Specifically, QIEA can jointly optimize parameters such as filter length, subcarrier spacing, and power allocation to balance objectives including BER, PAPR, spectral efficiency, and computational complexity. In FBMC transceivers, QIEA further supports the selection of prototype filters and equalization strategies under dynamic channel conditions, enabling rapid adaptability to high-mobility and rapidly varying environments expected in 6G networks. Figure 9 illustrates the various QIEAs.

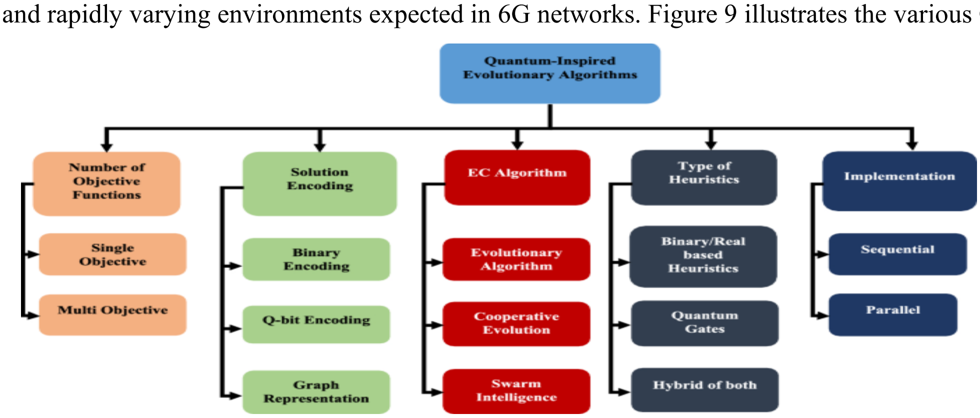

Fig. 9. Quantum-Inspired Evolutionary Algorithms [29]

5.2 Quantum-Inspired Particle Swarm Optimization (QPSO)

QPSO enhances classical PSO by incorporating quantum principles that influence particle movement through probabilistic tunneling and wave function-based updates. These quantum behaviors improve the exploration-exploitation balance, making QPSO well-suited for high-dimensional and nonlinear optimization. In FBMC transceivers, QPSO can optimize adaptive channel estimation, multiuser scheduling, beamforming, and PAPR reduction, supporting real-time signal processing in complex 6G scenarios with multiple users, antennas, and dynamic channels. Its simple mathematical formulation and low computational complexity enable implementation on hardware-constrained devices, while its stochastic nature ensures robustness against noisy and uncertain conditions typical in high-frequency 6G environments.

Algorithm: QPSO for PAPR and BER Calculation in FBMC System	
	Input
	• Number of particles: N • Maximum iterations: MaxIter • FBMC system parameters: number of subcarriers K, modulation order • Prototype filter g(t) , subcarrier spacing, symbol duration • Initial symbol set $\{d_{k,n}\}$ • Constraints: BER threshold, transmit power limit
	Step 1: Initialization
1	*Generate initial particles* $X_i \in R^K$, $for\ i = 1, 2, 3, ...N$
2	Assign initial positions $X_i(0)$ randomly
3	Set mean best position P_{mean}
4	Initialize personal best $P_i \leftarrow X_i$
	Step 2: Fitness Evaluation
5	For each particle X_i : • Map phase or symbol sequence onto FBMC transmitter. • Generate FBMC signal using: $s(t) = \sum_{n=-\infty}^{\infty} \sum_{k=0}^{K-1} a_{k,n} . g\left(t - \frac{nT}{2}\right) . e^{j2\pi kFt}$ • Compute PAPR : $PAPR = \frac{\max \lvert s(t) \rvert^2}{E\left[\lvert s(t) \rvert^2\right]}$ • Simulate channel, and compute BER using demodulation.
6	Define fitness function: $fi = w_1 . PAPR(X_i) + w_2 . BER(X_i)$ Where w_1, w_2 are weight factors balancing PAPR and BER (e.g., w1=0.7,w2=0.3)
	Step 3: Update Global and Personal Best
7	If $f_i < f(P_i)$, then update personal best: $P_i \leftarrow X_i$
8	Update global best $G \leftarrow \min(f(P_i))$
9	Compute mean best position: $P_{mean} = \frac{1}{N} \sum_{i=1}^{N} P_i$
	Step 4: Position Update Using QPSO Formula
	For each particle i:
10	Generate three random numbers $r_1, r_2, u \in [0,1]$
11	Compute local attractor: $P_i^* = r_1 . P_i + (1 - r_1) . G$
12	Update position using QPSO equation: $X_i(t+1) = P_i^* \pm \beta . \lvert P_{mean} - X_i(t) \rvert . \ln\left(\frac{1}{u}\right)$ Where β (0.5 to 1) is contraction-expansion coefficient

13	Reconstruct FBMC signal using new Xi
	Step 5: Iteration Control
14	Repeat Steps 2–4 until: • t=MaxItert • Convergence criteria (e.g., PAPR or BER threshold) is met
	Step 6: Output
15	• Optimal particle X^* minimizing fitness function • Corresponding minimum PAPR • Final simulated BER after FBMC demodulation

5.3 Quantum-Inspired Neural Networks (QINN)

QINNs integrate quantum-inspired principles into neural network architectures, training methods, or data encoding strategies to improve learning efficiency, adaptability, and generalization. Data may be represented using qubit-based encodings or complex-valued activation functions, and learning can leverage quantum-inspired phenomena such as amplitude modulation or phase encoding. In FBMC transceivers, QINNs enable intelligent decision-making and pattern recognition tasks, including dynamic spectrum access, modulation classification, interference detection, and adaptive equalization. For example, QINN-based adaptive equalizers can learn and generalize channel characteristics more efficiently than traditional neural networks, particularly in fast-fading and frequency-selective 6G channels. Their reduced training complexity and faster convergence make them suitable for energy-constrained devices like IoT sensors and wearables, which are integral to 6G ecosystems. QIC techniques, including QIEA, QPSO, and QINNs, provide advanced optimization, learning, and adaptive capabilities without requiring quantum hardware. By exploiting probabilistic exploration, parallelism, and tunneling effects, QIC effectively addresses complex, high-dimensional, and dynamic optimization problems. When applied to FBMC-based 6G transceivers, these techniques enhance performance, reliability, and efficiency, enabling real-time adaptation to high-frequency, variable environments. Overall, QIC offers a practical computational framework that complements FBMC's inherent advantages, positioning it as a key tool for next-generation intelligent communication system design.

TABLE I. CHARACTERISTICS

Characteristics	Description	Benefit	Application to FBMC
Probabilistic Exploration	In QIC, each potential solution is represented probabilistically, often in the form of a "quantum individual" described by a probability amplitude. This means that instead of selecting a single deterministic solution at each iteration, the algorithm explores a range of possible solutions simultaneously with varying probabilities.	This allows for a more diverse search across the solution space, avoiding premature convergence to local optima a common problem in traditional deterministic algorithms.	In 6G FBMC transceivers, where filter design, resource allocation, or channel estimation involves complex trade-offs, probabilistic exploration ensures that diverse configurations are considered, increasing the likelihood of finding globally optimal solutions.
Parallelism through Superposition-Like Behavior	While QIC does not use physical superposition, it simulates the effect by maintaining and evolving a population of solutions (often encoded in qubit-like structures) that represent multiple possibilities at once. This mimics the parallel evaluation capability of quantum systems.	Effective parallelism reduces the number of iterations required to explore the solution space, thereby speeding up convergence.	For real-time or near-real-time transceiver optimization in 6G (e.g., adaptive filter bank tuning or interference mitigation), such pseudo-parallelism helps in rapidly adapting to dynamic channel conditions with lower computational overhead.
Tunneling Effects	Quantum tunneling is a phenomenon where particles can pass through energy barriers that would be insurmountable under classical mechanics. In QIC, this concept is mimicked through stochastic transitions that allow the algorithm to escape local optima by making controlled "jumps" in the solution space.	This prevents the algorithm from becoming trapped in suboptimal regions, improving the robustness of optimization processes.	In multi-objective optimization tasks such as minimizing both BER and PAPR simultaneously, quantum-inspired tunneling mechanisms help explore non-linear and discontinuous solution landscapes more effectively than conventional techniques.

6. OPPORTUNITIES FOR QUANTUM-INSPIRED FBMC TRANSCEIVERS

The integration of QIC techniques with FBMC transceivers presents significant opportunities to enhance 6G wireless communication systems. By combining FBMC's inherent spectral efficiency and flexibility with quantum-inspired capabilities such as probabilistic representation, parallel search, and tunneling effects, these approaches enable advanced optimization, learning, and adaptive signal processing across heterogeneous and high-density networks. In dense 6G environments, QIC algorithms like QIEA and QPSO can optimize subcarrier assignments, power levels, and modulation formats in multi-user FBMC systems, improving throughput, fairness, and energy efficiency. FBMC's strong time-frequency localization, combined with quantum-inspired strategies, further enhances interference management through adaptive filtering and beamforming. Additionally, QINNs can implement robust adaptive modulation and coding by learning and predicting optimal schemes in dynamic channels, while QIEA and QPSO can reduce PAPR for power-sensitive applications such as IoT and wearable devices. Quantum-inspired techniques also improve channel estimation and equalization, particularly in fast-fading or high-frequency 6G environments, and offer energy-efficient solutions for edge devices and IoT nodes by reducing computational load and accelerating convergence. Moreover, QIC enhances dynamic spectrum access and cognitive radio capabilities, allowing transceivers to opportunistically utilize underused frequency bands while minimizing interference. Altogether, these methods enable the development of intelligent, context-aware FBMC transceivers capable of autonomously adapting to changing environments, user mobility, and diverse service demands, ensuring high performance, reliability, and efficiency across a wide range of 6G deployment scenarios.

7. ADVANTAGES OF QUANTUM-INSPIRED FBMC SYSTEMS

The advancement toward 6G wireless networks demands significant improvements in efficiency, adaptability, scalability, and overall performance across multiple layers of communication systems. FBMC modulation, with its superior spectral localization and ability to operate effectively in non-orthogonal and fragmented spectrum, is well-suited to address physical-layer challenges in 6G. However, FBMC systems also introduce computational complexity and implementation challenges that must be overcome to ensure real-time adaptability, robustness, and energy efficiency. Integrating QIC techniques with FBMC transceivers provides a promising solution, as QIC algorithms emulate quantum principles such as probabilistic behavior, parallel solution representation, and tunneling to solve complex problems efficiently. This synergy enables a range of advantages for 6G networks. Quantum-inspired optimization algorithms like QIEA and QPSO can handle high-dimensional, nonlinear, and multi-objective optimization tasks, including filter selection, subcarrier spacing, adaptive bit loading, and power allocation, thereby improving BER, PAPR, and spectral efficiency while enabling rapid adaptation to changing channel conditions. FBMC's inherent spectral efficiency is further enhanced through intelligent spectrum allocation and real-time modulation adjustments, maximizing utilization in scarce and fragmented frequency bands. Quantum-inspired methods also improve robustness to interference and channel variability, with QINNs dynamically adjusting equalization and receiver strategies based on channel states and interference patterns. Complexity is reduced through probabilistic search and adaptive learning, allowing efficient implementation on resource-constrained edge devices. Energy efficiency is further improved as QIC techniques minimize computational overhead, complementing FBMC's low out-of-band emissions and eliminating the need for cyclic prefixes. Moreover, advanced PAPR reduction is achieved through QIEA and QPSO, optimizing signal mapping and precoding to maintain power amplifier efficiency and signal integrity. Finally, quantum-inspired FBMC systems enable real-time adaptability and intelligence, allowing networks to self-optimize, self-configure, and respond dynamically to environmental changes, user behavior, and application demands, establishing a robust foundation for autonomous 6G infrastructures.

8. CHALLENGES

While the integration of Quantum-Inspired Computing (QIC) into FBMC systems offers promising advancements for 6G, several challenges remain that must be addressed for practical deployment. These challenges can be grouped into five main categories:

Algorithmic Challenges: Quantum-inspired algorithms like QIEA, QPSO, and QINNs, while efficient, still involve high computational complexity and iterative probabilistic computations. This can limit real-time applicability in high-dimensional tasks such as dynamic resource allocation, adaptive filtering, multi-user scheduling, and massive MIMO beamforming. Additionally, QIC methods are sensitive to parameter settings (e.g., population size, learning rates, rotation angles), making them less robust in rapidly changing 6G environments unless adaptive tuning mechanisms are implemented.

Hardware and Implementation Constraints: FBMC transceivers already require complex processing due to filter banks, overlapping symbols, and lack of cyclic prefixes. Integrating QIC increases demands on memory, processing power, and energy consumption. Efficient deployment on embedded systems, edge nodes, or base stations requires hardware-friendly adaptations of QIC algorithms and optimized implementations on DSPs, FPGAs, or ASICs, which are still in early development.

Standardization and Benchmarking: The QIC field lacks standardized models, evaluation frameworks, and benchmarks. Performance varies significantly with algorithm configuration and initialization, making it difficult to compare results or establish consistent deployment strategies. This is particularly critical in 6G, where multi-objective optimization is required for metrics like BER, PAPR, and spectral efficiency.

Scalability: Applying QIC to multi-user, multi-antenna, or large-scale FBMC systems can lead to exponential growth in computational complexity. As the number of users, antennas, or subcarriers increases, convergence times for QIEA or QPSO may become prohibitive, limiting suitability for real-time and high-density 6G scenarios.

Validation and Integration: Most studies remain theoretical or simulation-based, with limited experimental validation. Integration with existing 5G/6G protocols, backward compatibility, and alignment with communication standards pose additional challenges. Real-world testing is essential to confirm robustness, error tolerance, and performance under practical channel conditions, mobility, and interference scenarios.

Addressing these challenges will require coordinated research efforts in algorithm design, hardware optimization, standardization, and experimental evaluation to realize the full potential of quantum-inspired FBMC transceivers in 6G networks.

9. POTENTIAL APPLICATIONS IN 6G

Quantum-inspired FBMC transceivers hold strong potential for 6G applications. In URLLC, the blend of FBMC's spectral efficiency and quantum-inspired optimization ensures precise, adaptive resource allocation for remote surgery, industrial automation, and autonomous transport. For mMTC, FBMC's time-frequency localization and quantum-inspired interference management enable efficient communication in dense IoT settings like smart cities and factories. XR and holographic services benefit from seamless data streams supported by advanced filtering and dynamic scheduling. In vehicular networks, these transceivers enhance beamforming and channel estimation under mobility and Doppler effects. NTNs, including LEO satellites and high-altitude platforms, can exploit them for adaptive waveform design and robust link maintenance across varied environments. Quantum-inspired FBMC enhances spectral efficiency, reduces PAPR, improves energy efficiency, scalability, and reliability, outperforming other 6G communication solutions.

10. FUTURE TRENDS

As wireless communication progresses toward 6G, quantum-inspired FBMC transceivers are poised to evolve through several impactful trends. A major direction is the development of hybrid transceiver architectures, where quantum-inspired optimization complements conventional DSP to enable real-time adaptability under varying channel conditions, user densities, and spectral environments. Such designs will be crucial for scenarios involving intelligent surfaces, non-terrestrial networks, and high-mobility users. Another promising avenue is hardware-efficient implementation, with FPGAs, DSPs, and SoC platforms supporting lightweight quantum-inspired blocks for mobile and edge devices. This will enable compact, energy-efficient transceivers suitable for power-sensitive applications like wearables, drones, and smart sensors. Cross-layer optimization is also expected to gain momentum, extending quantum-inspired methods across physical, MAC, and network layers to enhance end-to-end performance in dense and delay-sensitive environments. Furthermore, integration with reconfigurable intelligent surfaces and THz communications will unlock optimized beamforming and spectrum use, establishing quantum-inspired FBMC as a key enabler of efficient, scalable 6G networks.

11. CONCLUSION

Quantum-inspired FBMC transceivers represent a promising advancement for 6G, combining FBMC's spectral efficiency and time-frequency localization with quantum-inspired optimization. Models such as QIEA, QPSO, and QINN enhance signal processing, resource management, and dynamic adaptation, supporting applications in URLLC, mMTC, high-mobility networks, and intelligent surfaces. While implementation challenges remain, their performance, flexibility, and efficiency make them strong 6G candidates. Future directions point toward hardware-efficient, RIS-compatible, and cross-layer optimized designs, paving the way for intelligent, adaptive, and energy-efficient 6G communication.

Conflicts of Interest

The authors declare no conflict of interest.

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