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Low-latency and High-Reliability FBMC Modulation scheme using Optimized Filter design for enabling NextG Real-time Smart Healthcare Applications

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Abstract

This paper presents a prototype filter design using the orthant optimization technique to assist a filter bank multicarrier (FBMC) modulation scheme of a NextG smart e-healthcare network framework. Low latency and very high reliability are one of the main requirements of a real-time e-healthcare system. In recent times, FBMC modulation has gotten more attention due to its spectral efficiency. The characteristics of a filter bank are determined by t's, prototype filter. A prototype filter cannot be designed to achieve an arbitrary time localization (for low latency) and frequency localization (spectral efficiency), as time and frequency spreading are conflicting goals. Hence, an optimum design needed to be achieved. In this paper, a constraint for perfect or nearly perfect reconstruction is formulated for prototype filter design and an orthant-based enriched sparse $\ell 1$-optimization method is applied to achieve the optimum performance in terms of higher availability of subcarrier spacing for the given requirement of signal-to-interference ratio. Larger subcarrier spacing ensures lower latency and better performance in real-time applications. The proposed FBMC system, based on an optimum design of the prototype filter, also supports a higher data rate as compared to traditional FBMC and OFDM systems, which is another requirement of real-time communication. In this paper, the solution for the different technical issues of physical layer design is provided. The presented modulation scheme through the proposed prototype filter-based FBMC can suppress the side lobe energy of the constituted filters up to large extent without compromising the recovery of the signal at the receiver end. The proposed system provides very high spectral efficiency; it can sacrifice large guard band frequencies to increase the subcarrier spacing to provide low-latency communication to support the real-time e-healthcare network.

Keywords NextG · Smart healthcare · Multi-carrier modulation · Prototype filter design

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Extended author information available on the last page of the article

Abbreviations

BER	Bit error rate
eMBB	Enhanced mobile broad band
FBMC	Filter bank multicarrier
FFT	Fast Fourier transform
IoHT	Internet of healthcare thing
ISI	Inter-channel interference
MIMO	Multiple input multiple output
mmtc	Massive machine type communication
NOMA	Non-orthogonal multiple access
NPR	Nearly perfect reconstruction
OESOM	Orthant-based enriched sparse ℓ1-optimization method
OFDM	Orthogonal frequency division multiplexing
OMA	Orthogonal multiple division access
OoB	Out of band
OQAM	Offset quadrature amplitude modulation
SIR	Signal-to-interference ratio
uRLLC	Ultra-reliable low-latency communication

1 Introduction

In the modern era, information and communication technologies have emerged as significant drivers for changes in the healthcare system [1]. Various smart e-healthcare scenarios utilize the advancements in the field of wearable medical sensors and efficient body area networks (BANs) [2]. Smart monitoring of various physiological parameters of patients in the intra-hospital scenario, remote home patients, etc., requires continuous acquisition, transmission and monitoring of such medical parameters [3]. The smart healthcare world offers healthcare facilities through smart gadgets and networks. The intelligent gadget collects medical data through biomedical sensors and healthcare systems (i.e., the application having information about medical science such as diagnosis, treatment, and prevention of disease) and analyzes the medical data to assist in treatment. Smart healthcare helps individuals of different demographics and health workers to access the best information and obtain the right strategies to eliminate medical problems. As a result, it increases the quality of service and decreases the expense of the medical sector. Digital healthcare plays a critical role in optimizing and installing a wide variety of applications, such as smart medication, telemedicine, disease management, and distant surgery. [4, 5]. Different smart healthcare systems leveraging cellular mobile networks have been suggested in the literature. As the communication technology evolved, e-healthcare architectures improved to facilitate a reliable fast and efficient healthcare delivery system. 3G-based m-healthcare system is presented in [6], and QoS of the system is evaluated. A 4G communication-based telemedicine architecture is presented in [7]. In [8], the e-healthcare framework to deliver healthcare services in a rural and remote location in India is developed. The 3G- and 4G-based network architecture are not able to fulfill the demand of high data rate, high bandwidth efficiency, low-latency and high-reliability conditions required for effective e-healthcare solutions.

Rural and remote locations lack the presence of an advanced healthcare system. Telemedicine or e-health is a handy tool to deliver decent healthcare services at these locations. Seventy-five percent of India's health system, including doctors and other health services, is situated in metropolitan areas, where just 27% of the country's population resides, as per the United Nations survey [9]. An effective tele-healthcare system is needed to be developed to deal with this uneven distribution of healthcare facilities and patients. In addition, the recent COVID-19 pandemic situation is a big motivation for developing a reliable and real-time smart e-healthcare system, which can provide priority-based guidance to a large number of infected people according to their medical conditions. However, high data rate, reliability, efficiency, accuracy and almost zero delay requirement cannot be fulfilled by existing 3G-, WiMAX- and 4G-based network architecture. Thus, a NextG-based flexible network architecture design for an e-healthcare system is required, which can be able to provide a very low data rate with very low delay to support real-time guidance and monitoring of a large number of patients simultaneously.

Cognitive radio-based prioritized and reliable e-healthcare architecture for the Internet of Healthcare Things (IoHT) is presented and evaluated in [10]. It proposes the utilization of cognitive radio technology to deal with the inconsistency of network availability in rural areas. Software-defined radio chooses the best available network among 2G, 3G, WiMAX and 4G to establish a connection between a patient and a doctor. Although it can deal with network inconsistency up to a large extent but may not be able to provide low latency and high data rate, which is required for real-time healthcare applications. Recently, the opportunity of NextG technology in the healthcare sector is studied and reported by many researchers.

In [11] and [12], the opportunities of NextG technology in the healthcare field are investigated. These initial research works presented an idea of the utilization of NextG technology in the field of the healthcare sector. A NextG and IoT framework was proposed to evaluate and track diabetes patients in [13]. A radio device fitted with a next-generation NextG and IoT is proposed for continuous surveillance of chronic patients in [14]. Medical systems have been introduced using IoT to enable smart healthcare programs (e.g. remote monitoring, remote medical assistance) in [15]. Biomedical sensors fitted in/on smart clothes and watches capture biomedical signals and aerobic activity for regular fitness tracking. The strategy is to employ a mobile gateway-based IoT network to track chronic patients in real time, i.e. intelligent support for the m-health environment. These works are limited to the theoretical design of a framework for a healthcare system based on the NextG network. The utilization of edge computing of the NextG network for healthcare improvement is presented in [16]. Edge computing server is implanted to provide a fast and energy-efficient solution to a wireless medical body area network. This is an automated process and does not provide specific medical solutions through patient–doctor interaction. The complete utilization of the NextG-based network for smart healthcare is presented in [17] and [18]. The research work presented a complete overview of the exploitation of various components of NextG-based technology for different specific purposes of healthcare solution. The work is limited to NextG network architecture-based framework design for healthcare solutions. The feasibility of such a system needs to be tested.

Based on the literature survey, limitations of the existing e-healthcare/smart healthcare systems can be listed as:

- Most of the proposed smart healthcare architectures are based on the previous generation communication technologies like 3G, 4G and WiMAX compared to new radio NextG technology.
- Some of the recently proposed NextG-enabled smart healthcare architecture is based on theoretical design. Evaluation of such system in practical condition needs to be performed, to test the feasibility of the system.
- Most researchers focus on IoT-based design for monitoring or video conferencing by utilization of massive machine type communication (mmtc) and enhanced mobile broad band (eMBB) services of NextG technology.
- The application-based physical layer design is required for real-time healthcare. uRLLC service application is needed to be explored for real-time applications such as remote surgery and distant radiology. In the case of a healthcare system, user-oriented design is needed, i.e., improvement of spectral efficiency by increasing the data rate for each user in the network.

1.1 Introduction of new radio/NextG communication technology

NextG is the next generation of 4G communication network that offers more capabilities such as fast speed, large capacity and scalability. Parameters of NextG technology are still under continuous modification. In 2015, the ITU introduced its plan for NextG in terms of IMT-2020. ITU also identified some key features that NextG technology should provide. Low-latency requirements are supported (1 ms or less than 1 ms). Data rate must reach up to 10–20 Gigabytes per second (Gbps) in various situations and environments, high-density networks must be facilitated, and high mobility must be provided throughout the network. There are three service categories of NextG [19]

Enhanced Mobile Broad Band (eMBB): The aim of the "eMBB" would be to have a better user interface. To have many fold improvement over the ability of 4G networks, disruptive strategies will be used to utilize the unused spectrum or to improve the spectral efficiency. Key technology for physical layer design includes: massive MIMO, mm-Wave and new waveform, and utilizing filtered orthogonal frequency division multiplexing (OFDM).

Massive Machine Type Communication (mMTC): "mMTC" is a service type to support a large number of machines to machine communication. mMTC-based services are needed to facilitate large network density and ultra-energy efficiency.

Ultra-Reliable Low-Latency Communication (uRLLC): is a service type intended to fulfill the low delay services requirement, such as vehicular communication, autonomous driving and real-time applications. In order to match the user reaction time, which is generally in a few milliseconds (ms), the reaction time for this service must vary in terms of a microsecond.

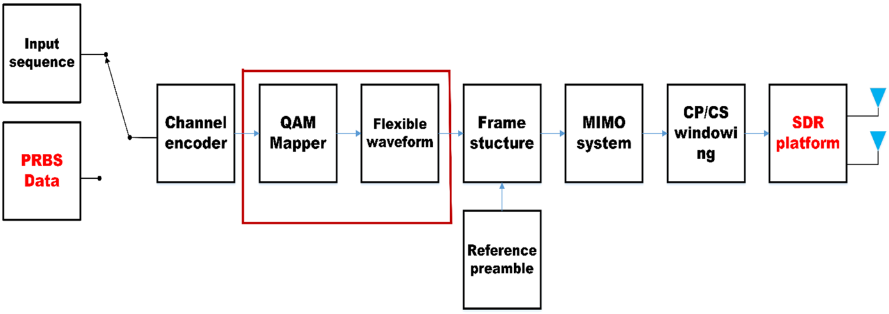

Fig. 1 Block diagram of NextG transmitter

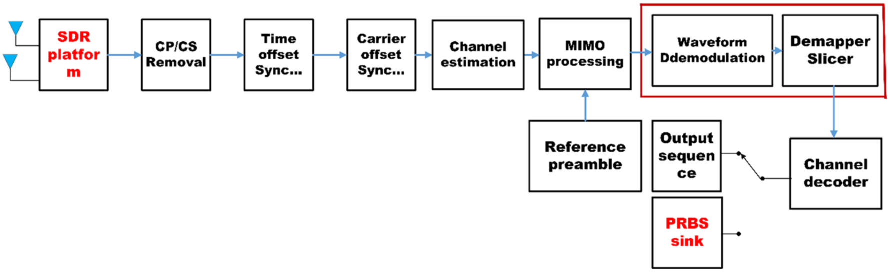

Fig. 2 Block diagram of NextG receiver

1.2 Physical layer design and multicarrier modulation

The physical layer design of 4G-based system and NextG-based system is almost similar, but the data rate for NextG-based system is very high and has a very low transmission range. There are multiple issues related to the design of a physical layer of NextG-supported communication systems, such as channel identification, channel response estimation, MIMO integration, error-correcting code, multicarrier modulation scheme with optimal carrier sub-spacing and multiple access techniques. The complete block diagram for the transmitter and receiver for NextG-based system is shown in Figs. 1 and 2, respectively. Multiple carrier-based modulation schemes are used for efficient resource utilization (time–frequency space) and to support millimeter wave (very high frequency) communication of new generation radio. Orthogonal frequency division multiplexing scheme is a very popular method to assist the multiple carrier modulation of new generation communication technology but, recently, filter bank multicarrier modulation-based transmission technique has captured a lot of attention due to its flexibility and efficiency. In order to deal with huge heterogeneous data traffic from a large number of devices, NextG wireless networks assisted by the design of advanced modulation and multiple access schemes are required. Generally, there are two types of multiple access techniques used in a NextG network: first, orthogonal multiple access (OMA) [20] and second is the non-orthogonal multiple access (NOMA) [21] technique. The NOMA is more efficient in bandwidth utilization, but reliability for each device is lower. NOMA improves bandwidth efficiency by increasing the number of users in the network, but interference for each user is high, and the structure of the receiver is very complex. In other words, the NOMA scheme is better for the service provider but bad for an individual user with respect to OMA-based schemes. Therefore, providing reliable and low-latency communication to the smart healthcare system OMA-based scheme would be a better choice.

Offset quadrature amplitude modulation with filter bank multicarrier modulation (OQAM-FBMC) [22] has been identified to be a potential multicarrier scheme to be implemented in smart healthcare systems. Conventional OQAM-FBMC systems use longer filters that give improved spectral form. Latency, also known as "system latency," is another critical aspect. Therefore, in this context, short prototype filters should be applied for OQAM-FBMC. We propose to develop short filters with low undesired spectral emission using an optimization approach.

The focus of this paper is the filter bank multi-carrier modulation-based modulation scheme. The multi-carrier modulation has advantages over single-carrier modulation in terms of data rate, spectral efficiency and latency. Thus, multicarrier modulation is employed by the new generation of radio systems. The orthogonal frequency division multiplexing (OFDM) and filter bank multi-carrier modulation are the most preferred modulation schemes in advanced communication systems. Procedures for multi-carrier modulations and demodulation are shown in Figs. 3 and 4. Figure 3 shows the transceiver structure for the OFDM system, whereas Fig. 4 shows the transceiver structure for the FBMC system.

In the OFDM scheme, the frequencies of the subcarriers coincide with the minimal overlapping and orthogonality is obtained between the subcarriers. In Fig. 3, the input data are into parallel streams with the help of the serial to parallel converter, and the parallel data streams are then fed to an inverse fast Fourier conversion system to create a time sequence of the streams.

The OFDM sequences are extended through the addition of cyclic prefix (CP), i.e., a replica of the latter part of the symbol, to limit the inter symbol interference (ISI). The modified signal is transformed into the analog format and is sent via the network.

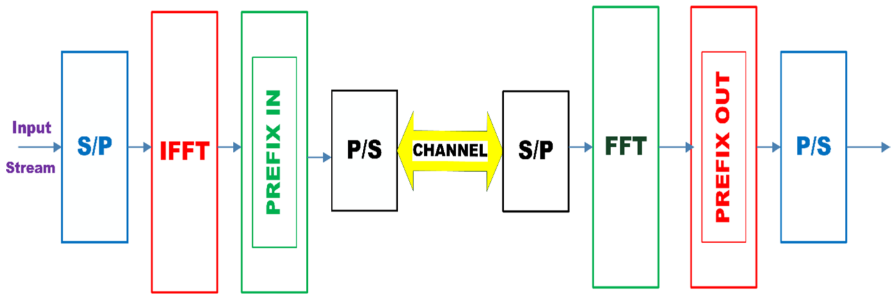

Fig. 3 Block diagram of procedure for modulation and demodulation using orthogonal frequency division multiplexing (OFDM) system

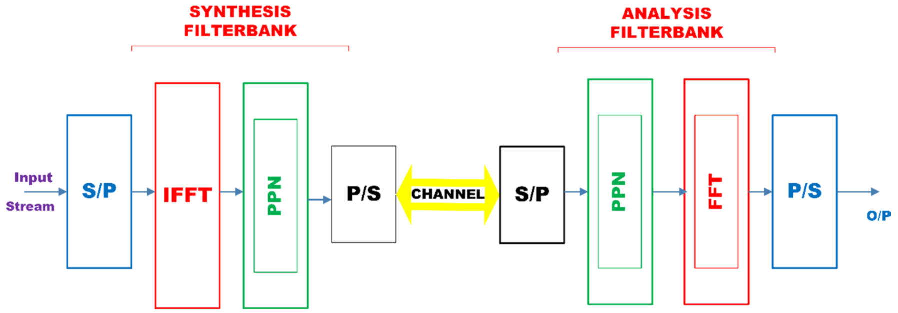

Fig. 4 Block diagram of procedure for modulation and demodulation using filter bank multi-carrier (FBMC) modulation system

At the receiver point, the signal can be retrieved to its original digital form and the fast Fourier transform (FFT) is performed on the obtained streams to remove the CP from the signal. Ultimately, the parallel data streams are compiled into a single source. The drawbacks of OFDM are listed down.

- Reduced spectral efficiency due to the cyclic prefix insertion;
- Large spectral wastage due to the rectangular windowing;
- Interference amid the unsynchronized signal in the neighboring spectrum bands.

The FBMC technique succeeds in dealing with the drawbacks of OFDM by inserting general pulse shaping filters, which can assure a local sub-channel in both the time and the frequency domains. In consequence, FBMC systems have better spectral containment and utilization of lower spectral resources than the traditional OFDM-CP scheme. Term ‘PPN’ in Fig. 4 represents a group of N number of more polyphase filters (filter banks) on the transmitter end and the receiver end, which processes N number of input signals to generate N number of outputs. The filter bank employed at the transmitter end is known as the ‘synthesis filter bank’, and the filter bank employed at the receiver end is known as the ‘analysis filter bank’. S/P designates the serial-to-parallel conversion, while P/S represents parallel-to-serial conversion.

The objectives of this paper are as follows:

- To integrate different techniques to support the physical layer’s various functions to provide end-to-end support for reliable and fast transmission to support NextG-enabled medical healthcare system.
- To develop an optimized short prototype filter to generate a filter bank to support a multi-carrier modulation for NextG-enabled smart healthcare system such that it increases the bandwidth efficiency and lowers the latency for users.

The filter optimization task is nonconvex and nonlinear. Nevertheless, observing that all the functions in the optimization problem are twice-differentiable. In several recent algorithms, the particular optimal FIIR designs could be formulated as convex problems and can be efficiently solved [23, 24]. Though with constraint of perfect reconstruction (PR) condition or nearly perfect reconstruction (NPR) condition, the optimization function for filter coefficients is nonconvex and extremely nonlinear and very responsive to initial values. Thus, the design of the filter becomes very complex and impractical. In addition, the global optimality cannot be ensured as the solution can be simply stuck in a local minimum [25, 26]. The proposed design begins with the formulation of the direct optimization function of the filter coefficients for the FBMC systems to reduce the stopband energy and limit the ISI/ICI, such that nearly perfect reconstruction is achievable. This paper proposes a second-order method (OESOM) [27] algorithm using orthant-wise-enriched optimization to produce the optimal solution. The rest of the paper is organized in the following manner: In Sect. 2, the smart healthcare scenario and physical layer architecture design challenges and solutions for the proposed NextG-based framework are presented. In Sect. 3, the novel prototype filter is designed to assist the modulation scheme of the proposed smart healthcare scenario. In Sect. 4, the performance of the proposed is evaluated and analyzed. In Sect. 5, the discussion of the result outcomes is presented. Finally, the conclusion of the paper is presented in Sect. 6.

2 NextG-based smart healthcare framework and solution for physical layer issues

The complete scenario for the proposed NextG-based smart healthcare system is depicted in Fig. 5. NextG technology offers a wide range of features and enables technology to fulfill the variety of smart healthcare requirement. The main characteristics of smart healthcare system, such as (1) ubiquity, (2) context awareness, (3) sensitivity, (4) adaptive, (5) intelligence, (6) anticipatory and (7) responsive, require a communication system that can deliver: (1) high bandwidth, (2) ultra-low latency, (3) ultra-high reliability and (4) low power requirement. New Radio NextG technology is supported by: (a) millimeter-wave communication, (b) device-to-device (D2D) communication, (c) edge computing, (d) software-defined network (SDN), and (e) network function virtualization (NFV) can fulfill the requirement of a smart healthcare system up to a large extent [17]. The focus of this paper is on different issues and solutions of the physical layer of NextG-enabled healthcare systems. Thus, this paper briefly highlights the different design requirements and solutions to the different physical layer issues of NextG system and proposes a prototype filter design to deal with the multicarrier modulation issue of MM wave communication.

There are various components needed to be integrated to establish a NextG-based connection. The first issue in physical layer design is identifying the channel characteristic and estimating different parameters to replicate the channel impulse response without any significant variation. Integration of multiple-input multiple-output (MIMO) technology increases the reliability of the system. Multiple antenna systems provide the multiple path message signal transmission between a pair of nodes. Hence, even if the signal through one path gets distorted or lost, the other paths can ensure the successful transmission of the message signal. Error control coding is another essential part of physical layer design. It can

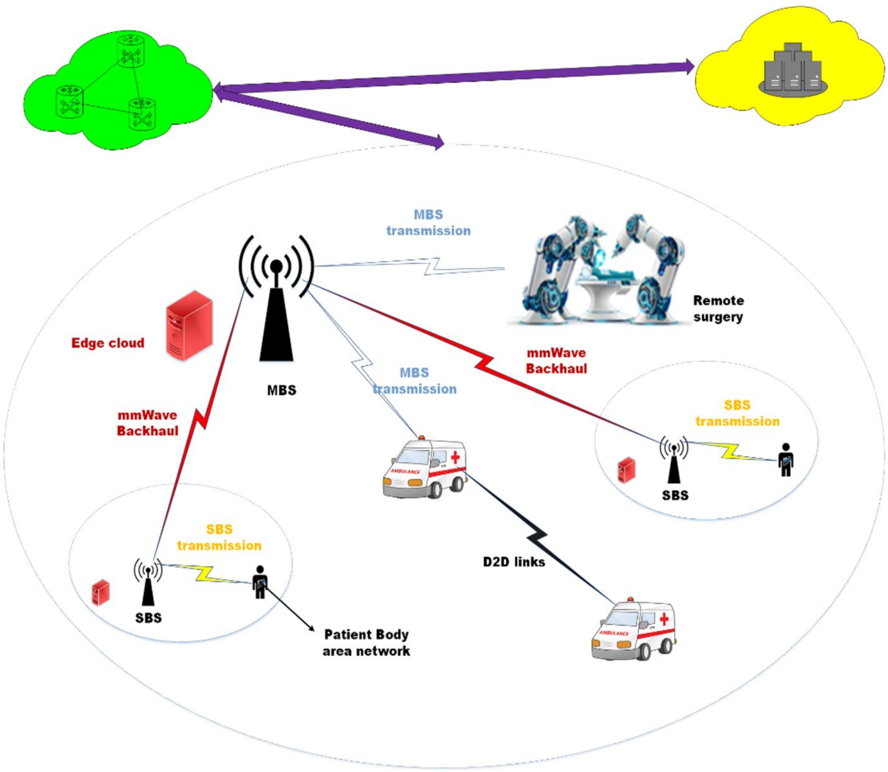

Fig. 5 Smart healthcare scenario of proposed scheme

limit detection error and thus reduce the number of retransmissions that occur due to detection error. Modulation is a procedure to embed a bit sequence into a high-frequency signal for transmission. In other words, the bits sequence is transformed into symbols through modulation. There can be multiple bits that can be embedded into per symbol, like BPSK has 2 bits per symbol, QPSK has 4 bits integrated into per symbol. Finally, the multi-carrier modulation scheme ensures optimum utilization time–frequency space of the available channel. In this paper, the following techniques are integrated together to provide a solution to multiple issues related to designing a physical layer of NextG-supported communication system and achieving end-to-end communication.

1. Channel (fast fading channel): for channel design, this paper utilizes the research reported in [28].
2. Channel Response Estimation: In order to estimate channel response, this paper utilizes the algorithm presented by [29]30.
3. Multiple Input Multiple Output (MIMO): MIMO-based communication increases the system's reliability. The proposed smart healthcare architecture integrates the method presented in [31].

4. Error-correcting code: Turbo cade presented in [32] is implemented for error control coding.
5. Multi-carrier Modulation and optimal carrier sub spacing: Offset quadrature amplitude modulation [33] with FBMC can be used to transform the stream of bit into the symbol stream.

3 Short optimized prototype filter design for FBMC modulation scheme

The main objective of this paper is to improve the multi-carrier modulation scheme by introducing perfect reconstruction optimized prototype filter to support low-latency real-time application of smart health care. In a next-generation communication system, the time and frequency space assignment to per symbol is determined by the type of service requirement. In Fig. 6, resource allocation per symbol as per various services is shown. The characteristic of the prototype filter and filter bank decide the characteristic of the distribution of the signal in time and frequency spaces. To achieve low-latency communication with high spectral efficiency and low bit error rate, an optimum prototype filter must be designed to attain localization of time and frequency of the pulse. A prototype filter cannot be designed to achieve an arbitrary time–frequency localization, as time and frequency spreading are conflicting goals. Thus, an optimal design of a prototype filter is required. Also, various parameters for both synthesis and analysis filter bank needed to be optimized for minimum distortion error.

The component for FBMC modulation (at Tx) and demodulation (at Rx) is shown in Figs. 7 and 8, respectively.

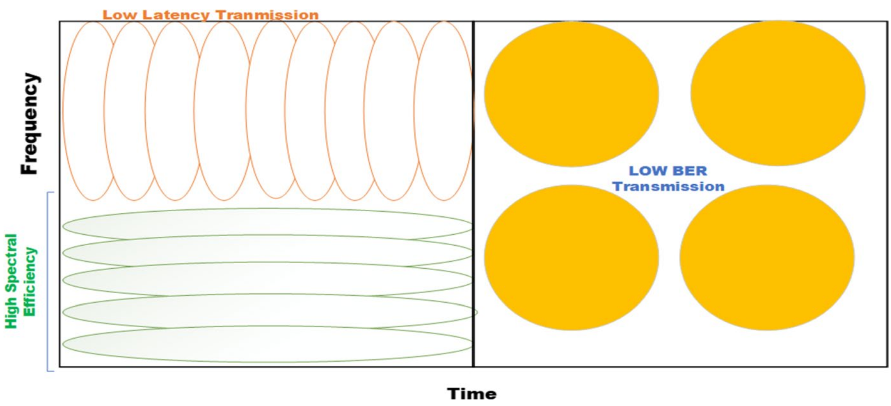

Fig. 6 Various transmission scheme in terms of resource allocation per symbol as per service requirement

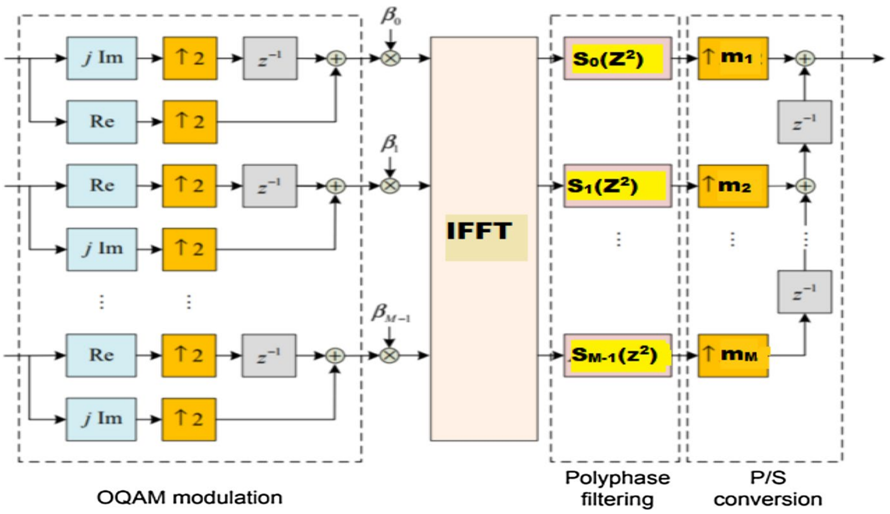

Fig. 7 FBMC modulation using a synthesis filter bank

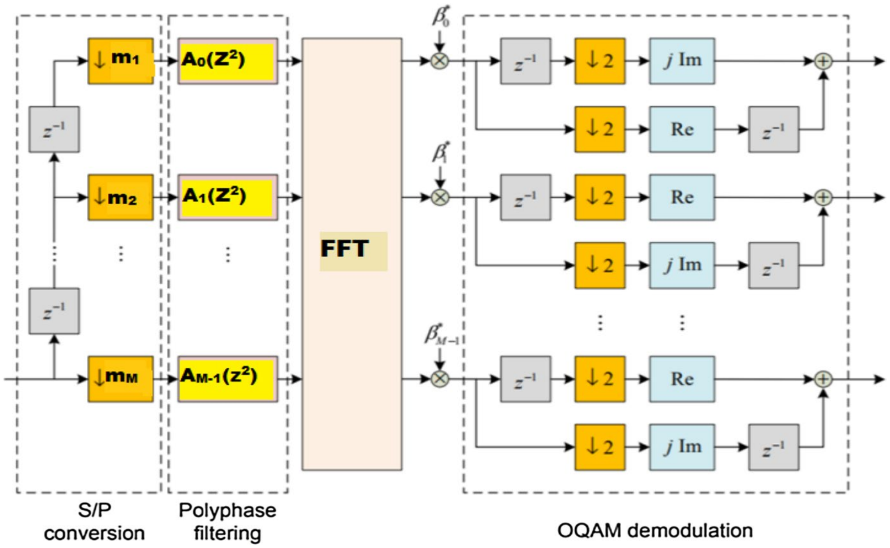

Fig. 8 FBMC demodulation using an analysis filter bank

3.1 Design method

In this section, a prototype filter design methodology with the help of the Orthant-based optimization method is described. The main focus of this design is to minimize the out-of-band (OoB) energy transmission without compromising a nearly perfect symbol reconstruction and ensuring a quick spectrum decay. The main challenge is to optimize the coefficients of the prototype filter for a specific objective function. Let us assume filter banks as shown in Figs. 6 and 7 with given variable sampling rates $[n_1\ n_2\ \ldots n_M]$ and the transmitted symbol is X and the reconstructed symbol is $X1$. The output of the filter bank in the Z-domain can be given by:

$$X1(Z) = \sum_{m=1}^{M} \frac{1}{n_m} S_m(z) \sum_{l=0}^{n_m - 1} X\left(Ze^{-j\frac{2\pi l}{n_m}}\right) A_m\left(ze^{-j\frac{2\pi l}{n_m}}\right) \tag{1}$$

In this $T_t(z)$ and $T_l(z)$ represent the total distortion transfer function and aliasing transfer function corresponding to $X\left(ze^{-j\frac{2\pi l}{n_m}}\right)$.

$$T_t(z) = \sum_{m=1}^{M} \frac{1}{n_m} A_m(z) S_m(z) \tag{2}$$

And

$$T_l(z) = \sum_{m=1}^{M} \frac{1}{n_m} A_m(z) S_m\left(ze^{-j\frac{2\pi l}{n_m}}\right) \quad \text{for} \quad l = 1, \ldots, M \tag{3}$$

For PR or NPR condition, $T_t(z) =$ only delay and $T_l(z) = 0$.
Which can be written as.
1- For Zero Distortion:

$$\sum_{m=1}^{M} \frac{1}{n_m} A_m(z) S_m(z) = z^{-d} \tag{4}$$

2- For Zero Aliasing Error:

$$\sum_{m=1}^{M} \frac{\alpha_{m,l}}{n_m} A_m(z) S_m\left(ze^{-j\frac{2\pi}{L}l}\right) = 0 \quad \text{for} \quad l = 1, 2, \ldots, L-1 \tag{5}$$

where L is the LCM of $[n_1, n_2 \ldots n_M]$ and $\alpha_{m,l}$ (for, $m = 1,2,\ldots, M$ and $l = 1,2,\ldots, L-1$) is defined as

$$\alpha_{m,l} = \{1l = 00 \quad \text{otherwise} \tag{6}$$

Equation (5) indicates that when the aliasing term $S_m\left(ze^{-j\frac{2\pi l}{n_m}}\right)$ does not overlap in the mth sub band, $\alpha_{m,l}$ would be set to zero. The equations indicate that the output $X1(Z)$ is a delayed version (by d samples) of the input $X(Z)$. The analysis and synthesis filters $S_m(Z)$ and $A_m(Z)$ are FIR filters.

The PR conditions, Eqs. (3) and (4), for FIR analysis and synthesis filters of the equal size N can be expressed as:

$$Ax = b \tag{7}$$

where

$$A = [\beta_{1,0}\phi(s_1)\beta_{2,0}\phi(s_2) \cdots \beta_{M,0}\phi(s_M)\beta_{1,1}\phi(s_1 \otimes \Psi_1)\beta_{2,1}\phi(s_2 \otimes \Psi_1) \cdots \beta_{M,1}\phi(s_M \otimes \Psi_1)\beta_{1,2}\phi(s_1 \otimes \Psi_2)\beta_{2,2}\phi(s_2 \otimes \Psi_2) \cdots \beta_{M,2}\phi(s_M \otimes \Psi_2) \vdots \vdots \ddots \vdots] \beta_{1,L-1}\phi(s_1 \otimes \Psi_{L-1})\beta_{2,L-1}\phi(s_2 \otimes \Psi_{L-1}) \cdots \beta_{M,L-1}\phi(s_M \otimes \Psi_{L-1})] \tag{8}$$

With

$$\beta_{m,l} = \{1/n_m l = 0\alpha_{k,l}/n_m l \neq 0 \tag{9}$$

The Φ can be defined as follows:

$$\phi\left([a_1 a_2 \dots a_N]^T\right) = [a_1 00 \cdots 0 a_2 a_1 0 \cdots 0 a_3 a_2 a_1 \cdots 0 \vdots \vdots \vdots \ddots \vdots a_N a_{N-1} a_{N-2} \cdots a_1 0 a_N a_{N-1} \cdots a_2 00 a_N \cdots a_3 000 \ddots \vdots 000 \cdots a_N] \tag{10}$$

$s_m (m = 1, 2, \dots, M)$ is a vector containing analysis filters' coefficients of mth subband, i.e. $s_m = [s_{m,0}, s_{m,1}, \dots, s_{m,N-1}]^T$ where T represents the transpose of the matrix. The sysmbol ⊗ stands for element-wise multiplication, and Ψ_i is defined as follows:

$$\Psi_i = \left[e^{j\frac{2\pi}{M}i(0)} e^{j\frac{2\pi}{M}i(1)} e^{j\frac{2\pi}{M}i(2)} \cdots e^{j\frac{2\pi}{M}i(N-1)}\right]^T \text{for} i = 1, \dots, L-1 \tag{11}$$

'x' is a MN×1 vector containing synthesis filters' coefficients, i.e. $x = [s_1^T\ s_2^T \dots\ s_M^T]^T$, b is a vector whose elements are all zero except the $d+1$th element, which is 1.

Filter banks are used to divide a signal into a number of frequency subbands and then process each subband individually. As a result, the first necessity is to have filters $S_m(Z)$ that meet several frequency specifications. The second requirement is that the analysis and synthesis filters meet the PR condition. The main objective is to create a filter bank that manages to achieve PR while also meeting some predefined requirements. To increase the degrees of freedom for a given length N, only the magnitude response will be considered, and the phase response of each individual analysis filter will be ignored. Each designed filter may not have a linear phase, but the PR conditions guarantee the linear phase of the whole filter bank.

It was established that the magnitude response of the mth FIR filter with coefficients $s_m = [s_{m,1}\ s_{m,2} \dots\ s_{m,N}]$, at the frequency ω, can be obtained as the square root of a quadratic function:

$$\left|S_m\left(e^{j\omega}\right)\right| = \left|\sum_{i=0}^{N-1} s_{m,i} e^{-j(i\omega)}\right| = \sqrt{s_k^H R(\omega) s_k} \tag{12}$$

where

$$R(\omega) = [1\cos\omega\cos 2\omega \cdots \cos(N-1)\omega\cos\omega 1\cos\omega \cdots \cos(N-2)\omega\cos 2\omega\cos\omega 1 \cdots \cos(N-3)\omega \vdots \vdots \vdots \ddots \vdots \cos(N-1)\omega \cos(N-2)\omega\cos(N-3)\omega \cdots 1]_{N\times N} \tag{13}$$

The design procedure requires finding the analysis and synthesis filters' coefficients (s_m and a_m) so that the PR conditions in Eq. 7 and the prescribed specifications for magnitude response filter (MRF) are satisfied. The design approach is based on minimizing the following performance index, combining PR error e_{PR} and magnitude response error e_F, with respect to filters' coefficients:

$$J = e_{\mathrm{PR}} + e_F = w_{PR} \parallel Ax - b \parallel^2 + w_F \sum_{m=1}^{M} e_{F,m} \tag{14}$$

where $e_{F,k}$, can be expressed as

$$e_{F,k} = \sum_{i=1}^{\rho} \parallel \sqrt{s_m^H R(\omega_i) s_m} - \gamma_m(\omega_i) \parallel^2 \tag{15}$$

w_{PR} and w_F are optional weights, which are L$_2$-normal. $\gamma_m(\omega_i)$ is the desired magnitude response. The optimization parameters are the analysis filters' coefficients. The synthesis filter coefficients are obtained as the least-square solution of Eq. (7).

Filter Bank Design Algorithm:

1. Pick ρ number different sampling frequencies at $\omega_0\omega_1 \ldots .\omega_\rho$ and calculate $R(\omega)$
2. Determine initial designs for analysis filters using established method have the desired magnitude response specifications.
3. Form Matrix A using Eq. (8)
4. Find x as the least-square solution of $Ax+b$.
5. Calculate total error through J using Eq. (14).
6. If the performance index is less than a specified error, terminate the algorithm, otherwise update the analysis filters' coefficients by minimizing J, and go to step 3

The optimization in step 6 is an unconstrained nonlinear optimization problem for which the second-order orthant-based methods with enriched Hessian information for sparse ℓ1-optimization [26] are used.

4 Result and analysis

In this section, the proposed design for NextG-based smart healthcare system is tested and analyzed. Firstly, the frequency response of the proposed optimized prototype filter is tested against its initial response with respect to the ability to suppress the stopband energy. Later the proposed filter bank-based FBMC modulation scheme is tested against OFDM scheme and PHYDYAS filter bank-based FBMC modulation. All the simulation is performed using MATLAB (version 2020a) installed on 64-bit Windows 10 operating systems with laptop configuration of 8 GB RAM, intel core i7 processor.

The designed prototype filter is tested and analyzed in terms of its ability to suppress stopband energy and to mitigate ISI/CSI. Figure 9 presents the frequency response of the proposed prototype filter. This filter is used to design the filter bank

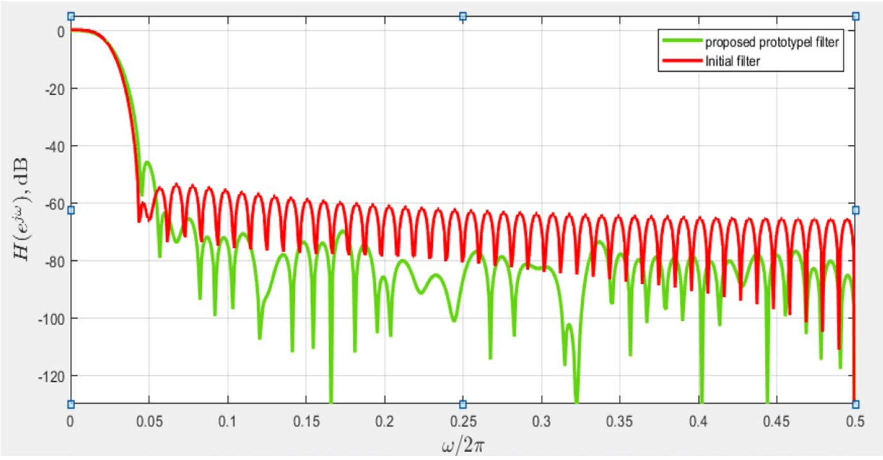

Fig. 9 Frequency response of proposed prototype filter

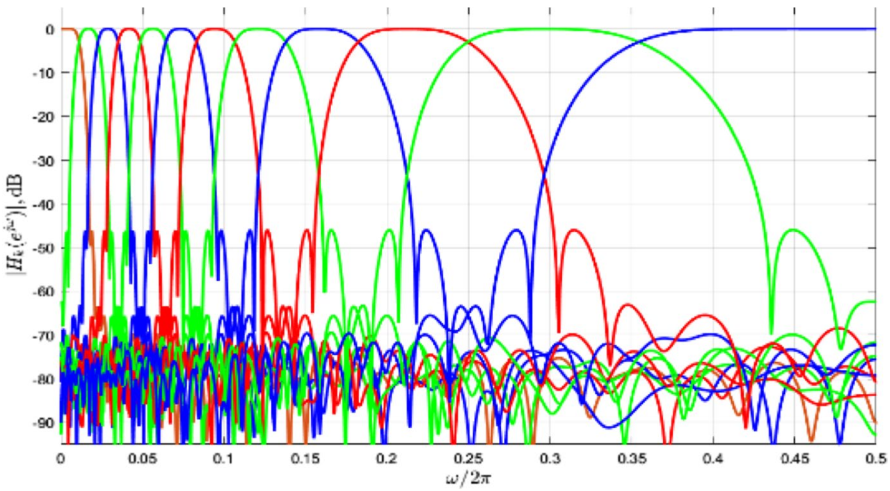

Fig. 10 Frequency response of proposed filter bank

to assist the multi-carrier modulation-based multiplexing scheme. The frequency response of the filter bank is shown in Fig. 10. The better attenuation of stopband with an assurance of perfect or nearly perfect reconstruction provides higher mitigation of ISI and guarantees a higher signal-to-noise interference ratio and high reliability of the system.

In Fig. 11, a comparison of distortion transfer function and aliasing transfer function between proposed and standard PHYDYAS filter banks is shown. Distortion transfer function $T_t(\omega)$ represents amplitude distortion caused by analysis and synthesis filters, whereas $T_a(\omega)$ represents the aliasing caused by spreading of pulse. In

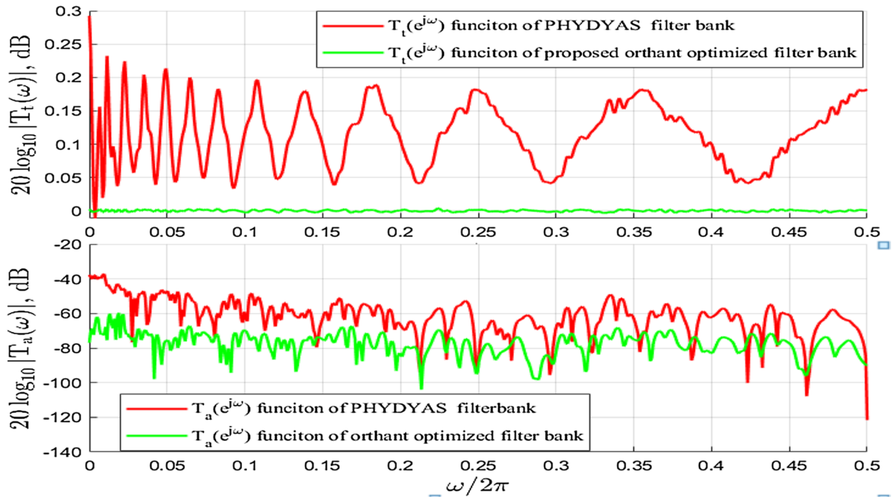

Fig. 11 Comparison of distortion transfer function and aliasing transfer function between proposed and standard PHYDYAS filter banks

ideal case, $T_a(\omega) = 0$ and $T_t(\omega) = 1$; from Fig. 11, it can be established that proposed filter bank design was closer to ideal condition for perfect reconstruction and outperformed the standard PHYDYAS filter bank.

Since it is established that the frequency response the proposed filter bank is superior than traditional filter bank. The FBMC modulation scheme was needed to be tested practical communication scenario. Now, a practical scenario for end-to-end next-generation communication is created and tested. The proposed FBMC modulation scheme is tested against the OFDM system and standard FBMC system. The OFDM system needed the cyclic prefix addition to avoid ISI, resulting in poor band utilization with respect to the FBMC system. Unlike OFDM system, FBMC has low side lobes and does not require cyclic prefix addition. An optimized prototype filter reduces the side energy further and improves the bandwidth efficiency. Although the OFDM system can provide high flexibility regarding the implementation of the MIMO system, the FBMC system also supports MIMO implementation without much sacrifice of spectral efficiency. One of the main advantages of a prototype filter-based FBMC system is its very high tolerance against the fading and Doppler effect. The FBMC performance is significantly better for the higher user mobility.

The signal-to-interference ratio (SIR) is one of the main parameters to determine the reliability of the system. The higher SIR ensures better recovery of the transmitted signal. Generally, due to some limitations of the receiver, it is required to maintain the SIR above the given level to accurately extract the transmitted signal from the received signal. In Fig. 12, the SIR value for different multi-carrier schemes is presented with respect to varying guard bands. For a low-latency system, the guard band should be higher, resulting in a reduced number of subcarriers available in each frequency band. The spectral efficiency is directly proportional to the number of the subcarriers in each frequency band. The relation between the number subcarrier

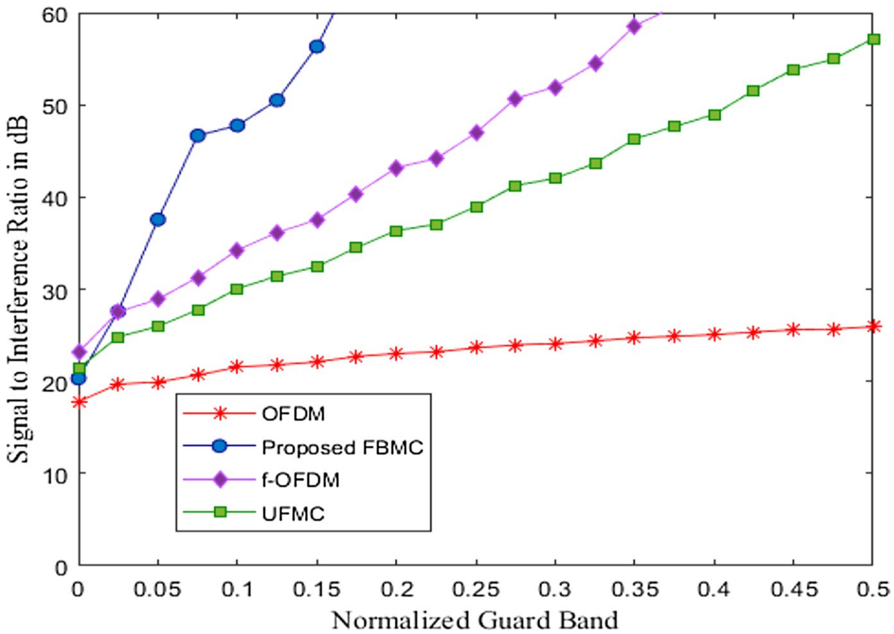

Fig. 12 Signal-to-interference ratio, comparison between proposed modulation scheme and different types of OFDM schemes

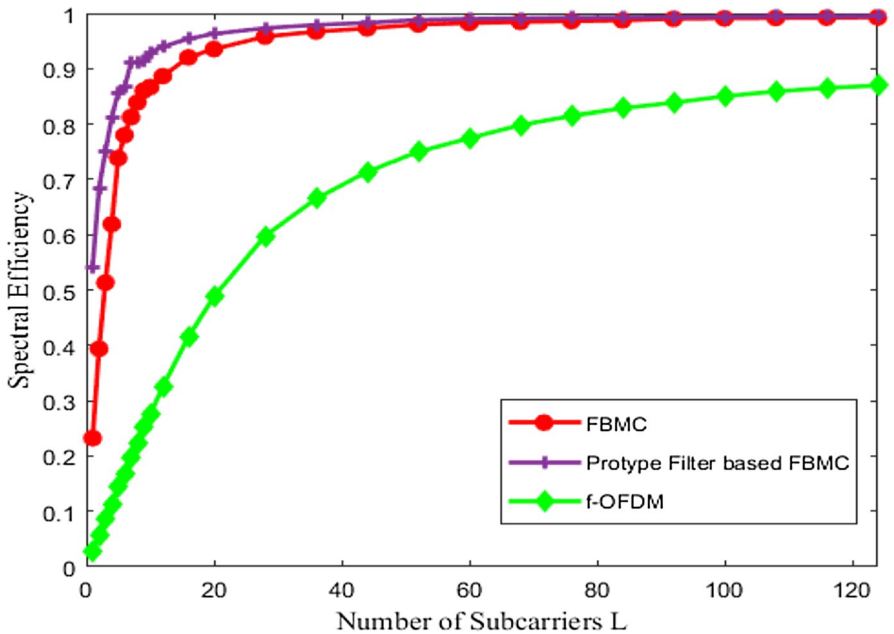

Fig. 13 Spectral efficiency of different multicarrier modulation schemes for varying number of subcarriers used

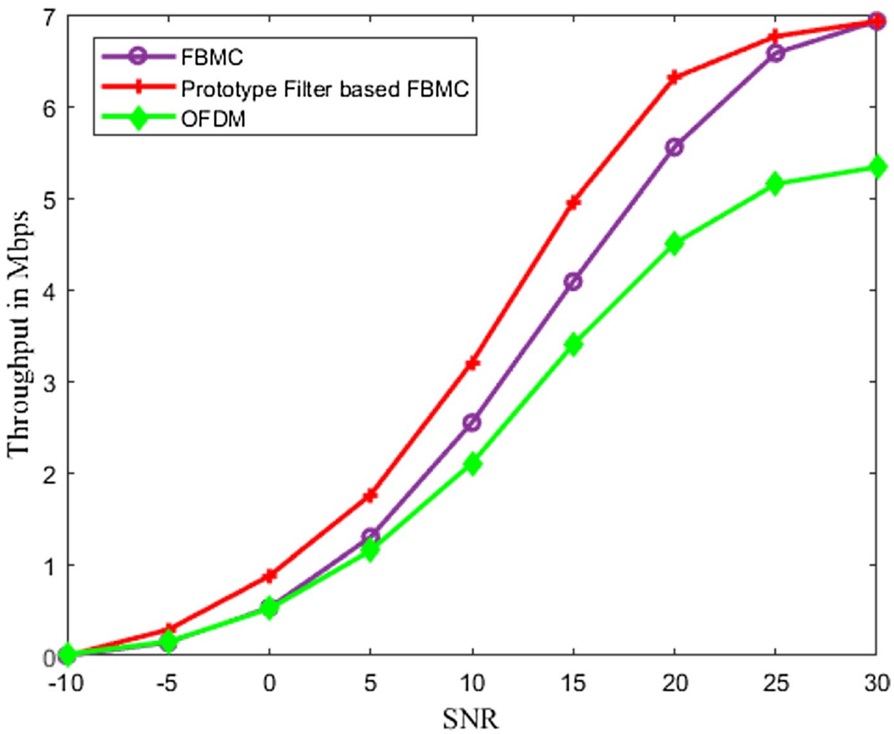

Fig. 14 Throughput comparison between proposed prototype filter-based FBMC and standard OFDM technique

Table 1 Parameter used for simulation

Parameters	OFDM	Prototype filter-based FBMC
Number of subcarriers	72	87
Number of symbols in time	14	30
Number of auxiliary symbols per pilot	1	1
Subcarrier spacing	15 kHz	15 kHz
Cyclic prefix length	10–3/(14 × 15)	Not needed

frequencies and spectral efficiency is shown in Fig. 13. As the proposed system provides very high spectral efficiency, it can sacrifice a higher number of subcarrier frequencies to increase the subcarrier spacing to provide low-latency communication.

Throughput comparison for 64 QAM, different modulation schemes are depicted in Fig. 14. It is evident that the proposed scheme outperforms the standard OFDM modulation scheme as well as the general RRC-based FBMC modulation system. In order to calculate the throughput, the Monte Carlo simulation is designed and the mean value of 100 iterations is depicted through the graph. The other parameters used for this simulation are listed in Table 1.

Figure 15 shows the bit-error-rate comparison of standard OFDM schemes against the proposed scheme with respect to the varying signal-to-noise ratio. The proposed scheme delivers almost equal accuracy to the standard OFDM scheme. Thus, high spectral efficiency, flexibility to achieve very low latency, high data rate, and good accuracy are the main characteristics of the presented scheme. In addition, integration of MIMO and error-correcting turbo code and channel estimation ensure the reliability of the system up to a very large extent.

5 Discussion

The main objective of this research is to create a filter bank design, which can support low latency and high data rate over a next-generation communication system without compromising the accuracy. An optimum prototype filter is created, and a filter bank is developed using this prototype filter. The initial frequency parameter of this filter bank is set to achieve optimal time spreading of the signal and further modified to achieve perfect reconstruction criteria, minimal aliasing transfer function and minimal distortion transfer function. The simulation results of frequency response of the filter bank

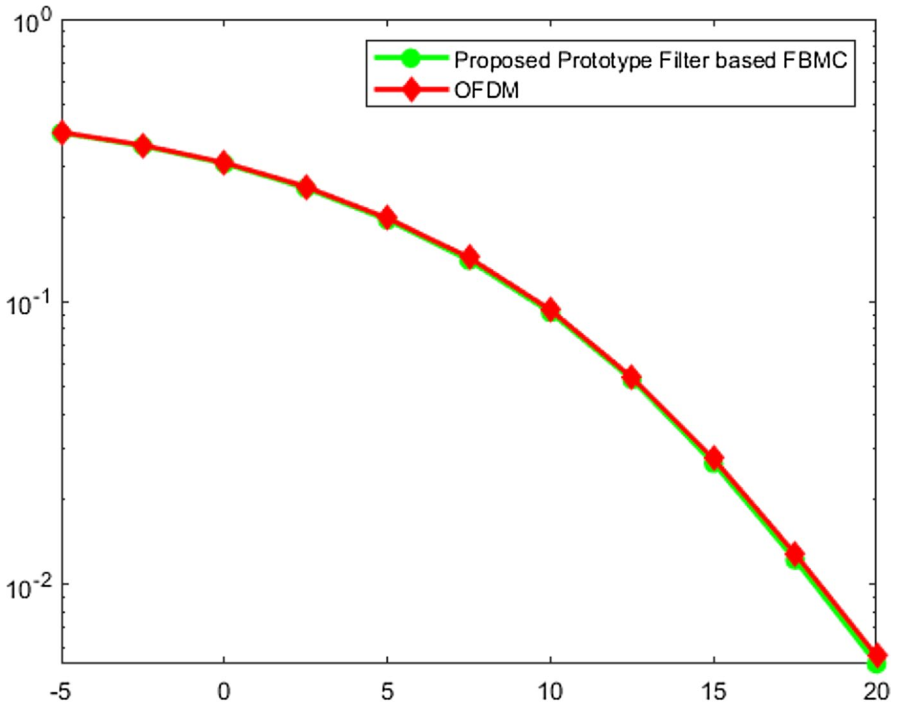

Fig. 15 Bit error rate of comparison between proposed modulation scheme and OFDM scheme

in results presented in Figs. 9, 10 and 11 theoretically validate the supremacy of the proposed filter bank as it shows almost zero distortion error and optimal localization of frequency band required for per symbol transmission. Again, the proposed filter bank is tested in an end-to-end communication scenario. To support the low-latency communication, the subcarrier spacing should be higher, and thus, the guard band requirement per symbol for given signal-to-interference ratio must be lower. From Fig. 12, it can be seen that in the proposed system, 60 dB of signal to interference can be achieved with a normalized guard band of 0.17 and it outperforms the other systems. The subcarrier spacing again boosted by the result shown in Fig. 13. It shows that very high spectral efficiency can be achieved through lower number of subcarriers as almost 90% of spectral efficiency can be achieved with 10 number of subcarriers per transmission. Thus, the proposed system can provide larger subcarrier spacing, which can support an ultra-low-latency communication. Figure 14 shows supremacy of the proposed system in terms of throughput. The proposed system is able to achieve throughput of 6 Mbps at 20 dB of SNR level, which indicates the proposed system can provide a higher data rate. Also, the combined result in Figs. 13 and 14, i.e., high throughput with low number subcarrier requirement, ensures the high data rate with respect to user end. Finally, Fig. 15 shows that the proposed system is able to match the accuracy of the orthogonal system (no frequency overlap). Based on this result, it can be established that the proposed system can provide ultra-low latency, high data rate and low BER. Thus, the proposed system can support a real-time e-healthcare application very effectively over a next-generation communication system.

6 Conclusion

This paper presented a complete framework for NextG to enable a smart healthcare system. Although the different enabling technologies of NextG communication and their applications in smart healthcare were discussed, the main focus of this article was on physical layer design for real-time application. The paper integrated the different existing solutions to deal with multiple issues (channel estimation, MIMO, modulation, subcarrier optimization) to provide end-to-end communication. To improve the spectral efficiency (with respect to a user), reliability and BER efficiency came with, a novel short prototype filter design to assist the multicarrier modulation scheme was presented. The performance of the proposed scheme was tested against the other standard schemes, and it was established that the proposed scheme was performing better.

Next-generation communication technology is evolving. In order to improve e-healthcare connectivity, the NextG technology is needed to integrate the various tools like, machine learning, cloud computing, edge computing and blockchain technology with NextG for efficient and priority-based resource utilization, faster response time, enhanced network security and better spectral efficiency.

Data availability statement The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors Dr. Abhinav Adarsh and Dr. Basant Kumar declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper titled; "Low Latency and High Reliability FBMC Modulation Scheme using Optimized Filter Design for enabling NextG Real Time Smart Healthcare Applications".

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