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A Review on Preamble-Based Channel Estimation Method for FBMC/OQAM Toward 6G: Advantages, Challenges and Future Works

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ABSTRACT

Filter bank multicarrier/offset quadrature amplitude modulation (FBMC/OQAM) is a multicarrier modulation that is expected to replace orthogonal frequency division multiplexing (OFDM) in future sixth-generation (6G) networks. FBMC/OQAM has high spectrum efficiency, cyclic prefix (CP)-free transmission, decreased out-of-band emission (OOBE), and asynchronous environment robustness. However, the orthogonality criteria of FBMC/OQAM are only in the real field. Therefore, imaginary components of complex-valued OQAM symbols cause imaginary interferences among subcarriers, affecting channel estimation (CE) processing operations. Channel estimation is a critical component of wireless communication systems. Channel estimate allows the receiver to approximate channel impulse response (CIR) to determine the impacts of the communication channel on the sent symbols. So, an accurate channel estimate is critical in FBMC/OQAM. In this review, we focus on the Preamble-based method, one of the basic methods for channel estimation in FBMC. Three preamble-based approaches have been studied: the interference approximation method (IAM), the interference cancellation method (ICM), and pairs of pilots (POP) using a single antenna and multiple input multiple outputs (MIMO). Compare them regarding bit error rate (BER) and mean square error. Also, it compares different interference approximation methods in terms of bit error rate (BER), magnitude, and peak average power ratio (PAPR). The review found the superiority of M-IAM and NPS in spectrum efficiency and PAPR. Future work that can help the researcher in this field.

Keywords:
Channel estimation; FBMC/OQAM; imaginary interference; channel impulse response (CIR); 6G; filter bank multicarrier

1. Introduction

Due to the expanding of applications in wireless communication, there is a strong demand for the frequency spectrum and high data rates [1-3]. Therefore, since 2018, businesses and academics have been concentrating on the 6G idea. With the help of widely utilised humanoid robots that are clever

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enough to make decisions with little to no human input, 6G vision has the potential to transform cities into very intelligent metropolises with a wealth of innovative services. Expected to offer wireless communications is the 6G network with more superior key performance indicators (KPIs) than the 5G network, ultra-high reliability, ultra-high connectivity, higher data rates of up to 1 Tbps, and a latency of 1 ms. Moreover, 6G allows for high mobility up to 1000 km/h [4]. Consequently, 6G wireless communications networks must implement a unique modulation strategy and an enhanced multiaccess technology to boost data rates. A multicarrier modulation (MCM) is a crucial approach that fulfils these needs by breaking down a wide-band frequency-selective fading channel into several narrow-band frequency-non-selective fading subchannels [5]. Therefore, huge amounts of data may be transmitted via a channel while guaranteeing that communication systems are resilient to channel imperfections. The main key performance indicators (KPIs) of MCM are high data rate, spectrum efficiency, out-of-band law emissions, robustness against the multipath, frequency localization, free of inter-symbol interference (ISI) and intercarrier interference (ICI), peak average power ratio (PAPR), low complexity of implementation, and MIMO compatibility. Over the past ten years, many wireless technologies, including WiMAX, DVB-T/DABT, WRAN 802.22, WiFi, LTE, and 5G, have been deployed with orthogonal frequency division multiplexing (OFDM). Because OFDM successfully met most of these KPIs [6]. CE is a much less complex procedure in OFDM [7]. However, OFDM has limitations, such as large out-of-band emission (OOBE) that affects nearby channels and decreases spectrum efficiency and high PAPR [8]. And orthogonality, which demands precise synchronization of time and frequency to avoid time and frequency offsets. This makes it a non-powerful candidate for 6G and new applications [9]. Filter bank multicarrier/offset quadrature amplitude modulation (FBMC/OQAM), also known as OFDM/OQAM, has been introduced as a substitute for OFDM. Because it almost meets the majority of KPI. It is more spectrum-efficient than OFDM systems. Furthermore, rectangular windows are replaced by pulse-shaping filters. As a result, FBMC systems have low spectral sidelobes. FBMC systems resist multipath fading channels [10]. It implements a prototype filter with efficient time and frequency domain localization characteristics to deal with ISI and ICI in the FBMC/OQAM system brought on by the frequency selective fading channel. Additionally, it can improve resistance to the channel frequency offset (CFO) and Doppler effect. FBMC/OQAM is therefore being investigated as a viable candidate technology for the physical layer of future 6G wireless communication networks [11].

The real and imaginary halves of each OQAM symbol are divided and transmitted as two pulse amplitude-modulated signals. Unfortunately, with FBMC/OQAM, only the real field symbols have orthogonality. Therefore, there is imaginary interference even on a no-distortion channel [12], known as intrinsic or imaginary interference. The intrinsic interference will be between the pilot and data symbols [13]. This imaginary-valued effect in the real-valued pilots increases the complexity of channel estimation (CE). Therefore, this leads to an imperfect mean-squared error (MSE) and bit error rate (BER) in CE [14]. Without enough null guard symbols between the training and the information phase, Spectral efficiency will decrease due to the solution [15]. There are two types of channel estimation methods: preamble-based and scatter-based. The current preamble estimation approaches are examined in this review for single input, single output (SISO) scenarios, and multiple input multiple outputs (MIMO).

This study thoroughly overviews the preamble CE methods, including the most current scenario, examining them and addressing future research directions. We aim to present these approaches' key concepts and architectures and their advantages and limitations. The following are the contributions of the paper:

i. The description of the FBMC system, deployment, and computation of associated preamble-base procedures utilized in the FBMC are all included in this work.
ii. The fundamental channel estimation concepts for filter bank multicarrier waveforms, which are seen to be prospects for the physical layer of future wireless networks, are thoroughly in the current scenario in this paper, making it essential for wireless communication systems.
iii. Types of preamble channel estimation, advantages, and limitations

The rest of this review paper is organized as follows: Section 2 describes the FBMC/OQAM system. Section 3 presents the concept and description of channel estimation methods and their advantages and disadvantages. Section 4 presents the challenges and future work of channel estimation in FBMC. This review is concluded in Section 5.

2. Filter Bank Multicarrier/Offset Quadrature Amplitude Modulation (FBMC/OQAM)

FBMC/OQAM is a digital modulation technique that has gained attention in wireless communication. FBMC is designed to address some of the limitations and challenges of OFDM, especially in scenarios with stringent requirements on spectral efficiency and low latency [16]. The FBMC was initially introduced by Saltzberg and Chang in 1971 [17]. FBMC/OQAM, or OFDM-OQAM, staggered multi-tone (SMT). OQAM is a process of sending a real and imaginary sample in the FBMC/OQAM system with a shift of half of the symbol time. The transmitter's first block contains the OQAM pre-processing modulation method. The three basic components of OQAM modulation are initial QAM mapping of the input signal, up sampling of the mapping signal, and applying a delay to either the real or imaginary component [18]. The filter bank comprises synthesis filters (SFB) at the transmitter and analysis filters (AFB) at the receiver, as shown in Figure 1.

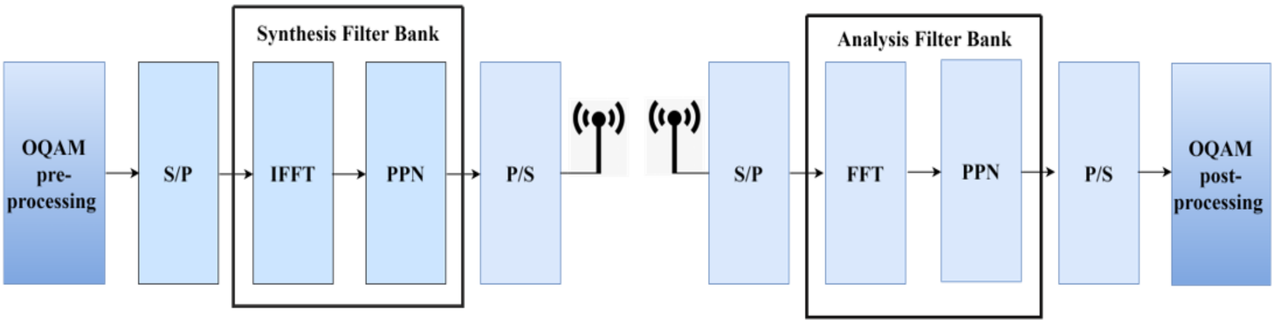

Fig. 1. Block diagram of PPN-FBMC [4]

A prototype filter is an essential component of the filter bank, and it has been proposed for FBMC systems to decrease OOB emissions. As a result, the prototype filter's qualities greatly impact the filter bank quality; therefore, prototype filters fulfil the Nyquist theory. The Nyquist theory states that the pulse response of the filter must equal zero at the end of the period [19]. These Nyquist pulse shaping filters were frequently used to reduce the sensitivity to symbol timing errors [9]. The two most widely used FBMC filters are Phydyas and Hermite [20]. The number of filter coefficients, or the number of times symbols overlap in time, is indicated by the Overlapping factor, K. Table 1 lists the coefficients H and k of the Phydyas prototype filter for a range of K values.

Table 1
Frequency coefficient of Phydyas filter [21]

K	H_0	H_1	H_2	H_3
2	1	$2\sqrt{2}$	-	-
3	1	0.911438	0.411438	-
4	1	0.971960	$2\sqrt{2}$	0.235147

Frequency Spreading (FS) and PolyPhase (PP) implementation are two strategies used for FBMC signal modulation. However, FBMC is employed to improve the wireless networks' performance. The imaginary interference represents the main drawback for FBMC/OQAM, making channel estimation difficult.

The discrete-time signal at the output of an FBMC synthesis filter bank (SFB) is denoted by:

$$s(l) = \sum_{m=0}^{M-1} \sum_{n} d_{mn} g_{mn}(l) \quad (1)$$

$$g_{mn}(l) = g\left(l - n\frac{M}{2}\right) e^{j\frac{2\pi m}{M}(l - lg - 1)/2} e^{j\emptyset mn} \quad (2)$$

$$s(l) = \sum_{m=0}^{M-1} \sum_{n} d_{mn}\, g\left(l - n\frac{M}{2}\right) e^{j\frac{2\pi m(l - lg - 1)}{M}} e^{j\emptyset mn} \quad (3)$$

- $\emptyset_{mn} = (m+n)\frac{\pi}{2}) + mn\pi$

d_{mn} Real OQAM symbol.
mn Frequency time points, m: subscriber index of OQAM symbol, n: the time index.
$g(l - n\frac{M}{2})$ a real symmetric prototype filter's impulse response.
M Is an even number of subscribers
lg the length of the filter (lg=KM), and K is the overlap factor.

The surrounding subcarrier functions $g_{mn}(l)$ are only orthogonal since the pulse g is built in this way. This results in some ISI at the AFB output being completely imaginary. The imaginary interference width is given by:

$$\sum g_{mn}(l) g_{p,q}^{*}(l) = j<g>_{m,n}^{p,q} \quad (4)$$

$j<g>_{m,n}^{p,q}$ is the interference width in frequency-time (FT) between (p,q) and (m,n) FT points. Subcarrier index p and OQAM symbol time index q is both used. Assuming that the channel goes through the prototype filter with all spectral components passing through with roughly equal power, linear phase (coherence bandwidth) at each subcarrier, and time-invariant (coherence time), the following results are obtained for the pth subcarrier and qth FBMC symbol of the AFB output.

$$y_{p,q} = H_{p,q} d_{p,q} + j \sum_{m=0}^{M-1} \sum_{n} H_{m,n} d_{m,n} <g>_{m,n}^{p,q} + \eta_{p,q} \quad (5)$$

where

- $I_{p,q} = j \sum_{m=0}^{M-1} \sum_{n} H_{m,n} d_{m,n} <g>_{m,n}^{p,g}$

$$y_{p,q} = H_{p,q}[d_{p,q} + j \sum_{m=0}^{M-1} \sum_{n} d_{m,n} <g>_{m,n}^{p,g} + \eta_{p,q} \quad (6)$$

where FT point $H_{p,q}$ is the CFR (channel frequency response), $\eta_{p,q}$ is a Gaussian noise component with zero mean and variance σ^2, and $I_{p,q}$ is associated interference. With an accurately timed, localized pulse, the most common assumption is that the Ip,q originates just from the neighbourhood of (p,q) first order called $\Omega_{p,q}$, $\Omega_{p,q}$, = (p,q±1) , (p±1,q±1) or (p±1,q). Interference coming from FT points outside of a neighbourhood is insignificant.

$$y_{p,q} = H_{p,q}c_{p,q}+\eta_{p,q} \quad (7)$$

where,

$$c_{p,q} = d_{p,q} + j\sum_{m=0}^{M-1}\sum_n d_{m,n}<g>_{m,n}^{p,g} \quad (8)$$

$u_{p,q}$is the virtual transmitted symbol at (p, q),

$$u_{p,q} = \sum_{(m,n)\in\Omega_{p,q}} d_{mn}<g>_{m,n}^{p,q} \quad (9)$$

The imaginary component of the interference from nearby FT points. We can compute the CFR by the following equations at the corresponding FT point.

$$\hat{H}_{p,q}=\frac{y_{p,q}}{c_{p,q}},\ \hat{H}_{p,q}=\frac{H_{p,q}c_{p,q}+\eta_{p,q}}{c_{p,q}}$$
$$\hat{H}_{p,q}= H_{p,q}+\frac{\eta_{p,q}}{c_{p,q}} \quad (10)$$

Finding a preamble structure that enhances the power of ($d_{p,q}$ +j$d_{m,n}$) while maintaining a constant preamble power at the transmitter. As a result, the estimation becomes more accurate [26]. The MIMO technique employs several antennas at the transmitter and receiver to service several UE simultaneously and often on a single resource [36]. The equation above may be easily modified for the MIMO scenario. Consider a N_t xN_r MIMO setup where each broadcast and receive antenna has a set of identical SFBs and AFBs. Each receive antenna in the equation may be expressed as j=1, 2,. N_r .

$$y_{p,q}^{j} \approx \sum_{i=1}^{N_t} H_{p,q}^{j,i}c_{p,q}^{i}+\eta_{p,q}^{i} \quad (11)$$

where $H_{p,q}^{j,i}$ M-point of the channel CFR for ith transmit to jth receive antennas.$\eta_{p,q}^{i}$ is the noise $c_{p,q}^{i}$ is the complex value,

$$c_{p,q}^{i}=d_{p,q}^{i}+jd_{p,q}^{i}<g>_{m,n}^{p,q}=d_{p,q}^{i}+ju_{p,q}^{i} \quad (12)$$

For all receive antennas for each FT point

$$H_{p,q} = \begin{bmatrix} H_{p,q}^{1,1} & H_{p,q}^{1,2} & \dots & H_{p,q}^{1,N_t} \\ \vdots & \vdots & \dots & \vdots \\ H_{p,q}^{N_r,1} & H_{p,q}^{N_r,2} & \cdots & H_{p,q}^{N_r,N_t} \end{bmatrix} \quad (13)$$

$$d_{p,q} = [d_{p,q}^{1}, d_{p,q}^{i2}\dots\dots d_{p,q}^{N_t}]^T \quad (14)$$

3. Channel Estimation (CE)

CE is critical in FBMC, where the channel conditions can vary rapidly due to mobility, multipath propagation, and fading. Before rebuilding symbols, the channel estimate is used to adjust for the channel effect. The goal of channel estimation is to acquire information about how the channel affects the transmitted signal, encompassing factors such as amplitude, phase, delay, and channel frequency response [24] so that the information can be utilized to equalize the received signal and correct for channel effects [25]. Accurate channel estimation is crucial for signal processing to mitigate the impact of challenging channels on the received signal [26]. Channel state information (CSI) is knowledge or information about the communication channel parameters, which generally defines how the signal is impacted by the communication channel effects, such as fading [27]. Unfortunately, in FBMC/OQAM, the orthogonality is just in the real symbols. Therefore, the receiver will be even on a free distortion channel with well time, and frequency localization suffers from imaginary interferences, which can affect channel estimation [28-30]. The interference significantly impacts the pilot design, which often complicates pilot symbol design, causes extra resource overhead [31], and decreases the spectrum efficiency and channel estimation effectiveness [25,31]. In order to attain optimal system performance, imaginary interference must be removed [12]. For FBMC systems, some schemes demand 1.5 complex-valued symbols as the preamble sequence symbols be transmitted [23]. On the other hand, only systems using CP-OFDM require two real-valued symbol durations equal to one complex-valued symbol duration [32]. Various aspects, including system requirements, channel conditions, computing complexity, and accessible prior knowledge, influence the technique chosen. FBMC CE methods include preamble-based and scattered pilot-based techniques, as shown in Figure 2.

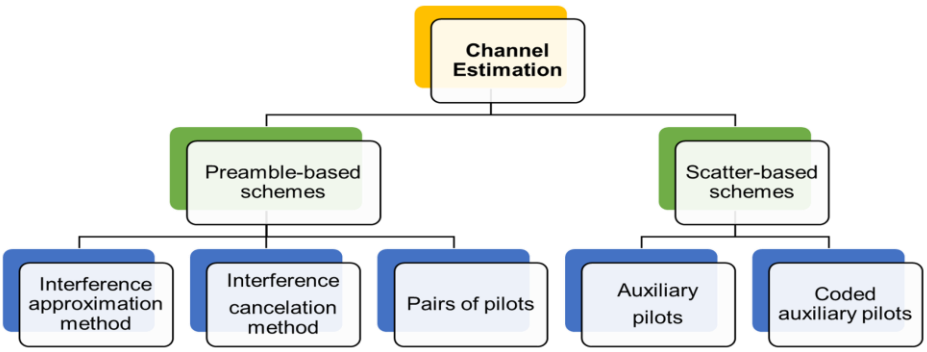

Fig. 2. Channel estimation methods

The preamble is used for channel estimate in preamble-based algorithms. The preamble is a known training (sequences) inserted at the beginning of the transmitted signal. The preamble is a reference for estimating the channel response between the transmitter and the receiver [33]. Overall, preamble-based channel estimation is a widely used technique in FBMC systems, offering a reliable and effective way to estimate the channel response and enhance system performance in challenging wireless environments. Three alternative methods for preamble-based channel estimates exist: interference approximation method (IAM), interference cancellation method (ICM), and pairs of pilots (POP) [16,33].

3.1 Interference Approximation Method (IAM)

The IAM is one of the popular methods of channel estimate for FBMC preamble-based channel estimation [34]. To estimate and utilize this interference for simplifying CE and improving its effectiveness, known neighbourhood pilots are necessary [35]. The IAM was developed by enclosing pilot symbols in zeros or other well-known symbols to remove interference to pilot symbols for channel estimate [25]. The goal is to perform CE as in CP-OFDM while merging the real-valued to complex-valued pseudo-pilots [14,23]. The pilot power magnitude should be as large as feasible for better estimation [36]. Since the IAMs preamble comprises three filled columns of symbols, FBMC has a higher pilot overhead than OFDM systems. Several different IAM systems are available, and some IAMs enhance channel estimation performance by maximizing the power of the pseudo pilot [14]. As a result, the IAM technique experiences a significant decrease in spectrum efficiency, particularly for big numbers of antennas. Additionally, compensating pilot and additional data symbols were produced to substitute zero-valued symbols, which greatly increases the complexity of the demodulation process [25]. The weights of interference $< g>_{m,n}^{p,q}$ For the neighbours (m, n) ∈ Ω p,q of each FT point (p, q) of interest using the prototype filter g as a basis, it is possible to determine the interference weights a priori. If the interference $u_{p,q}$ is only due to the closest neighbours of (p,q), and these FT points have training symbols, then an estimate of this interference can be computed, as mentioned above. This may then be used to build the complex pseudo-pilots $c_{p,q}$ and they can be used to estimate the channel. The below quantities δ, ε, γ and β can be shown to be given in Table 2.

$$\begin{matrix} (-1)^p\varepsilon & 0 & -(-1)^p, \varepsilon \\ (-1)^p\delta & -\beta & (-1)^p\delta \\ -(-1)^p\gamma & d_{p,q} & (-1)^p\gamma \\ (-1)^p\delta & \beta & (-1)^p \\ (-1)^p\varepsilon & 0 & -(-1)^p\varepsilon \end{matrix} \tag{15}$$

Table 2
Interference weights of pattern quantities [37]

Interference weight pattern quantities	M=512 & K=3	M=512 & K=4
$\beta=e^{-j\frac{2\pi}{M}\frac{L_g-1}{2}}\sum_{l=0}^{L_g-1} g^2\, e^{j\frac{2\pi}{M}l}$	0.25	0.2393
$\gamma=\sum_{l=0}^{L_g-1} g(l)g(l-\frac{M}{2})$	0.553	0.5644
$\delta=-je^{-j\frac{2\pi}{M}\frac{l_g-1}{2}}\sum_{l=\frac{M}{2}}^{L_g-1} g(l)g(l-\frac{M}{2})\, e^{j\frac{2\pi}{M}l}$	0.2172	0.2058
$\varepsilon=e^{\pm j\frac{2\pi}{M}L_g-1}\sum_{l=\frac{M}{2}}^{L_g-1} g(l)g(l-\frac{M}{2})\, e^{\pm j2\frac{2\pi}{M}l}$	≈ 0.0004	0

Pseudo-pilot magnitude is equivalent to the power of $d_{p,q}+ju_{p,q}$ may be written as

$$Mag=E\{\left| d_{p,1}+ j(d_{p+1,1}<g>_{p+1,1}^{p,1}+ d_{p-1,1}<g>_{p-1,1}^{p,1}+d_{1,g+1}<g>_{1,q+1}^{p,1}+d_{1,q-1}<g>_{1,q-1}^{p,1}\right|^2\} \tag{16}$$

Several IAM variants have been proposed to decrease imaginary interference and enable the transmission of complex OQAM symbols to simplify receiver signal processing [14]. The preamble structure varies for each IAM, as shown in Figure 2 [36]. It was suggested that IAM-R (IAM-Real) add nulls into the first and third symbols of the preamble to create a pilot with a substantial magnitude dp,0 = dp,2 = 0 for P = 0,1, 2,..., M-1. The IAM-R signifies the authenticity of its pilot symbols, producing robust pseudo-pilots exclusively [23]. IAM-C (Complex), which, at all subcarriers p, combines real and imaginary. In the first and third symbol positions, nulls are trained d_p,0 = d_p,2 = 0. It is intended to set the centre symbols to equal that in IAM-R but with the pilots at the odd subcarriers multiplied by j [37].

E-IAM-C (Extended IAM-C) is another strategy that results in pilots. Compared to IAM-R and IAM-C, the pilots are powerful and have a higher magnitude [13]. With the pilot ±jd in the centre of an odd-indexed subcarrier p, $\mp$d is positioned to the right, which is negative, while $\pm$d, is positioned to the left [23]. Compared to the other IAM schemes, E-IAM-C provides the best CE performance. However, since the three pilots of the E-IAM preamble are nonzero, more power must be sent, in addition to probable interference from the frames data [33,36].

N-IAM (New-IAM) is the new preamble structure that is based on transmitting pseudo pilots at the places of γ and β because they have the biggest weights in comparison to the values of ε and δ is the basis for the new preamble structure, known as N-IAM. The N-IAM schemes pseudo-pilot magnitude at odd indexed subcarriers is higher than IAM-C, IAM-R, and NPS, and it is equal to IAM-R and at even subcarriers, higher than NPS. N-IAM has a lower magnitude at odd and even-indexed subcarriers than E-IAM-C [33]. The NPS and N-IAM perform nearly equally well in terms of improved BER performance and are significantly better than the above IAM [37].

The M-IAM (Modified IAM) method differs from conventional IAMs because it requires less transmitted power and has a larger pilot magnitude. The highest interference weight values are for γ,β,δ, and ε respectively. Consequently, we transmit the pilots in the location of γ and β. Since nulls are positioned at δ and ε, the transmitted power is decreased. Three preamble pilots in M-IAM are nulls located at the corners of the negative odd and even indexed pilots, focusing only on positive odd-indexed subcarriers. The M-IAM uses real values for all its pilots, making it simpler [23]. Figure 3 shows all IAM preamble structures.

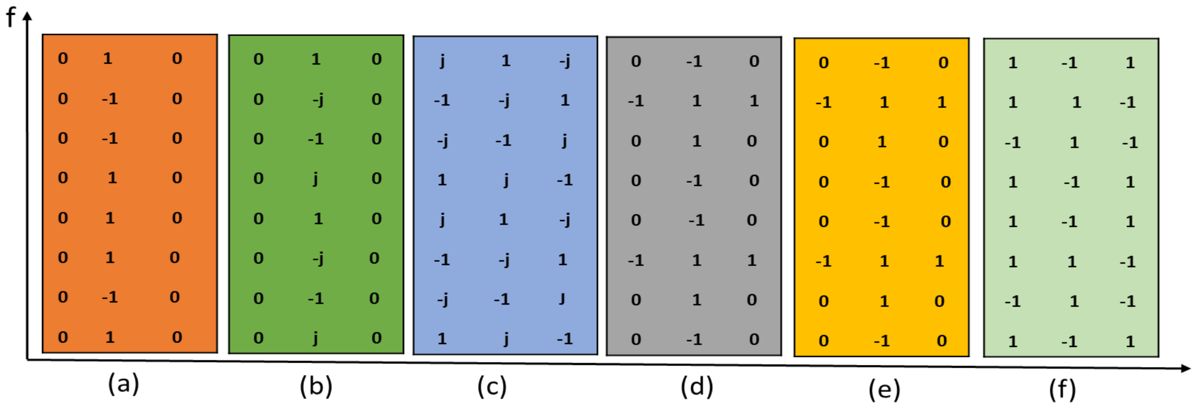

Fig. 3. Preamble design for (a) IAM-R, (b) IAM-C, (c) E-IAM-C, (d) N-IAM, (e) M-IAM, (f) NPS M = 8

A novel preamble scheme (NPS) combines ICM and the IAM preamble. NPS pseudo pilots have a bigger magnitude than other ICM schemes and a lesser than IAM-C and E-IAM-C schemes [38]. NPS is much better in BER performance when compared to IAMs, and it is nearly the same as N-IAM. NPS has pseudo-pilots with magnitudes smaller than conventional IAM schemes and greater than other ICM systems [23]. Table 3 shows the comparison between the IAMs scheme.

Table 3
Comparison between the IAM preamble based

	IAM-C	E-IAM-C	M-IAM	IAM-R	N-IAM	NPS	Ref
Pilot	one column nonzero	All nonzero	Nulls at the corners of the negative odd-indexed and even-indexed pilots and nonzero only at positive odd-indexed subcarriers	One column nonzero	The corners of the even-indexed pilots have null values.	All column nonzero	[23,33,37]
Magnitude Value	$d\|1+2\beta\|$	$d\|1+2(\beta+\gamma)\|$	Odd=$d\sqrt{1+4(\beta+\gamma)^2}$ Even= $d\sqrt{1+\beta^2}$	$d\sqrt{1+\beta^2}$	Odd=$d\sqrt{1+4\beta^2}$ $Even =$ $d\sqrt{1+4\beta^2}$	Odd=$d\sqrt{1+4(\beta+\partial)^2}$ Even=$d\sqrt{1+4(\beta-\gamma)^2}$	[33,37]
BER	Worst	Good	Better than NPS	Better	Best	Better	[23,33,37]
Improve channel estimation	Lower	Good	Good	Lower	Lower	Good	[23,35,37]
PAPR	Smallest	Large	Smaller (smaller than NPS)	Small	Smaller	Smaller than E-IAM	[33,37]
NMSE	lower	Lowest	low	Low	Low	Low	[36]

Because MIMO uses a large number of antenna arrays, channel estimation in a MIMO system is a significant difficulty [39]. IAM preambles from its SISO counterparts to MIMO could be built easily. For MIMO IAM, the baseband signal broadcast across the pth branch is represented in general form as follows: Assuming a multiple antenna setup with N_t is transmit antennas, N_r is receive antennas and M subcarriers, the received signal will be

$$y^r_{p,q} = \sum_{t=0}^{T} H^{r,t}_{p,q} d^t_{p,q} + jI^r_{p,q} + \eta^r_{p,q} \tag{17}$$

$$jI^r_{p,q} = \sum_{t=0}^{T} \Sigma^{m,n \neq p,q} H^{r,t}_{p,q} d^t_{m,n} <g>^{p,g}_{m,n} \tag{18}$$

$$< g>^{p,q}_{m,n} = \sum g_{mn}(l) g^*_{p,q}(l) \tag{19}$$

$$y^r_{p,q} = \sum_{t=0}^{T} H^{r,t}_{p,q} (d^t_{p,q} + ju^r_{p,q}) + \eta^r_{p,q} \tag{20}$$

The MIMO model can be as follows:

$$\begin{pmatrix} y^1_{p,q} \\ \vdots \\ y^r_{p,q} \end{pmatrix} = \begin{pmatrix} H^{1,1}_{p,q} & \cdots & H^{1,t}_{p,q} \\ \vdots & \ddots & \vdots \\ H^{r,1}_{p,q} & \cdots & H^{r,t}_{p,q} \end{pmatrix} \begin{pmatrix} c^1_{p,q} \\ \vdots \\ c^r_{p,q} \end{pmatrix} + \begin{pmatrix} \eta^1_{p,q} \\ \vdots \\ \eta^r_{p,q} \end{pmatrix} \tag{21}$$

The preambles symbols for the IAM approach's N_t xN_r the system needs 2N_t +1 OFDM/OQAM symbols. In other words, the length of the preamble grows linearly as N_t. In a two-by-two antenna scenario. Each transmit antenna comprises five pilot columns if the IAM method's preamble is used. As seen in Figure 4, the second nonzero symbol on the other antenna uses a similar preamble but with the opposite signs.

0	1	0	1	0	0	1	0	1	0
0	-j	0	-j	0	0	-j	0	-j	0
0	-1	0	-1	0	0	-1	0	-1	0
0	j	0	j	0	0	j	0	j	0
0	1	0	1	0	0	1	0	1	0
0	-j	0	-j	0	0	-j	0	-j	0
0	-1	0	-1	0	0	-1	0	-1	0
0	j	0	j	0	0	j	0	j	0

(a) (b)

Fig. 4. MIMO preamble structure IAM-C for two antennas [34]

$$[y_{P,1} \quad y_{P,3}] = H_{P,1}\begin{bmatrix} c_{p,1}^{1} & c_{p,3}^{1} \\ c_{p,1}^{2} & c_{p,3}^{2} \end{bmatrix} + [\eta_{p,1} \quad \eta_{p,3}] \tag{22}$$

Where $c_{p,q}^{1}$ is the pilot symbols, considering the nature of this preamble and noting the premise that first-order FT neighbours largely cause the interference can simplify that $c_{p,1}^{1}$=$c_{p,3}^{1}$=$c_{p,1}^{2}$=$c_{p,3}^{2} = c_P$ hence

$$[y_{P,1} \quad y_{P,3}] = H_{P,1}\begin{bmatrix} c_P & c_P \\ c_P & -c_P \end{bmatrix} + [\eta_{p,1} \quad \eta_{p,3}] \tag{23}$$

$$y_P = H_{P,1} c_P A_2 + [\eta_{p,1} \quad \eta_{p,3} \text{ w } A_2 = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \tag{24}$$

Where A_2 is an orthogonal matrix, and the pseudo-pilot c_P the gain has already been determined, similar to the SISO example. Then, it is possible to calculate an estimate as

$$\hat{H}_{p,1} = [y_{P,1} \quad y_{P,3}]\frac{1}{c_p}A_2^{-1} \tag{26}$$

$$\hat{H}_{P,1} = H_{P,1} + \frac{1}{2c_P}[\eta_{p,1} \quad \eta_{p,3}]A_2 \tag{27}$$

IAM has a low degree of complexity; for two pilots, the preamble length is $2N_t$ +1. Therefore, due to its periodic nature, this method generates a high overhead pilot, reducing spectrum efficiency and generating a significant PAPR at the output of the synthesis filter.

3.2 Interference Cancellation Method (ICM)

The ICM is an alternative method or strategy to cancel or avoid imaginary (intrinsic) interference [40]. Contrarily, the IAM strategy described above uses interference to enhance the channel estimation accuracy [32]. To do this, choose the entries $dp,_0$ of the FBMC pilot symbol wisely in order to prevent or remove interference between them, and rely on the null guards to prevent it from the unknown frame region. Changing the pilot's surrounding data to zero or using the interference coefficient's symmetry to balance each other [41]. ICM's preamble structure is similar to IAM's, with three symbols columns and zero-based adjustable with no additional power overhead and zero around the pilot symbol [24]. The disadvantage is that the intrinsic interferences cannot be entirely removed if the number of symbols is insufficient. It used a similar IAM channel estimation equation.

Figures 4(a), 4(b) and 4(c) demonstrate the three standard preambles for ICM, respectively. The preamble in Figure 4(b) and 4(c) must meet the requirement is $H_{p-1}=H_{p+1}$ to ensure the correctness of the channel estimation [42]. It would result in an increased PAPR. A high PAPR transmitted signal requires a high-power amplifier [42].

3.3 Pairs of Pilots (POP) Method

The POP approach employs two columns of real-valued pilots for channel estimation and tracking [43], as shown in Figure 5. Pilot pairs are used to accomplish channel estimates across time or frequency. These pairings are intended to be orthogonal to one another, which means there will be less interference between them, enabling precise channel estimates. CFR's real and imaginary parts can be computed by solving pairwise equations of the demodulated pilots [31]. The pop technique uses Eq. (7) at two distinct (in practice successive) time instants q_1, $q_2$to create an equation of the system for its real and imaginary portions of the $H_{p,q}$. With the neglecting noise is presented by $H_{p,q} = 1/ w_{p,q}$ the equivalent Zero Forcing (ZF) equalizer coefficients allow us to write

$$y_{p,q1}\ W_{pq_1}, = d_{p,q_1} + ju_{p,q_1} \tag{28a}$$

$$y_{p,q2}\ W_{pq_2} = d_{p,q_2} + ju_{p,q_2} \tag{28b}$$

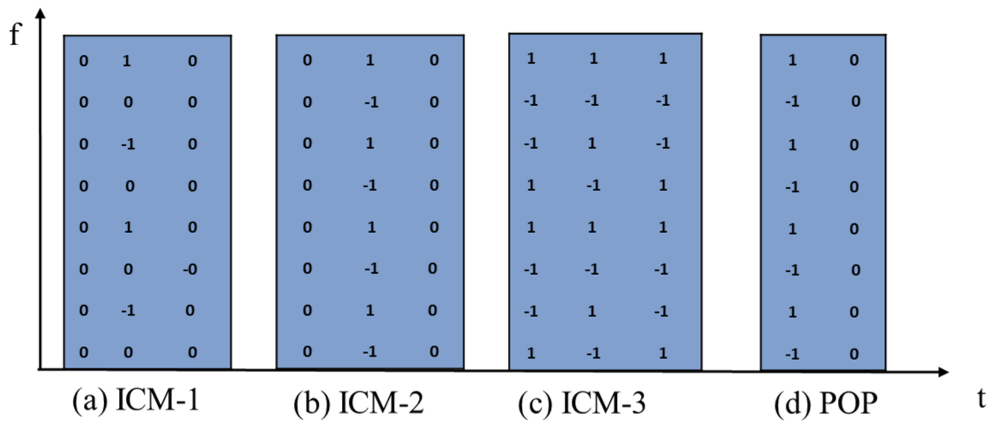

Fig. 5. Preamble structures of interference cancellation method pair of pilots [12,42]

$$y^R_{p,q_1} W^R_{p,q_1} - y^I_{p,q_1} W^I_{p,q_1} = d_{p,q_1}\ ;\ y^R_{p,q_2} W^R_{p,q_2} - y^I_{p,q_2} W^I_{p,q_2} = d_{p,q_2} \tag{29}$$

Notice that $W_{pq_1}, = W_{pq_2}$ due to time invariance

$$\begin{bmatrix} y^R_{p,q_1} & -y^I_{p,q_1} \\ y^R_{p,q_2} & -y^I_{p,q_2} \end{bmatrix} \begin{bmatrix} W^R_{p,q_1} \\ W^I_{p,q_1} \end{bmatrix} = \begin{bmatrix} d_{p,q_1} \\ d_{p,q_2} \end{bmatrix} \tag{30}$$

$$W_{p,q_1} = W^R_{p,q_1} + jW^I_{p,q_1} = j\,\frac{d_{p,q_1} y^*_{p,q_2} - d_{p,q_2} y^*_{p,q_1}}{\mathrm{Im}(y^*_{p,q_1} y_{p,q_2})} \tag{31}$$

In actuality, the preamble would consist of the first two $q_1 = 0$ and $q_2 = 1$ symbol used in OFDM/OQAM shown in Figure 5(d). If so, along with the preamble, where $d_{p,0} = (-1)^p$, all zeros in the second symbol, the equation will be simplified to

$$W_{p,0} = j\frac{(-1)^p y^*_{p,0}}{Im(y^*_{p,0} y_{p,1})} \quad (32)$$

Then, the CFR could be calculated as $H_p = 1/W_p$ .Take into account the following to simply adapt it to the MIMO situation. Assume noise is not considered and that $H_{p,q}$ is left invertible for every p,q (hence $N_r \geq N_t$) known by the W (per-sub-carrier) ZF equalisation matrix, that is, $w_{p,q} = H^{\dagger}_{p,q}$], where $H^{\dagger}_{p,q}$ is the left inverse of $H_{p,q}$. Write Eq. (10) in the form $W_{p,q}\, y_{p,q=}\, c_{p,q}$ for 2 N_r time instants, say q= 0,1, . . . ,2$N_r - 1$, suppose that W can be considered as time-invariant. Then

$$W^R_{p,0}\, y^R_{p,0} - W^I_{p,0}\, y^I_{p,q} = d_{p,q} \quad (33)$$

$$[W^R_{p,0} \quad W^I_{p,0}] = \underbrace{\begin{bmatrix} y^R_{p,0} & y^R_{p,1} & \cdots & y^R_{p,\,2N_{r-1}} \\ -y^I_{p,0} & -y^I_{p,1} & \cdots & -y^I_{p,\,2N_{r-1}} \end{bmatrix}}_{y_p} = \underbrace{[d_{p,0} \quad d_{p,1} \quad \cdots\cdots \quad d_{p,2N_{r-1}}]}_{D_p} \quad (34)$$

Or

$$[W^R_{p,0} \quad W^I_{p,0}]Y_p = D_p \quad (35)$$

The zero-force equalizer is computed as

$$[W^R_{p,0} \quad W^I_{p,0}] = D_p Y^{-1}_p \quad (36)$$

The channel matrix can be found as

$$W_{p,0} = W^R_{p,0} + jW^I_{p,0} = D_p Y^{-1}_p \left(\begin{bmatrix} 1 \\ j \end{bmatrix} \otimes I_{N_r} \right) \quad (37)$$

In addition to being simple, the POP approach has the advantage of not relying on the used prototype filter. It has to be highlighted. Nonetheless, the derivation above only applies when there is minimal noise [7]. Table 4 summarizes the advantages and drawbacks of channel estimation methods.

Table 4
The advantages and drawbacks of channel estimation methods

Channel estimation technics	Advantages	Drawbacks	Ref
IAM	Simple Efficient channel estimation	High pilot overhead, especially for the MIMO system. Minimize spectrum efficiency More power to be transmitted.	[4,12,24]
ICM	More spectrally efficient	Pilot overhead	[6]
POP	Simple Is independent of the prototype filter used	Its performance can be unexpected when there is noise.	[7,13]

The experiments used a prototype filter with M = 512 and K = 3. Two situations, one with low-frequency selectivity and the other with high-frequency selectivity, are plotted against the received SNR using the normalised mean-squared error (NMSE) $\frac{(H-\hat{H})^2}{H}$. No data are sent before or after the preamble in order to more clearly demonstrate the impact of the modelling assumptions on the accuracy of the estimation. The CP-OFDM curve is also provided for reference; the LS estimator was applied with an all-equal pilot preamble. Figure 6 compares preamble methods according to the channel estimation metric. We observe that the NMSE values for IAMs are lowest compared with POP and ICM. These findings support the optimality of IAM-C and show that IAM-R performs almost optimally across the board for all SNR values examined. However, POP has good spectrum efficiency as it just uses two pilot columns. The literature shows that IAM has better BER performance than ICM and POP. We observe that all schemes' NMSE performance increases as the SNR value increases.

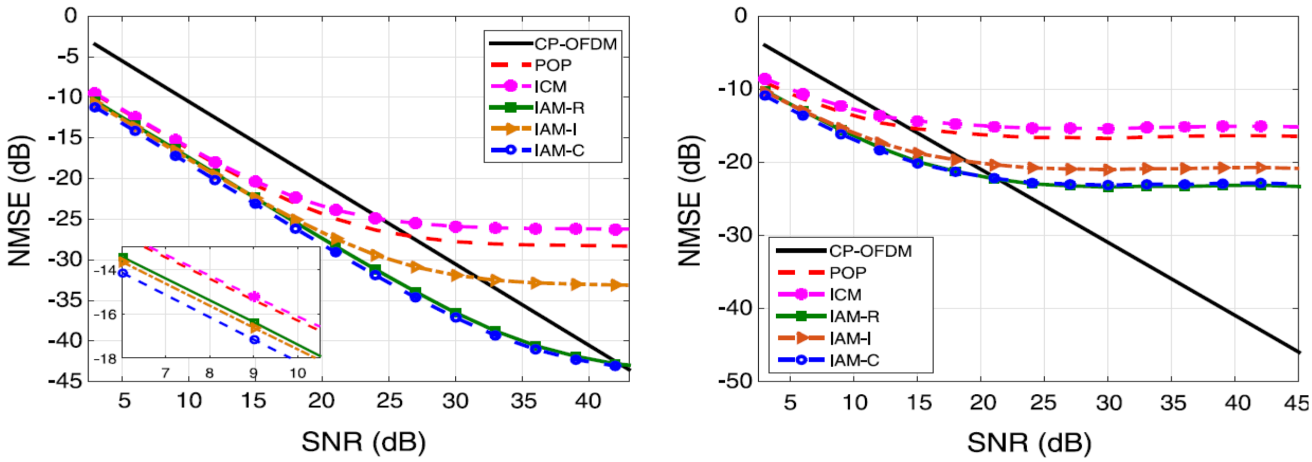

Fig. 6. Performance comparison of preamble-based channel estimation methods Phdyas K=4 (a) ITU Ped-A (b) ITU Veh-B [44]'

Due to complexity and power efficiency, traditional channel estimation techniques in communication systems face limitations. Research focuses on developing innovative algorithms and training schemes to improve CE [45]. Nissel *et al.,* [45] increased the feasible capacity for small to medium SNR and the PAPR by employing two auxiliary symbols per pilot instead of one. They present a technique to obtain the necessary coding matrix for interference cancellation based on linear precoding, which can further boost the possible capacity. [28] employed complex symbols as the POP technique; nonetheless, the solutions led to increased complexity. A novel compressive sensing (CS) approach was put out by Chen *et al.,* [25], who also enhanced the pilot by utilising intrinsic interference. They examined and used the distributional features of the demodulated OQAM symbols to propose a line-fitting-based CE technique. The simulation results demonstrated that the recommended method outperformed the traditional IAM with the best possible pilot structure. Despite performing worse than the E-IAM-C, the FDM technique fared better in the CE when compared to the IAM-R and IAM-C methods. Sun *et al.,* [12] proposed using two-column symbols in the preamble pilot to reduce the pilot overhead of CE. Nonetheless, it was discovered that the recommended approach significantly decreased the pilot overhead without requiring more energy from the pilot. A new approach was presented by Li *et al.,* [13] in contrast to the traditional coded auxiliary pilot technique. The results showed that the recommended strategy had a higher spectrum and equivalent power efficiency without appreciably reducing BER performance. They recommended a preamble arrangement to improve spectrum efficiency that only included one-value guard symbols. In Huang *et al.*, method [61], all overheads were removed except from the pilot, and the experimental results showed that the proposed method surpassed the AP method in terms of BER performance and MSE without any extra overhead by using an interference cancellation method at the receiver. Huang *et al.,* method eliminated intrinsic interference without compromising any data symbols. Wang *et al.,* [46] introduced a pilot indices optimisation approach and a sparse adaptive orthogonal subspace pursuit (SAOSP) algorithm based on the 2-D channel modelling technique. The guard pilots are first placed to lessen the impact of ICI. Next, the index optimisation and SAOSP approaches are applied to generate a high-accuracy estimate of sparse channel coefficients. Simulation results show an improvement of 3-5 dB in channel estimation accuracy. In order to prevent interference and the need for guard symbols, Chen *et al.,* [47] proposed an interference avoidance direct symbol decision (IAD) approach that makes use of dual pilot symbols. We provide a line fitting based IAD (LF-IAD) strategy that improves the symbol reconstruction performance in addition to the minimal symbol distortion-based IAD (MIAD) method, using multiple identical pilot symbols. The investigation shows that recommended methods are less difficult than the traditional interference approximation (IAM). The results of the simulation also demonstrate the effectiveness of the proposed LF-IAD and LF-MIAD approaches.

4. Challenges and Future Work

From this study, we can summarise the challenges as follows:

i. Channel Estimation Overhead: Minimizing overhead while maintaining accuracy is crucial for spectral efficiency and throughput in MIMO-IAM methods [12].
ii. Channel Estimation in Massive MIMO Systems with multiple antennas is a complex task that requires a method that can handle the increasing complexity [49].
iii. Significant increase in transmit power E-IAM-C [30].

Future work aims to improve FBMC channel estimation by addressing challenges and utilizing AI and ML techniques [51]. AI systems offer high accuracy and improved communication system performance, overcoming the limitations of conventional methodologies [52]. Also, the positioning and design of pilots can be improved to increase CE accuracy. Examine the best pilot spacing, patterns, and power-saving methods to estimate the channel response effectively and precisely. It is necessary to use efficient pilot designs and interference mitigation strategies.

5. Conclusions

FBMC is predicted to play an essential role in developing future cellular networks. However, it suffers from imaginary interference, which makes channel estimation difficult, so accurate channel estimation is required to provide information for additional signal processing. This paper focuses on the benefits and challenges of the preamble-based and preamble designs to improve channel estimation performance. A comparison of various IAMs, including IAM-R, IAM-C, E-IAM-C, NPS, N-IAM, and M-IAM, has been provided. Results from PAPR demonstrate the advantages of M-IAM, N-IAM, and IAM-C, enabling them to reduce the transmitted power of FBMC/OQAM. And the superiority of NPS, M-IAM and IAM-E in channel estimation performance. Despite good performance, Pilots-based CE methods suffer from increased pilot overhead, especially with the MIMO system and transmitted power.

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References

[1] Letaief, Khaled B., Wei Chen, Yuanming Shi, Jun Zhang, and Ying-Jun Angela Zhang. "The roadmap to 6G: AI empowered wireless networks." *IEEE communications magazine* 57, no. 8 (2019): 84-90. https://doi.org/10.1109/MCOM.2019.1900271

[2] Chumchewkul, D., C. Tsimenidis, and S. Mumtaz. "Outage Probability Analysis of MRC Detection in OFDM-MMIMO System Utilizing Incomplete Gamma Function." In *2023 IEEE International Conference on Communications Workshops (ICC Workshops)*, pp. 1800-1805. IEEE, 2023. https://doi.org/10.1109/ICCWorkshops57953.2023.10283651

[3] Hanafi, Hafizul Fahri, Muhamad Hariz Adnan, Miftachul Huda, Wan Azani Mustafa, Miharaini Md Ghani, Mohd Ekram Alhafis Hashim, and Ahmed Alkhayyat. "IoT-Enabled GPS Tracking System for Monitoring the Safety Concerns of School Students." *Journal of Advanced Research in Computing and Applications* 35, no. 1 (2024): 1-9.

[4] Alhaj, Nura A., Mohd Faizal Jamlos, Sulastri Abdul Manap, Samah Abdelsalam, Abdelmoneim A. Bakhit, Rizalman Mamat, Mohd Aminudin Jamlos, Mohammed SM Gismalla, and Mosab Hamdan. "Integration of Hybrid Networks, AI, Ultra Massive-MIMO, THz Frequency, and FBMC Modulation Towards 6G Requirements: A Review." *IEEE Access* (2023). https://doi.org/10.1109/ACCESS.2023.3345453

[5] Aldababseh, Mahmoud, and Ali Jamoos. "Estimation of FBMC/OQAM fading channels using dual Kalman filters." *The Scientific World Journal* 2014, no. 1 (2014): 586403. https://doi.org/10.1155/2014/586403

[6] Şahin, Alphan, Ismail Güvenç, and Hüseyin Arslan. "A comparative study of FBMC prototype filters in doubly dispersive channels." In *2012 IEEE Globecom Workshops*, pp. 197-203. IEEE, 2012. https://doi.org/10.1109/GLOCOMW.2012.6477569

[7] Kofidis, Eleftherios, Dimitrios Katselis, Athanasios Rontogiannis, and Sergios Theodoridis. "Preamble-based channel estimation in OFDM/OQAM systems: A review." *Signal processing* 93, no. 7 (2013): 2038-2054. https://doi.org/10.1016/j.sigpro.2013.01.013

[8] Affan, Affan, Shahid Mumtaz, Hafiz M. Asif, and Leila Musavian. "Performance analysis of orbital angular momentum (oam): A 6g waveform design." *IEEE Communications Letters* 25, no. 12 (2021): 3985-3989. https://doi.org/10.1109/LCOMM.2021.3115041

[9] Abdel-Atty, Heba M., Walid A. Raslan, and Abeer T. Khalil. "Evaluation and analysis of FBMC/OQAM systems based on pulse shaping filters." *IEEE Access* 8 (2020): 55750-55772. https://doi.org/10.1109/ACCESS.2020.2981744

[10] Subalatha, M., S. Jayashri, J. Raja, and K. Sakthidasan@ Sankaran. "Low complexity maximum likelihood FBMC QAM for improved performance in longer delay channels." *Wireless Personal Communications* 117 (2021): 3051-3066. https://doi.org/10.1007/s11277-020-07427-7

[11] Lv, Siying, Junhui Zhao, Lihua Yang, and Qiuping Li. "Genetic algorithm based bilayer PTS scheme for peak-to-average power ratio reduction of FBMC/OQAM signal." *IEEE Access* 8 (2020): 17945-17955. https://doi.org/10.1109/ACCESS.2020.2967846

[12] Sun, Jun, Xiaomin Mu, Dejin Kong, Qian Wang, Xinmin Li, and Xing Cheng. "Channel estimation approach with low pilot overhead in FBMC/OQAM Systems." *Wireless Communications and Mobile Computing* 2021, no. 1 (2021): 5533399. https://doi.org/10.1155/2021/5533399

[13] Li, Jiazhe, Siyi Li, Heng Dong, and Zhuoming Li. "Intrinsic interference cancellation scheme for FBMC-OQAM systems based on power multiplexing." *Electronics* 11, no. 9 (2022): 1443. https://doi.org/10.3390/electronics11091443

[14] Kong, Dejin, Xing Zheng, Yue Zhang, and Tao Jiang. "Frame repetition: A solution to imaginary interference cancellation in FBMC/OQAM systems." *IEEE Transactions on Signal Processing* 68 (2020): 1259-1273. https://doi.org/10.1109/TSP.2020.2971185

[15] Kofidis, Eleftherios. "On Preamble-based FBMC/OQAM Highly Frequency Selective Channel Estimation Without Guard Symbols." In *2021 IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6. IEEE, 2021. https://doi.org/10.1109/GLOBECOM46510.2021.9685747

[16] Wang, Han, Wencai Du, Xianpeng Wang, Guicai Yu, and Lingwei Xu. "Channel Estimation Performance Analysis of FBMC/OQAM Systems with Bayesian Approach for 5G-Enabled IoT Applications." *Wireless Communications and Mobile Computing* 2020, no. 1 (2020): 2389673. https://doi.org/10.1155/2020/2389673

[17] Patle, M. T. S. R., and Mrs Deepti Agrawal. "Survey Paper on Performance Evaluation of 5G System using Filter Bank Multicarrier Technique." *Int. J. Sci. Res. Eng. Trends* 7, no. 6 (2021).

[18] Mecheri, Belkacem, Larbi Talbi, Ahmed Lakhssassi, and Mokhtaria Mesri. "Low complexity transceiver design for FBMC-OQAM system for future generation wireless communication." *J Electr Eng* 8 (2020): 21-26. https://doi.org/10.17265/2328-2223/2020.01.004

[19] Alhaj, Nura A., Mohd Faizal Jamlos, Sulastri Abdul Manap, Abdelmoneim A. Bakhit, and Rizalman Mamat. "A review of multiple access techniques and frequencies requirements towards 6G." In *2022 IEEE International RF and Microwave Conference (RFM)*, pp. 1-4. IEEE, 2022. https://doi.org/10.1109/RFM56185.2022.10065342

[20] Abou-Elkheir, Aya T., Ehab F. Badran, and Omar YK Alani. "Performance Evaluation of OQAM-FBMC System with STBC/SM MIMO over Rayleigh Fading Channel." In *2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, pp. 0854-0859. IEEE, 2020. https://doi.org/10.1109/IEMCON51383.2020.9284838

[21] Azzahhafi, Hachim, Moussa El Yahyaoui, and Ali El Moussati. "Performance analysis of frequency spreading FBMC in mobile radio channel." In *2018 International Symposium on Advanced Electrical and Communication Technologies (ISAECT)*, pp. 1-3. IEEE, 2018. https://doi.org/10.1109/ISAECT.2018.8618823

[22] Lele, Chrislin, Pierre Siohan, and Rodolphe Legouable. "2 dB better than CP-OFDM with OFDM/OQAM for preamble-based channel estimation." In *2008 IEEE International Conference on Communications*, pp. 1302-1306. IEEE, 2008. https://doi.org/10.1109/ICC.2008.253

[23] Roshdy, Radwa A., Mohamed A. Aboul-Dahab, and Mohamed M. Fouad. "A modified interference approximation scheme for improving preamble based channel estimation performance in FBMC system." *arXiv preprint arXiv:2002.11676* (2020). https://doi.org/10.5121/ijcnc.2020.12102

[24] Chen, Da, Yuan Tian, Daiming Qu, and Tao Jiang. "OQAM-OFDM for wireless communications in future Internet of Things: A survey on key technologies and challenges." *IEEE Internet of Things Journal* 5, no. 5 (2018): 3788-3809. https://doi.org/10.1109/JIOT.2018.2869677

[25] Chen, Da, Rui Wang, and Tao Jiang. "Channel estimation and pilot symbol optimization based on intrinsic interference utilization for OQAM/FBMC systems." *IEEE Transactions on Signal Processing* 69 (2021): 4595-4606. https://doi.org/10.1109/TSP.2021.3101829

[26] Liu, Wenfeng, Da Chen, Kai Luo, Tao Jiang, and Daiming Qu. "FDM-structured preamble optimization for channel estimation in MIMO-OQAM/FBMC systems." *IEEE Transactions on Wireless Communications* 17, no. 12 (2018): 8433-8443. https://doi.org/10.1109/TWC.2018.2877600

[27] Hirose, Hiroki, Tomoaki Ohtsuki, and Guan Gui. "Deep learning-based channel estimation for massive MIMO systems with pilot contamination." *IEEE Open Journal of Vehicular Technology* 2 (2020): 67-77. https://doi.org/10.1109/OJVT.2020.3045470

[28] Liu, Wenfeng, Stefan Schwarz, Markus Rupp, and Tao Jiang. "Pairs of pilots design for preamble-based channel estimation in OQAM/FBMC systems." *IEEE Wireless Communications Letters* 10, no. 3 (2020): 488-492. https://doi.org/10.1109/LWC.2020.3035388

[29] Liu, Wenfeng, Da Chen, Stefan Schwarz, Markus Rupp, and Tao Jiang. "Preamble power optimization based on intrinsic interference utilization for OQAM/FBMC channel estimation." *IEEE Transactions on Vehicular Technology* 69, no. 11 (2020): 13556-13566. https://doi.org/10.1109/TVT.2020.3030661

[30] Liu, Wenfeng, Stefan Schwarz, Markus Rupp, Da Chen, and Tao Jiang. "Preamble-based channel estimation for OQAM/FBMC systems with delay diversity." *IEEE Transactions on Wireless Communications* 19, no. 11 (2020): 7169-7180. https://doi.org/10.1109/TWC.2020.3008736

[31] Chen, Da, Rui Wang, Yujuan Mei, and Tao Jiang. "Distribution Line Fitting-Based Channel Estimation Without Guard Symbols for OQAM/FBMC Systems." *IEEE Transactions on Wireless Communications* 20, no. 6 (2021): 3659-3669. https://doi.org/10.1109/TWC.2021.3052757

[32] Yuan, Hang, Su Hu, Lu Yin, and Jie Zhou. "Efficient channel estimation for FBMC systems based on auxiliary preamble design." In *2015 10th International Conference on Information, Communications and Signal Processing (ICICS)*, pp. 1-5. IEEE, 2015. https://doi.org/10.1109/ICICS.2015.7459990

[33] El-Ganiny, M. Youssef, Ashraf AM Khalaf, Aziza I. Hussein, and Hesham FA Hamed. "A preamble based channel estimation methods for FBMC waveform: A comparative study." *Procedia Computer Science* 182 (2021): 63-70. https://doi.org/10.1016/j.procs.2021.02.009

[34] Raslan, Walid A., Mohamed A. Mohamed, and Heba M. Abdel-Atty. "Deep-BiGRU based channel estimation scheme for MIMO–FBMC systems." *Physical Communication* 51 (2022): 101592. https://doi.org/10.1016/j.phycom.2021.101592

[35] Ijiga, Owoicho E., Olayinka O. Ogundile, Ayokunle D. Familua, and Daniel JJ Versfeld. "Review of channel estimation for candidate waveforms of next generation networks." *Electronics* 8, no. 9 (2019): 956. https://doi.org/10.3390/electronics8090956

[36] Kofidis, Eleftherios, and Dimitrios Katselis. "Improved interference approximation method for preamble-based channel estimation in FBMC/OQAM." In *2011 19th European signal processing conference*, pp. 1603-1607. IEEE, 2011. https://doi.org/10.1109/ICSIPA.2011.6144161

[37] AboulDahab, Mohammed A., Mohammed M. Fouad, and Radwa A. Roshdy. "A proposed preamble based channel estimation method for FBMC in 5G wireless channels." In *2018 35th National Radio Science Conference (NRSC)*, pp. 140-148. IEEE, 2018. https://doi.org/10.1109/NRSC.2018.8354382

[38] Wang, Han, Wencai Du, and Lingwei Xu. "Novel preamble design for channel estimation in FBMC/OQAM systems." *KSII Transactions on Internet and Information Systems (TIIS)* 10, no. 8 (2016): 3672-3688. https://doi.org/10.3837/tiis.2016.08.014

[39] Hassan, Beenish, Sobia Baig, Hafiz M. Asif, Shahid Mumtaz, and Sami Muhaidat. "A survey of fdd-based channel estimation schemes with coordinated multipoint." *IEEE Systems Journal* 16, no. 3 (2021): 4563-4573. https://doi.org/10.1109/JSYST.2021.3111284

[40] Wang, Han, Lingwei Xu, Xianpeng Wang, and Sohail Taheri. "Preamble design with interference cancellation for channel estimation in MIMO-FBMC/OQAM systems." *IEEE Access* 6 (2018): 44072-44081. https://doi.org/10.1109/ACCESS.2018.2864221

[41] Hu, Su, Zilong Liu, Yong Liang Guan, Chuanxue Jin, Yixuan Huang, and Jen-Ming Wu. "Training sequence design for efficient channel estimation in MIMO-FBMC systems." *IEEE access* 5 (2017): 4747-4758. https://doi.org/10.1109/ACCESS.2017.2688399

[42] Xue, Lunsheng, Shangfei Qiu, Peng Wu, and Dejiang Chen. "An improved interference cancellation channel estimation method for OQAM/OFDM system." In *Journal of Physics: Conference Series*, vol. 1169, no. 1, p. 012053. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1169/1/012053

[43] Cui, Wenjia, Daiming Qu, Tao Jiang, and Behrouz Farhang-Boroujeny. "Coded auxiliary pilots for channel estimation in FBMC-OQAM systems." *IEEE Transactions on Vehicular Technology* 65, no. 5 (2015): 2936-2946. https://doi.org/10.1109/TVT.2015.2448659

[44] Kofidis, Eleftherios, Leonardo Gomes Baltar, Xavier Mestre, Faouzi Bader, and Vincent Savaux. "FBMC channel estimation techniques." In *Orthogonal Waveforms and Filter Banks for Future Communication Systems*, pp. 257-297. Academic Press, 2017. https://doi.org/10.1016/B978-0-12-810384-5.00011-6

[45] Nissel, Ronald, and Markus Rupp. "On pilot-symbol aided channel estimation in FBMC-OQAM." In *2016 IEEE international conference on acoustics, speech and signal processing (ICASSP)*, pp. 3681-3685. IEEE, 2016. https://doi.org/10.1109/ICASSP.2016.7472364

[46] Wang, Ying, Qiang Guo, Jianhong Xiang, and Yang Liu. "Doubly selective channel estimation and equalization based on ICI/ISI mitigation for OQAM-FBMC systems." *Physical Communication* 59 (2023): 102120. https://doi.org/10.1016/j.phycom.2023.102120

[47] Chen, Da, Kai Luo, Wei Peng, and Wei Wang. "Low-Complexity Symbol Reconstruction Based on Direct Symbol Decision for FBMC-OQAM Systems." *IEEE Transactions on Signal Processing* (2023). https://doi.org/10.1109/TSP.2023.3328061

[48] Kong, Dejin, Pei Liu, Qian Wang, Jian Li, Xinmin Li, and Xing Cheng. "Preamble-based MMSE channel estimation with low pilot overhead in MIMO-FBMC systems." *IEEE Access* 8 (2020): 148926-148934. https://doi.org/10.1109/ACCESS.2020.3015809

[49] SIvakumar, Renukka, Saidatul Norlyana Azemi, Lee Yeng Seng, Kok Yeow You, and Ping Jack Soh. "3-D Printed Antennas with Dielectric Lens for Free-Space Constitutive Parameters Measurement." *Semarak International Journal of Electronic System Engineering* 1, no. 1 (2024): 1-25.

[50] Huang, Kaiwen, Zhongnian Li, Hongbo Xu, and Guoping Zhang. "Pilot Design with Low Overhead in Spread-Spectrum-Based FBMC/OQAM Systems." In *2022 IEEE 8th International Conference on Computer and Communications (ICCC)*, pp. 7-11. IEEE, 2022. https://doi.org/10.1109/ICCC56324.2022.10066052

[51] Shatnawi, Hashem, and Mohammad N. Alqahtani. "Delving into the Revolutionary Impact of Artificial Intelligence on Mechanical Systems: A Review." *Semarak International Journal of Machine Learning* 1, no. 1 (2024): 31-40.

[52] Kamarudin, Nurzatulshima, Nik Mawar Hanifah Nik Hassan, Mohd Mokhtar Muhamad, Othman Talib, Haryati Kamarudin, Norhafizan Abdul Wahab, Aidatul Shima Ismail, Haza Hafeez Borhan, and Nazihah Idris. "Unveiling Collaborative Trends in Fuzzy Delphi Method (FDM) Research: A Co-Authorship Bibliometrics Study." *International Journal of Computational Thinking and Data Science* 2, no. 1 (2024): 1-20.