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Energy And Spectrally Efficient Signalling For Next Generation Iot

D.Anusha[1], K. Rishika[2], D. Tanuja[3], M. Sravani[4]
[1]Assistant Professor; Department of Electronics and Communication Engineering Bhoj Reddy Engineering College for Women Hyderabad, India.
[2,3,4]B. Tech Students; Department of Electronics and Communication Engineering Bhoj Reddy Engineering College for Women Hyderabad, India.
Mail Id; rishikakoyagura88@gmail.com , tanujatanuja945@gmail.com , mandasravani2905@gmail.com
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Abstract
The rapid expansion of Internet of Things (IoT) applications has created a demand for communication systems that are both energy-efficient and spectrally efficient. Narrowband IoT (NB-IoT), operating within a limited bandwidth of 180 kHz, faces challenges in achieving high data rates while maintaining low power consumption.
This project proposes an energy- and spectrally efficient signalling technique based on Hilbert Transform-assisted Fast Orthogonal Frequency Division Multiplexing (HT-FOFDM) combined with Pulse Amplitude Modulation (PAM). The proposed method aims to enhance spectral efficiency by compressing subcarrier spacing while maintaining energy efficiency suitable for low-power IoT devices.
The system is designed and evaluated under Additive White Gaussian Noise (AWGN) channel conditions, and its performance is compared with the conventional Single Carrier Frequency Division Multiple Access (SC-FDMA) scheme. Simulation results demonstrate that the proposed HT-FOFDM system achieves higher spectral efficiency, improved Bit Error Rate (BER) performance, and reduced power consumption within the same bandwidth constraints. The proposed approach provides a promising solution for next-generation IoT communication systems and can be further extended to support massive connectivity in future wireless networks.

Keywords
Internet of Things (IoT), Narrowband Internet of Things (NB-IoT), Hilbert Transform, Fast Orthogonal Frequency Division Multiplexing (FOFDM), HT-FOFDM, Pulse Amplitude Modulation (PAM), Spectral Efficiency, Energy Efficiency, Bit Error Rate (BER), Additive White Gaussian Noise (AWGN), Single Carrier Frequency Division Multiple Access (SC-FDMA), Wireless Communications.

Introduction

Background of Internet of Things (IoT)

The rapid advancement of wireless communication technologies has accelerated the development of the Internet of Things (IoT), a communication paradigm that enables billions of interconnected devices to sense, collect, process, and exchange information with minimal human intervention. IoT has become an integral component of numerous application domains, including smart cities, healthcare, industrial automation, precision agriculture, environmental monitoring, and intelligent transportation systems. Unlike conventional wireless communication networks that primarily focus on high-speed data services, IoT applications typically involve a massive number of resource-constrained devices that transmit relatively small amounts of data. These devices are generally battery-powered and are expected to operate continuously for several years without battery replacement. Consequently, communication technologies for IoT must emphasize low energy consumption while ensuring reliable connectivity. Moreover, the exponential increase in connected devices has intensified the demand for efficient utilization of the limited radio spectrum, making both energy efficiency and spectral efficiency essential design objectives for modern IoT communication systems.

Evolution Toward Narrowband IoT (NB-IoT)

To address the communication requirements of large-scale IoT deployments, the 3rd Generation Partnership Project (3GPP) introduced Narrowband Internet of Things (NB-IoT) as a Low-Power Wide-Area Network (LPWAN) technology. NB-IoT operates within a bandwidth of 180 kHz, enabling deployment over existing LTE infrastructure through standalone, in-band, or guard-band modes without requiring significant network modifications. The technology provides extended coverage, low device complexity, reduced power consumption, and support for massive device connectivity, making it suitable for applications such as smart metering, environmental sensing, industrial monitoring, and asset tracking. Despite these advantages, the narrow operating bandwidth restricts achievable data rates and limits spectral efficiency. As emerging IoT applications demand higher communication capacity and improved quality of service, there is a growing need for signalling techniques capable of increasing spectral efficiency without expanding the available bandwidth.

Literature Survey

The increasing adoption of the **Internet of Things (IoT)** has transformed the requirements of modern wireless communication systems. Unlike conventional communication networks, which primarily emphasize high data rates and broadband services, IoT networks are designed to support a large number of low-power devices that periodically transmit small volumes of data. These devices are expected to operate efficiently under strict energy constraints while maintaining reliable connectivity over extended periods. Consequently, the design of communication techniques for IoT has shifted toward improving both energy efficiency and spectral efficiency without increasing system complexity or bandwidth requirements.

To satisfy these requirements, researchers have investigated several communication technologies, including Narrowband Internet of Things (NB-IoT), Single Carrier Frequency Division Multiple Access (SC-FDMA), Orthogonal Frequency Division Multiplexing (OFDM), Fast Orthogonal Frequency Division Multiplexing (FOFDM), Hilbert Transform-assisted FOFDM (HT-FOFDM), and Pulse Amplitude Modulation (PAM). Each technique offers specific advantages while presenting certain limitations in terms of bandwidth utilization, power efficiency, interference management, or implementation complexity. This chapter reviews the existing literature related to these technologies, identifies their strengths and shortcomings, and establishes the motivation for developing the proposed HT-FOFDM-based signalling technique for NB-IoT systems.

Narrowband Internet of Things (NB-IoT)

Narrowband Internet of Things (NB-IoT) is a Low-Power Wide-Area Network (LPWAN) technology introduced by the 3rd Generation Partnership Project (3GPP) to provide reliable communication for massive IoT deployments. Operating within a narrow bandwidth of 180 kHz, NB-IoT can be integrated into existing LTE networks using standalone, in-band, or guard-band deployment modes. The technology is specifically designed for applications requiring low data rates, extended coverage, and long battery life, including smart metering, environmental monitoring, healthcare, industrial automation, and smart agriculture.

Several studies have demonstrated that NB-IoT significantly improves coverage by offering approximately 20 dB higher coverage gain than conventional LTE systems while supporting battery lifetimes of up to 10 years through optimized power-saving mechanisms. Furthermore, the simplified hardware architecture reduces device cost and enables the connection of a massive number of IoT devices within a single cellular network. Despite these advantages, the restricted bandwidth imposes limitations on achievable data rates and spectral efficiency. As IoT applications continue to evolve toward supporting larger data volumes and more frequent transmissions, researchers have focused on developing advanced signalling techniques capable of improving bandwidth utilization without requiring additional spectrum resources.

Existing Methodologies

The design of physical-layer communication techniques for next-generation **Internet of Things (IoT)** networks is primarily driven by the need for low energy consumption, efficient spectrum utilization, reliable connectivity, and reduced device complexity. Unlike conventional broadband communication systems that focus on maximizing data throughput, IoT networks are designed to support a massive number of battery-powered devices transmitting small amounts of data over limited bandwidth. Therefore, selecting an appropriate signalling technique is essential to achieve reliable communication while extending device lifetime and efficiently utilizing the available spectrum.

Narrowband Internet of Things (NB-IoT) operates within a bandwidth of 180 kHz, making bandwidth efficiency a critical performance requirement. Various multicarrier transmission techniques have been investigated to improve communication performance under these constraints. Among them, Single Carrier Frequency Division Multiple Access (SC-FDMA), Orthogonal Frequency Division Multiplexing (OFDM), Fast Orthogonal Frequency Division Multiplexing (FOFDM), and Hilbert Transform-assisted Fast Orthogonal Frequency Division Multiplexing (HT-FOFDM) have attracted considerable research attention. This chapter presents a comprehensive review of these existing methodologies, discussing their operating principles, mathematical models, advantages, limitations, and suitability for NB-IoT communication systems.

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SC-FDMA Transmitter and Receiver Architecture

The SC-FDMA transmission process begins with a sequence of input symbols represented by $x(n)$. These symbols are transformed into the frequency domain using the DFT operation and subsequently mapped onto allocated subcarriers. Following subcarrier mapping, the IFFT converts the frequency-domain symbols into the corresponding time-domain signal for transmission through the wireless channel.

The transmitted signal after DFT spreading is represented as

$$X(k) = DFT\{x(n)\}$$

After propagation through the communication channel, the received signal is equalized in the frequency domain and recovered using the Inverse Discrete Fourier Transform (IDFT), expressed as

$$\hat{x}(n) = IDFT\left\{\frac{Y(k)}{H(k)}\right\}$$

where $Y(k)$represents the received signal in the frequency domain and $H(k)$denotes the channel frequency response.

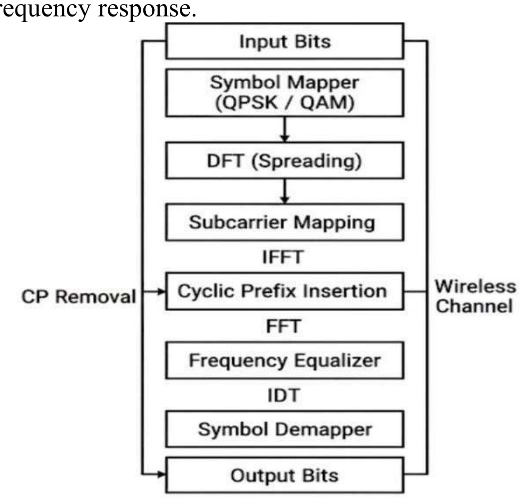

Figure 1; mathematical model of the SC-FDMA transmitter and receiver architecture.

Orthogonal Frequency Division Multiplexing (OFDM)

Working Principle of OFDM

In an OFDM transmitter, the incoming serial data stream is first converted into multiple parallel data streams. Each stream is independently modulated and assigned to a distinct orthogonal subcarrier. The collection of frequency-domain symbols is transformed into a time-domain signal using the **Inverse Fast Fourier Transform (IFFT)** before transmission through the wireless channel.

At the receiver, the received signal is processed using the **Fast Fourier Transform (FFT)** to recover the transmitted frequency-domain symbols. Equalization is then performed to compensate for channel effects before demodulation reconstructs the original information sequence. This multicarrier transmission approach provides excellent resistance against frequency-selective fading and significantly simplifies receiver design.

3.3.2 OFDM Transmitter and Receiver Architecture

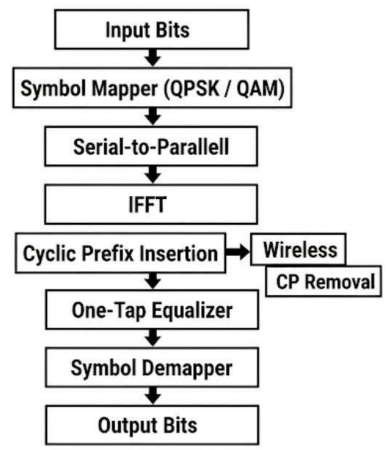

Figure2; presents the transmitter and receiver architecture of the OFDM communication system.

Proposed System

To address the limitations of conventional signalling techniques such as Single Carrier Frequency Division Multiple Access (SC-FDMA), this work proposes an energy- and spectrally efficient signalling technique based on Hilbert Transform-assisted Fast Orthogonal Frequency Division Multiplexing (HT-FOFDM) integrated with Pulse Amplitude Modulation (PAM). The proposed approach is specifically designed for Narrowband Internet of Things (NB-IoT) communication systems, where the available transmission bandwidth is limited to 180 kHz and IoT devices operate under stringent energy constraints. The primary objective is to improve spectral efficiency while maintaining low power consumption, reliable communication, and reduced implementation complexity. By combining the bandwidth compression capability of FOFDM with the interference suppression properties of the Hilbert Transform and the simplicity of PAM, the proposed system offers an effective solution for next-generation IoT communication networks.

Design Philosophy

The proposed HT-FOFDM system is developed to satisfy the fundamental requirements of modern NB-IoT communication, including efficient spectrum utilization, low energy consumption, and reliable data transmission. The design philosophy is based on maximizing the amount of information transmitted within the available bandwidth while minimizing computational complexity and power requirements.

To achieve these objectives, the proposed system integrates three complementary techniques. **Fast Orthogonal** Frequency Division Multiplexing (FOFDM) is employed to improve spectral efficiency by reducing the spacing between adjacent subcarriers, thereby allowing more information to be transmitted within the same bandwidth. Since bandwidth compression introduces inter-carrier interference, the Hilbert Transform is incorporated to generate orthogonal quadrature signal components that effectively suppress interference while preserving communication reliability. Finally, Pulse Amplitude Modulation (PAM) is adopted because of its low implementation complexity, reduced Peak-to-Average Power Ratio (PAPR), and improved power efficiency, making it particularly suitable for battery-powered IoT devices.

System Architecture

The proposed HT-FOFDM communication system consists of three major functional blocks: the **transmitter**, the wireless communication channel, and the receiver. The transmitter converts the input binary data into PAM symbols, generates multicarrier signals using the FOFDM framework, and applies the Hilbert Transform to produce orthogonal analytic signal components. The transmitted signal then propagates through an Additive White Gaussian Noise (AWGN) channel that models the effects of wireless transmission.

At the receiver, the received signal undergoes inverse processing, including Hilbert Transform-based signal reconstruction, FFT processing, symbol demodulation, and data recovery. The receiver architecture is designed to accurately recover the transmitted information while maintaining low computational complexity. The overall transceiver configuration is illustrated in Figure 4.1, which depicts the complete HT-FOFDM communication framework.

Transmitter Design

The transmitter is responsible for converting the binary information sequence into an energy-efficient multicarrier signal suitable for wireless transmission. Initially, a random binary data sequence is generated to represent the source information. These binary bits are subsequently mapped into amplitude levels using Pulse Amplitude Modulation (PAM). The modulated symbols are then converted from serial to parallel format to facilitate multicarrier transmission.

Following serial-to-parallel conversion, the frequency-domain symbols are processed using the **Inverse Fast Fourier Transform (IFFT)** to generate the Fast OFDM signal. Since FOFDM compresses the spacing between adjacent subcarriers to improve spectral efficiency, the resulting signal is processed using the **Hilbert Transform** to generate orthogonal quadrature components. The generated analytic signal reduces inter-carrier interference while maintaining efficient utilization of the available bandwidth. Finally, the processed signal is transmitted through the wireless communication channel.

Simulation Results and Discussion

Simulation Setup

The performance of the proposed HT-FOFDM system is evaluated using Monte Carlo simulations implemented in MATLAB. The communication channel is modeled as an Additive White Gaussian Noise (AWGN) channel, which provides a standard benchmark for evaluating physical-layer communication performance. The simulation parameters are selected according to NB-IoT specifications so that the proposed signalling scheme can be fairly compared with the conventional SC-FDMA system.

The transmitter employs Pulse Amplitude Modulation (PAM), Fast Orthogonal Frequency Division Multiplexing (FOFDM), and Hilbert Transform-based signal generation. At the receiver, inverse processing is performed to recover the transmitted symbols, followed by BER calculation over a range of Signal-to-Noise Ratio (SNR) values.

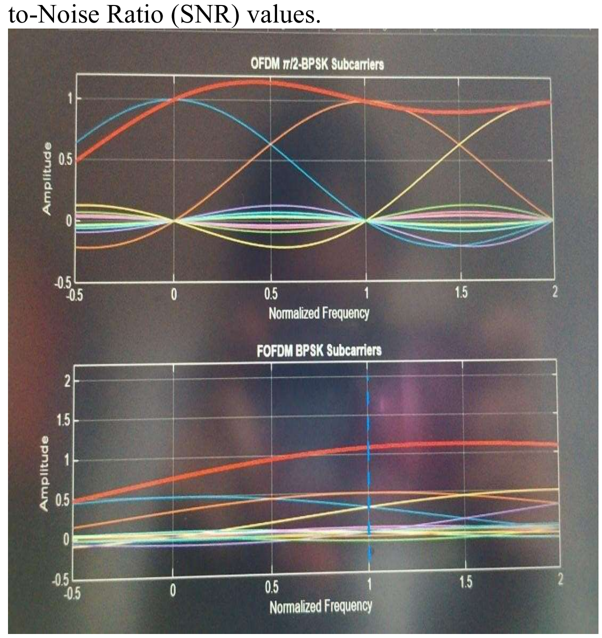

Figure 3 illustrates the subcarrier representation of conventional OFDM using π/2-BPSK together with the compressed subcarrier arrangement adopted in FOFDM.

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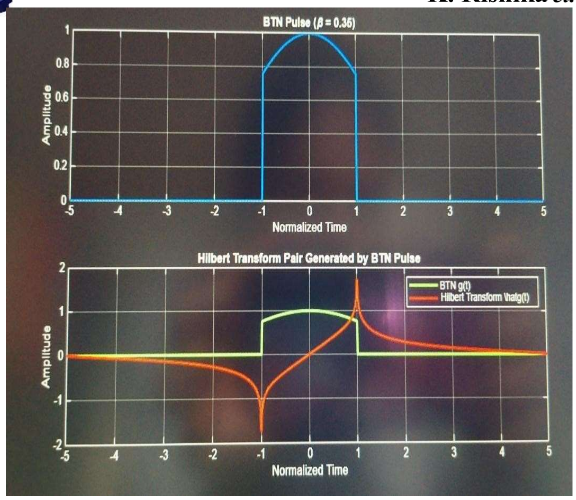

Figure 4 presents the Better Than Nyquist (BTN) pulse-shaping waveform with a roll-off factor of **β = 0.35** and its corresponding Hilbert Transform pair used for orthogonal signal generation.

These figures demonstrate the waveform generation process adopted in the proposed communication system.

Performance Metrics

The effectiveness of the proposed signalling technique is evaluated using several important communication performance metrics. These include:

Bit Error Rate (BER) to evaluate communication reliability.

Spectral Efficiency to measure bandwidth utilization.

Energy Efficiency based on transmit power requirements.

Constellation Analysis to examine modulation robustness under noisy channel conditions.

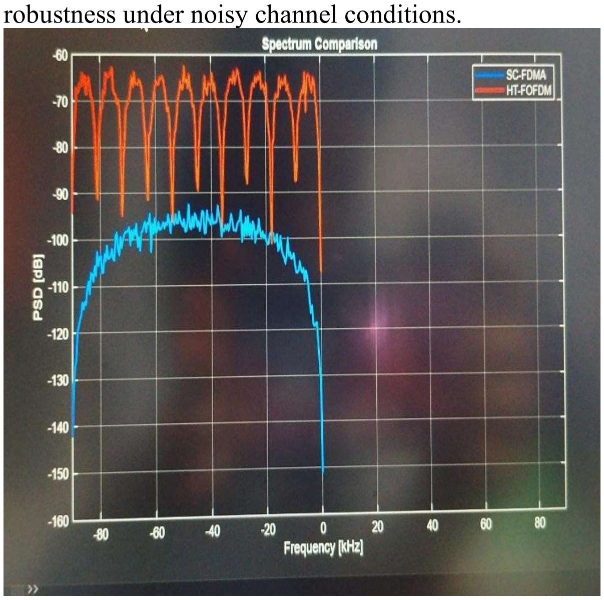

Figure 5 compares the **Power Spectral Density (PSD)** of SC-FDMA and the proposed HT-FOFDM signalling technique. The spectral characteristics demonstrate that HT-FOFDM provides better spectral containment with reduced sidelobe levels, resulting in improved bandwidth utilization and lower adjacent-channel interference.

Bit Error Rate (BER) Analysis

The BER performance of the proposed HT-FOFDM system is evaluated over a wide range of **Signal-to-Noise Ratio (SNR)** values and compared with conventional SC-FDMA and conventional FOFDM systems.

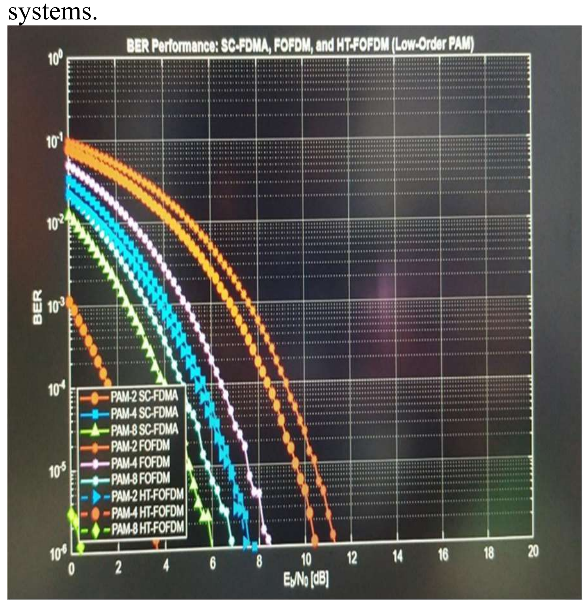

Figure 6 presents the BER comparison of SC-FDMA, conventional FOFDM, and the proposed HT-FOFDM employing low-order PAM modulation.

The simulation results indicate that the proposed HT-FOFDM system consistently achieves lower BER than the existing communication techniques, particularly at moderate and high SNR values. At lower SNR levels, the BER performance of all signalling schemes is relatively similar because channel noise dominates the received signal. However, as the SNR increases, HT-FOFDM exhibits a significantly faster reduction in BER.

For a target BER of approximately 10^{-4}, the proposed system achieves an SNR improvement of nearly **2–3 dB** compared with conventional SC-FDMA. This performance enhancement can be attributed to the improved spectral confinement achieved through Hilbert Transform-generated orthogonal signal pairs, reduced inter-symbol interference, and efficient utilization of compressed subcarrier spacing within the FOFDM framework.

Effect of Compression Factor on System Performance

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The bandwidth compression factor plays an important role in determining the performance of the proposed HT-FOFDM system. Different compression factors are investigated to analyze the trade-off between spectral efficiency and BER performance.

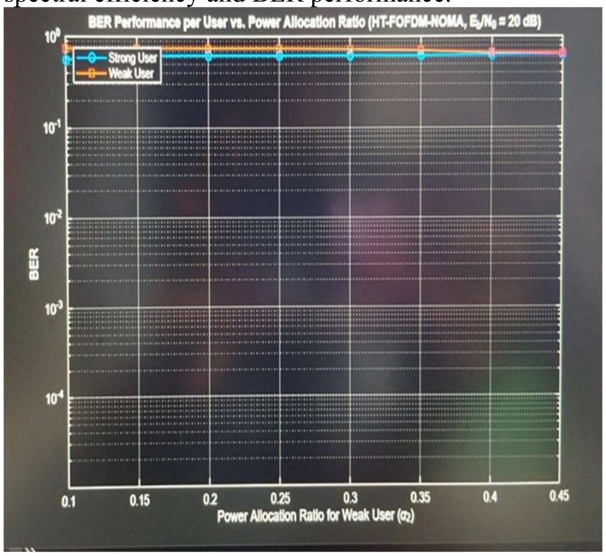

Figure 7 compares the BER performance of the proposed PAM-based HT-FOFDM system with the conventional high-order QAM-based SC-FDMA scheme under different bandwidth compression conditions.

The results demonstrate that larger compression factors produce lower inter-carrier interference and consequently improve BER performance. Conversely, smaller compression factors provide higher spectral efficiency by allowing additional subcarriers to occupy the available bandwidth but introduce increased interference, leading to a slight degradation in BER.

The simulation indicates that an optimal compression factor provides an effective compromise between communication reliability and spectral efficiency, making the proposed system suitable for bandwidth-constrained NB-IoT applications.

Conclusion

The rapid expansion of Internet of Things (IoT) applications has created an increasing demand for communication systems that simultaneously provide high spectral efficiency, low energy consumption, reliable communication, and support for massive device connectivity within limited bandwidth. Although Single Carrier Frequency Division Multiple Access (SC-FDMA) has been widely adopted for NB-IoT uplink communication because of its low Peak-to-Average Power Ratio (PAPR), its limited spectral efficiency and scalability restrict its suitability for future large-scale IoT deployments. This work addressed these limitations by proposing an energy-and spectrally efficient signalling technique based on Hilbert Transform-assisted Fast Orthogonal Frequency Division Multiplexing (HT-FOFDM) combined with Pulse Amplitude Modulation (PAM) for Narrowband IoT communication systems.

The proposed HT-FOFDM framework improves bandwidth utilization by compressing the spacing between adjacent subcarriers while employing Hilbert Transform-generated orthogonal signal pairs to suppress the inter-carrier interference introduced by bandwidth compression. Furthermore, the adoption of Pulse Amplitude Modulation (PAM) simplifies both transmitter and receiver architectures by utilizing real-valued signalling, thereby reducing computational complexity and power consumption. These characteristics make the proposed signalling technique highly suitable for battery-powered IoT devices operating under stringent energy constraints.

The performance of the proposed system was evaluated through comprehensive MATLAB simulations under Additive White Gaussian Noise (AWGN) channel conditions and compared with the conventional SC-FDMA scheme. The simulation results demonstrated that the proposed HT-FOFDM system achieves higher spectral efficiency, improved Bit Error Rate (BER) performance, and lower transmit power requirements while operating within the fixed 180 kHz NB-IoT bandwidth. The improved spectral containment and efficient bandwidth utilization achieved through Hilbert Transform-assisted FOFDM enable greater transmission capacity without requiring additional spectrum resources.

Overall, the outcomes of this research demonstrate that the proposed HT-FOFDM signalling technique successfully addresses the conflicting requirements of energy efficiency and spectral efficiency in Narrowband IoT systems. The combination of FOFDM, Hilbert Transform processing, and PAM modulation provides an effective communication framework capable of supporting future IoT applications that require reliable, low-power, and bandwidth-efficient wireless connectivity. Therefore, the proposed HT-FOFDM system represents a promising physical-layer signalling solution for next-generation NB-IoT and future wireless communication networks.

Future Scope

Although the proposed HT-FOFDM signalling technique demonstrates significant improvements over conventional SC-FDMA under AWGN channel conditions, several research opportunities remain for further enhancing its performance and practical applicability.

Future work may focus on extending the proposed system to multi-user communication environments by integrating advanced multiple-access techniques that improve network capacity while maintaining energy efficiency. Efficient resource allocation and scheduling algorithms can also be investigated to further optimize bandwidth utilization in dense IoT deployments.

The current research evaluates system performance using an AWGN channel. Future investigations should consider more realistic wireless propagation environments, including Rayleigh fading, Rician fading, and frequency-selective fading channels. Evaluating the proposed HT-FOFDM system under these channel conditions would provide a more comprehensive assessment of its performance in practical wireless communication scenarios.

Another important research direction involves the development of adaptive channel estimation and equalization algorithms specifically designed for HT-FOFDM systems. Accurate channel estimation techniques can improve communication reliability while maintaining low computational complexity suitable for low-cost IoT devices.

Energy efficiency may be further enhanced by incorporating adaptive power allocation, dynamic modulation selection, and energy-aware resource management algorithms. Such optimization techniques can extend battery lifetime while satisfying Quality of Service (QoS) requirements for different IoT applications.

Future studies can also investigate the integration of Machine Learning (ML) and Artificial Intelligence (AI) techniques for intelligent signal detection, adaptive interference mitigation, and automatic parameter optimization. These intelligent algorithms have the potential to improve communication reliability under dynamic network conditions while reducing computational overhead.

To validate the practical feasibility of the proposed signalling technique, future research should include hardware implementation using Software-Defined Radio (SDR) or Field-Programmable Gate Array (FPGA) platforms. Experimental validation would provide valuable insights into real-time latency, computational complexity, synchronization performance, and power consumption.

Finally, the proposed HT-FOFDM framework can be extended to support emerging 5G Advanced and 6G IoT communication architectures. Its combination of high spectral efficiency, low implementation complexity, and reduced energy consumption makes it a promising candidate for future applications such as massive machine-type communications (mMTC), smart cities, industrial Internet of Things (IIoT), precision agriculture, intelligent transportation systems, and ultra-reliable low-latency communications (URLLC).

In conclusion, the proposed HT-FOFDM signalling technique establishes a strong foundation for future research in energy-efficient and spectrally efficient wireless communication systems. Continued advancements in waveform design, adaptive signal processing, intelligent communication algorithms, and practical hardware implementation are expected to further enhance its capability for supporting next-generation IoT and future wireless networks.

References

[1] 3GPP TS 36.300, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description, Release 13, 2016.

[2] 3GPP TS 36.211, E-UTRA; Physical Channels and Modulation, Release 13, 2016.

[3] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, “An overview of massive MIMO: Benefits and challenges,” IEEE Journal of Selected Topics in Signal Processing, vol. 8, no. 5, pp. 742–758, Oct. 2014.

[4] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, “Non-orthogonal multiple access (NOMA) for cellular future radio access,” in Proc. IEEE VTC Spring, 2013, pp. 1–5.

[5] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, “On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users,” IEEE Signal Processing Letters, vol. 21, no. 12, pp. 1501–1505, Dec. 2014.

[6] A. Benjebbour, Y. Saito, A. Li, A. Harada, and T. Nakamura, “Concept and practical considerations of non-orthogonal multiple access (NOMA) for future radio access,” in Proc. IEEE ISPACS, 2013, pp. 770–774.

[7] L. Hanzo, M. Münster, B. J. Choi, and T. Keller, OFDM and MC-CDMA for Broadband Multi-User Communications, Wiley, 2003.

[8] Y. Medjahdi, M. Terré, D. Le Ruyet, D. Roviras, and A. Dziri, “Performance analysis in the downlink of a multi-carrier system based on the fast-orthogonal frequency division multiplexing,” IEEE Transactions on Communications, vol. 57, no. 7, pp. 2063–2075, July 2009.

[9] Y. Medjahdi, D. Le Ruyet, and D. Roviras, “Spectral efficiency improvement of FOFDM systems using Hilbert transform,” IEEE Communications Letters, vol. 14, no. 9, pp. 838–840, Sept. 2010.

[10] D. Roviras, Y. Medjahdi, and D. Le Ruyet, “Hilbert transform based waveforms for spectrally efficient communications,” IEEE Transactions on

Communications, vol. 60, no. 8, pp. 2265–2274, Aug. 2012.
[11] Y. Medjahdi, D. Roviras, and D. Le Ruyet, "Fast-OFDM with Hilbert transform: A bandwidth-efficient multicarrier modulation," EURASIP Journal on Advances in Signal Processing, vol. 2011, Article ID 516202.
[12] A. Goldsmith, Wireless Communications, Cambridge University Press, 2005.
[13] J. G. Proakis and M. Salehi, Digital Communications, 5th ed., McGraw-Hill, 2008.
[14] M. Chiani, "Diversity in communications systems," IEEE Transactions on Information Theory, vol. 44, no. 4, pp. 1502–1516, July 1998.
[15] H. Ochiai and H. Imai, "On the distribution of the peak-to-average power ratio in OFDM signals," IEEE Transactions on Communications, vol. 49, no. 2, pp. 282–289, Feb. 2001.
[16] S. Verdu, Multiuser Detection, Cambridge University Press, 1998.
[17] M. Shirvanimoghaddam, M. Dohler, and S. J. Johnson, "Massive non-orthogonal multiple access for cellular IoT," IEEE Communications Magazine, vol. 55, no. 9, pp. 196–202, Sept. 2017.
[18] Z. Ding, F. Adachi, and H. V. Poor, "The application of MIMO to non-orthogonal multiple access," IEEE Transactions on Wireless Communications, vol. 15, no. 1, pp. 537–552, Jan. 2016.