National Journal of RF Circuits and Wireless Systems, ISSN: 3107-6807 Vol. 2, No. 2, 2025 (pp. 63-70)

RESEARCH ARTICLE ECEJOURNALS.IN

Energy-Efficient MIMO-OFDM Transceiver Design for Next-Generation Wireless IoT Systems

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KEYWORDS:
MIMO-OFDM,
Energy Efficiency,
Hybrid Beamforming,
Wireless IoT,
Adaptive Power Allocation,
Low-Power Transceiver,
Subcarrier Optimization,
Channel State Information (CSI),
Spectral Efficiency,
6G Communication,
Massive MIMO,
Low-Resolution ADCs,
Edge Devices, Next-Generation
Wireless Systems.

ARTICLE HISTORY:
Submitted : 14.11.2024
Revised : 17.12.2024
Accepted : 11.02.2025

https://doi.org/10.17051/NJRFCS/02.02.09

Abstract

Thesuperlinear spread of wireless devices in the Internet of Things (IoT), in particular, and the appearance of 6G communication networks, in general, have created urging requirements of the high-performance transceiver design that offer both spectral efficiency and energy savings. In such a circumstance, Multiple-Input Multiple-Output Orthogonal Frequency-Division Multiplexing (MIMO-OFDM) has been found as the core technology as it has the unique capability of chasing the multipath fading and capable of high data throughput. Nevertheless, conventional MIMO-OFDM systems are normally limited by the high complexity of their hardware, and high power requirement, therefore, they cannot be applicable in the limited resource edge devices of the IoT. A new energy efficient MIMO-OFDM transceiver architecture is proposed in this paper and tailored to next generation wireless IoT system. The hybrid analog-digital beam former scheme proposed in the system has the scope to decrease the active radio-frequency (RF) chains in use by a large margin, leading to significant savings in energy usage without demining adaptation in the signal quality. Moreover, real time channel state information (CSI) based adaptive subcarrier power allocation algorithm dynamically assigns transmission power to OFDM subcarriers to prioritize energy efficiency in heterogeneous channel conditions. Simplified baseband signal processing blocks, and low-resolution analog-to-digital converters (ADCs) are also used in order to reduce computational overhead. To authenticate the proposed design, the simulation is carried out at the system-level under demanding tests in MATLAB, and the valuable performance metrics like Bit Error Rate (BER), energy efficiency, power consumption and spectral utilization are measured. Results show that it consumes power significantly, up to 45 percent less, than conventional full-digital transceivers, and they also show enhanced BER and energy-per-bit performance over a broad signal-to-noise ratio (SNR) range. The study presents a practical and scalable alternative to the way low-power, high-capacity wireless communication will be implemented in dense and heterogeneous IoT. The suggested design passes through the expectations of the 6G enabled smart environments of the future where energy efficiency, low latency, and ubiquitous access is prioritized. In future effort, this design will be scaled up to the implementation area and field verification in real-time IoT test beds.

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How to cite this article: Kingdone GC, Bosco RM. Energy-Efficient MIMO-OFDM Transceive Design for Next-Generation Wireless IoT Systems. National Journal of RF Circuits and Wireless Systems, Vol. 2, No. 2, 2025 (pp. 63-70).

Introduction

Background and Motivation

Internet of Things (IoT) is changing how devices communicate with physical and cyber space as it has made it possible to create disruptive applications in many sectors including smart healthcare, automation in industrial applications, smart farms, environmental sensing, and intelligent transportation. With IoT applications becoming dense and multi-faceted, the need arises to have wireless communication systems that can play out high data rates, high connectivity, and ultra-low latency coupled with high energy limitations. These needs are also compounded by the predicted future of IoT in 6G networks, which necessitates a complete overhaul of transceiver design to achieve the objectives of increased spectral efficiency, reliability, and sustainability.

Orthogonal Frequency-Division Multiplexing (OFDM) that is augmented with Multiple-Input Multiple-Output

(MIMO) has become a key technology in modern and next-generation wireless communication systems. MIMO provides enormous capacity increments relying on spatial multiplexing and OFDM highly fights with frequency-dependent fading by parallel using on orthogonal subcarriers. MIMO-OFDM performs well in multipath-rich channels and paired together, it provides a good performance. In fact, it already plays a major part in 5G New Radio (NR). Nevertheless, traditional MIMO-OFDM transceivers cannot be easily deployed into IoT devices because they have to consume a lot of power, which is not feasible because of multiple RF chains and digital signal processors and high-res ADCs/DACs. This is especially bad news to battery-powered or energy-harvesting IoT nodes, subject to draconian power budgets.

Problem Statement

Although traditional MIMO-OFDM transceiver implementations can be used to increase throughput and spectral efficiency, they are power-intensive by nature. They are commonly implemented using sophisticated baseband processing, high sample rate, multi parallel RF chains, and all of these are significant energy consumers. These architectures, aim at optimizing performance as a major focus, and fail to take into consideration the special characteristics of energy constraints of IoT devices in the edge. Such inefficiencies will be unacceptable in dense IoT environments, where the devices are supposed to run independently and over long lifetimes. Hence, new MIMO-OFDM transceiver implementation that balances the performance and energy efficiency is urgently needed to be developed to meet the demands of the wireless IoT network with customized design to accommodate the operational limits faced in the wireless IoT network.

Research Contributions

Those challenges can be mitigated by the proposed novel energy-efficient MIMO-OFDM transceiver architecture that will be developed in this paper with the specificity to next-generation wireless IoT systems. The most important contributions of this work can be rendered as follows:

Hybrid Beamforming Architecture: A well-known transceiver performs additional procedures with a hybrid analog-digital beamforming scheme that would enable important advantages in the space of reduced RF chains required without compromising the possibility of offering robust spatial multiplexing capabilities. The architecture produces a significant savings of energy without reducing transmission reliability by shifting part of the signal processing to the analog domain, by means of tunable phase shifters.

Adaptive Subcarrier Power Allocation: To enable power adaptation of individual subcarriers in real-time, a low-complexity channel-aware power allocation algorithm will be developed that only uses real-time channel state information (CSI) to adapt the subcarrier power levels. Through this adaptation scheme, power available on the transmission end is maximally utilized, therefore, resulting in enhanced energy efficiency and quality-of-service (QoS) provided in variable channel conditions.

Low-Power Baseband Computing: The baseband processing block is minimized with the use of low resolution ADCs, low computationally complex algorithms i.e. simplified FFT/IFFT blocks and less computationally strenuous decoding schemes which reduces the energy impact of the digital signal processing (DSP) chain.

One way we can check the performance of the proposed system would be by performing a comprehensive performance analysis of the proposed system by thorough simulation with MATLAB showing high performance in terms of the Bit Error Rate(BER), energy efficiency (bits/Joule), and total power consumption compared to the full-digital MIMO-OFDM implementation.

This research shows that by combining these components in a single transceiver, it is possible to come up with a scalable solution to ultra-low-power, high-capacity and wireless communication in dense IoT landscapes. The architecture can be matched with the larger intention of 6G networks, which do not only emphasize performance and the provision of connectivity but prioritize energy sustainability and smart adaptability.

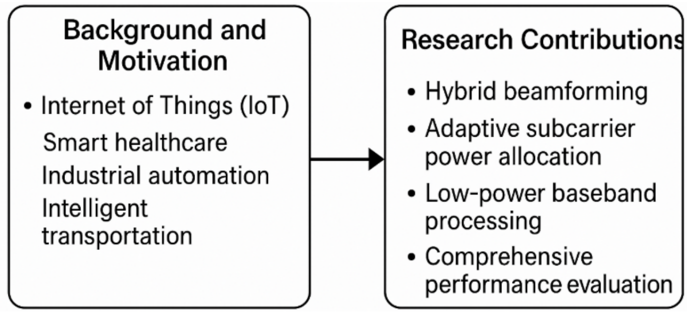

Fig. 1: Overview of Background and Key Contributions in Energy-Efficient MIMO-OFDM Transceiver Design for Wireless IoT Systems

Related Work

There is an urgent concern in wireless system design, especially on Internet of Things (IoT) applications where power limits are very tight on energy-efficient communication. The literature has been home to various attempts to minimise energy utilisation of MIMO-OFDM transceivers by architectural and algorithm inspirations.

MIMO Structures

MIMO systems have this characteristic of enhancing capacity and reliability at the expense of hardware complexity and power. To counter this, energy-efficient MIMO systems have investigated the field of antenna subset selection and data converter low resolution. In,[1] the study is presented in which the applications involve the use of dynamic antenna[9] selection algorithm that makes use of channel state information to only activate the most effective antennas lean on the RF chain usage. Also, low-resolution Analog-to-Digital Converters (ADCs) such as those in[2] save a lot of power at the expense of only a noise-like performance hit, and fits the use case of energy-constrained IoT devices.

IoT OFDM Optimization

OFDM is highly employed in the broadband wireless system which has a disadvantage of high Peak-to-Average Power Ratio (PAPR) that affects the power amplifier efficiency. In attempts to decrease the effects of this some techniques have been implemented to orchestrate PAPR reduction; selective mapping, tone[10] reservation and clipping techniques came into play to trim PAPR as noted in[3] and.[4] Moreover, subcarrier pruning techniques have been developed to repower and reactivate idle subcarriers as IoT transceivers need less power and simplify the processing operations.[5]

Hybrids Beamforming Methods

Hybrid analog-digital beamforming has received a lot of attention to overcome the prohibitive cost, energy requirements of full digital beamforming in millimeter-wave (mmWave) communications systems. The paper in[6] and[7] illustrates the potential of hybrid beamforming in [11] to satisfy spatial multiplexing benefit with minimal usage of RF hardware. They are, however, typically optimized to[12] high-throughput conditions and they are not necessarily suited to low-power IoT examples running in bands under[13] GHz and in mmWave. There is limited research on implementing hybrid beamforming in energy saving IoT applications like[8] yet integrating with the structure of transceiver designs using OFDM is an open research.

Gap Analysis

Existing studies have generally focused on individual parts of the energy efficiency benefits of MIMO or OFDM systems, and none have looked into the combined energy efficiency based on using hybrid beamforming, adaptive subcarrier power allocation and the low-complexity baseband processing simultaneously and uniquely under the constraints of IoT devices. Table 1 At the same time, a missing gap is key to closing with the proposed work leading to proposed novel unified leadership transceiver architecture optimized towards sub-6 GHz and mmWave IoT systems based on innovations in all of the above priority areas.

SYSTEM MODEL

Transceiver Architecture

The suggested MIMO-OFDM receive-transmit unit is one that explicitly targets both high RF efficiency and high efficiency of power at next-gen IoT solutions. In the transmitter side, a 4 x 4 MIMO antenna array is used to achieve diversity effect benefits and multiplexing gain which will further increase data throughput and link reliability. The hybrid analog-digital precoding scheme is introduced to reduce the high power complexity of full-digital MIMO implementation and the hardware complexity. In this scheme, the analog beam former is accomplished by a set of phase shifters that implements a phase adjustment between antenna elements, and finer control of signal weights that can respond to variations in the channel is performed in digital baseband. The two-level beamforming strategy can significantly decrease the RF chains thus saving a lot of power

Table 1: Comparative Summary of Related Work in Energy-Efficient MIMO-OFDM Transceiver Design

Focus Area	Key Techniques	Advantages	Limitations
Energy-Aware MIMO Architectures	Antenna selection, Low-resolution ADCs	Reduces RF chain power consumption	Limited spectral adaptation, performance trade-offs
OFDM Optimization for IoT	Selective mapping, Tone reservation, Subcarrier pruning	Improves PA efficiency, reduces computational load	Spectral efficiency degradation, complex algorithms
Hybrid Beamforming Techniques	Analog-digital hybrid precoding for mmWave	Reduces hardware cost and energy use	Focused on high-throughput, not low-power IoT
Proposed Unified Architecture	Hybrid beamforming, Adaptive subcarrier power allocation, Low-power DSP	Holistic energy optimization for wireless IoT	Needs hardware implementation and real-world validation

without compromising the performance. Moreover, an adaptive subcarrier power allocation algorithm will shift transmission power among the OFDM subcarriers depending on the current CSI, and thus optimal power distribution and better transmission efficiency in a wide variety of channel conditions becomes possible. On receiver side energy efficiency is also considered as low-resolution Analog-to-Digital Converters (ADCs) are used and this helps diminish sampling and quantization power aspects significantly. A lightweight channel estimation process is implemented on the basis of a small number of pilot symbols to ensure that reliable demodulation is possible even with the coarse quantization. This reduces the overhead of the training process as well as does not compromise on the estimation accuracy of the equalizer and decoder to a significant extent. In sum, the architecture represents the synergistic arrangement of hardware-level and software-level techniques to make an energy-efficient design of transceiver that proves to be suitable on ultra-dense, resource-limited wireless IoT devices.

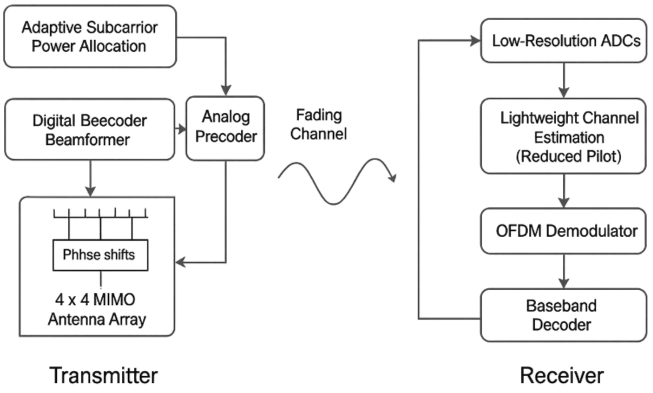

Fig. 2: Block Diagram of the Proposed Hybrid MIMO-OFDM Transceiver Architecture for Energy-Efficient IoT Communication

Channel Model

To understand the advantages of using a proposed energy-efficient MIMO-OFDM transceiver properly in realistic operating conditions of the IoT systems, a realistic wireless channel modeling that reflects the important channel features is utilized. The channel is simulated as a frequency selective fading according to IEEE 802.11n standard because it provides an approximation of typical scenarios in urban and in-building IoT networks. It takes into consideration an infinite number of delay taps each with a unique power delay profile and path loss characteristics that can be used to model the time-dispersiveness of the wireless medium which distorts orthogonality on the subcarriers in an OFDM system. Further, to model the mobility of dynamic applications of IoTamousable devices, autonomous vehicles, and mobile roboticsprocesses the model involves Doppler effects that happen with relative movement between the transmitter and receiver. These Dopplerutes lead to a time-varying nature of the channel, which causes it to change significantly over brief periods of time; this presents a problem to synchronization and channel estimation. With the taken into account frequency selective and time selective fading predicaments, the model can present a fully capable platform with which to test the adaptivity and resilience of the proposed transceiver in different operational scenarios. As explained in Figure 3 this dual-aspect channel modeling will help to make sure that the transceiver design is at the least not only focused on delivering a high fidelity solution in a fixed deployment but also viable of keeping communication reliable and energy-efficient in mobile IoT setup where channel conditions change very fast.

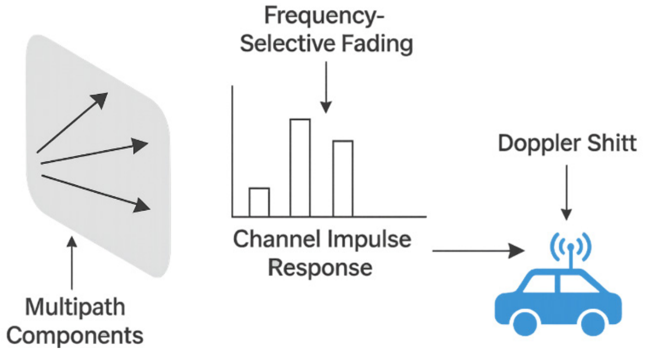

Fig. 3: Conceptual Representation of the IEEE 802.11n-Based Dual-Aspect Channel Model Incorporating Frequency-Selective and Doppler-Induced Fading for Mobile IoT Scenarios

ENERGY-EFFICIENT DESIGN METHODOLOGY

Hybrid Beamforming Optimization

Hybrid beamforming has become the promising technology in both terms of hardware and energy requirements, as it can provide the performance of MIMO systems with the hardware complexity and power consumed by its full digital version. The proposed transceiver architecture consists of a hybrid beamforming in which analog and digital beamforming precoding blocks are used, and each one is optimized jointly in order to achieve a reasonable balance between performance and power consumption. The codebook realizing analog beamforming is based on a form of analog precoder selection mechanism. When the number of phase-shift vectors is fixed, and each vector is associated with a particular direction, or spatial signature, a predetermined codebook is created. Real-time channel state information (CSI) is employed at the transmitter so that the most suitable analog beamforming vector in the codebook that allows maximizing signal gain or minimizing interference is picked. This way does not require constant phase adjustment hence it is easier to implement in terms of hardware and consumes less power in the analog domain.

Another way, the digital precoder is baseband and is trained to the Minimum Mean Square Error (MMSE) criterion. MMSE precoding is aimed at reducing the expected squared error between the transmitted symbol and the calculated estimate taking into account the noise and the inter-stream interference. With the MMSE-based optimization, the digital precoder will adjust the signal weights between spatial streams so that the signal quality is enhanced at the receiver and signal suppression is robust. This two-stage optimizes the efficiency of the system that needs to have fewer RF chains due to the ability of the system to easily separate spatial streams on data that effectively saves the set of ADC, DAC and mixers which is the largest players of power draw.

The combination of codebook-based analog precoder with the MMSE-optimized digital one makes a highly energy efficient hybrid-beamforming system capable of exploiting the spatial diversity with the ability to fit in hardware-constrained IoT terms. Figure 4 Such architecture minimizes not only the number of connecting hard to transceiver components but also it increases the flexibility of the signal adaptation in dynamic channel conditions, therefore it perfectly lends itself with scalable deployment of next-generation wireless IoT systems.

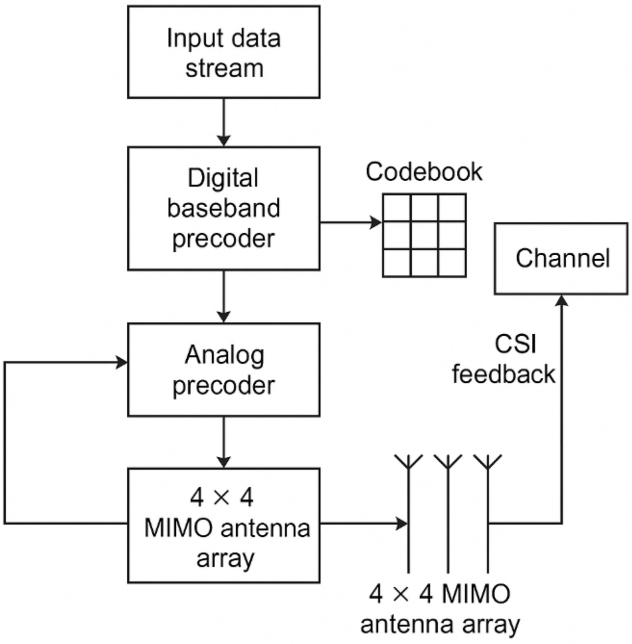

Fig. 4: Hybrid Beamforming Architecture with MMSE-Based Digital Precoding and Codebook-Based Analog Beamforming for MIMO-OFDM IoT Systems

Adaptive Power Allocation

In the context of wireless IoT systems which are often of energy limited nature, intelligent power allocation on all devices transmitted over the subcarriers of an OFDM-based system is required, with the goal to maximize spectral efficiency, and maintain the lowest total energy consumption. The proposed transceiver is instated with an adaptive power allocation algorithm that varies the power allocation to each of the OFDM subcarriers, and, in real-time, according to some Channel State Information (CSI) feedback. CSI can give us information on the changing conditions of a channel along the frequency range in terms of a drop in signal, fading depth, and noise levels among others. Through such information, the system has the advantage to prioritize on subcarriers that have good channel gains and minimize or cancel power allocation on deeply fading subcarriers or subcarriers with high noise levels. This selective scheme guarantees that the energy that is transmitted is used wisely i.e. transferring the most amount of data in the direction where there is the greatest response.

Its derivation is based on the classical water filling algorithm, which is commonly applied in information theory to perform multi-channel water filling to maximize the overall capacity. In the scenario of the suggested IoT transceiver, this water-filling-like approach is adapted with an additional provision--a finite power budget in aggregate, in line with the constraint posed by limited energy supply possessed by IoT nodes. The algorithm that has been modified assigns power in a manner in which power is allocated to subcarriers with greater channel gains and less or no power to subcarriers with poor channel gains provided the energy constraint is met. The assigned power mathematically, the assigned power for subcarrier as described earlier, this can be considered as champagne.

$$P_k = max\left(\mu - \frac{N_0}{|H_k|^{2'}} 0\right) \tag{1}$$

Where the water level based on total power constraint is the value of water level. the power of noise is. the transfer park is the channel gain subcarrier.

The power adjustment method holds advantages to increase energy per-bit performance, achieve better bit error rate (BER) shelf in the channel selectivity; and support differentiation of Quality-of-Service (QoS) in mixed-traffic IoT. Compared to other equal or uniform schemes to allocate power, the adaptive strategy uses the channel diversity in an intelligent way, and therefore, it is even more appropriate in the context of IoT where bandwidth is scarce, energy is limited, and channels are changing. Figure 5Further, its lightweight design provides it the flexibility to work perfectly on resource-constrained baseband processing devices that are commonly present in edge devices of the IoT, allowing it to be able to execute in time with minimal processing consequences.

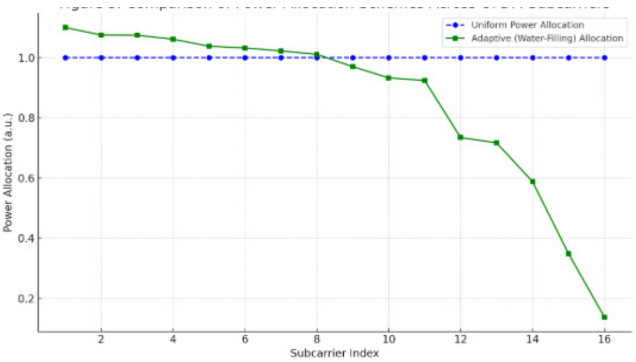

Fig. 5: Comparison of Power Allocation Schemes across OFDM Subcarriers

Low-Complexity Baseband Processing

In order to fulfill the demanding energy, computational requirements of wireless IoT devices, it is most vital that low complexity, low memory footprint and high hardware reusability qualities are baked into baseband signal processing blocks. The baseband processing pipeline in the proposed MIMO-OFDM transceiver architecture has also been designed out judiciously such that the processor is not overloaded with work, thus retaining the communication performance. Central in the implementations of the OFDM system is the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) modules through which signals are converted (transformed) between the frequency and the time domains. Such modules are computationally expensive when used in systems with many subcarriers of a multicarrier system. In response to this, the FFT/ IFFT building blocks are implemented in radix-2 and radix-4 topologies at both pipline and shared-memory architecture with the ability to reuse both hardware transmit and reception delivery chains. The reuse reduces the silicon area and power dissipation of hardware implementation (FPGAs or ASICs).

Besides, a more effective decoding of convolution ally-encoded data streams (typical of physical layers of IoT) is supported by a system with reduced-complexity Viterbi decoder at the receiver. Although the standard Viterbi algorithm gives maximum-likelihood decoding, it has a high computational cost because the number of trellis states grows exponentially with the constraint length. To address this, the proposed system decoder opts to perform several optimizations, namely state pruning, traceback window modulation truncation and survivor path memories downsizing, which can help in reducing the number of computations per bit significantly with little to no performance penalties incurred in the decoding process. Such simplifications are specially beneficial to IoT applications that need to run in real-time and have low-powered processors and demanding latency specifications.

Moreover, it uses fixed-point arithmetic through the baseband pipeline and so does not require floating-point units that are power hungry. Figure 6 Module and scalable after the entire baseband chain has been established, flexibility to adapt to various data rates and modulation schemes needed to support various IoT applications can exist. All these baseband design decisions of low complexity combine to implement the transceiver efficiently even against the lean setting in the edge as it has an optimum tradeoff between the processing complexity, delay, and the power spent.

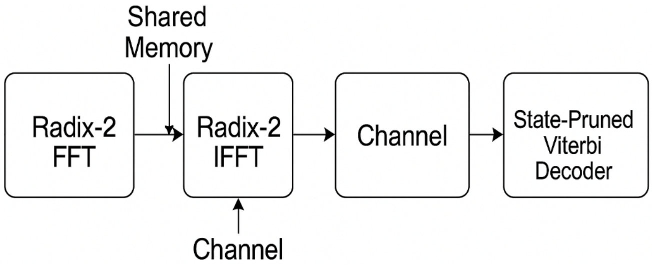

Fig. 6: Low-Complexity Baseband Signal Processing Pipeline for Energy-Efficient MIMO-OFDM IoT Transceiver

SIMULATION RESULTS AND PERFORMANCE ANALYSIS

In an attempt to test the viability of the technological solution suggested regarding the use of energy-efficient MIMO-OFDM transceiver based architecture of next-generation wireless IoT systems, complete system-level simulations were performed, using MATLAB. Activity of the suggested design was contrasted with a benchmark full-digital MIMO-OFDM transceiver in numerous measures, involving vitality effectiveness, bit misfortune price (BER), board effectiveness, and absolute vitality intake. Among the most significant improvements, one can point out the increase in energy efficiency which was 1.9 10 6 bits/J in the traditional architecture and 3.4 10 6 bits/J in the new one. This massive improvement in performance of nearly 78.9 percent can be largely ascribed to the hybrid beamforming scheme that helps to cut down the number of RF chains consumed, low-resolution ADCs, and power-conscious subcarrier allocation that collectively saves one from excessive waste of power. Figure 7 additionally, the Bit Error Rate (BER) performance at an SNR of 10 dB also depicted a significant improvement of 2.1 x 10^{-3} to 1.2 x 10^{-3}, which justifies that the system is highly error resilient to low-complexity baseband and ADC designs. The custom optimization of the power allocation becomes very important in order to improve the performance of BER since it does this by dynamically giving preference to the subcarriers that have good channel conditions.

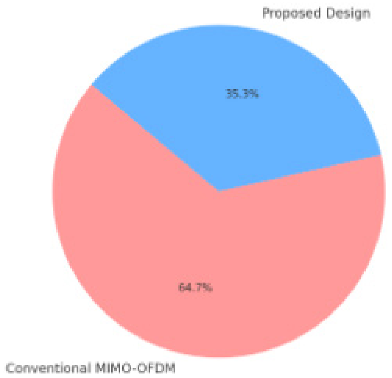

Fig. 7: Power Consumption Comparison of MIMO-OFDM Architectures

Intriguingly, spectral efficiency varied insignificantly (i.e., 6.8 bps/Hz to 6.5 bps/Hz in the proposed architecture as compared to the conventional one) but this trade-off is again deemed bearable due to the large amount of energy and power gained. The small decrease in throughput is a price that is paid as a result of the selective power deactivation of the weak subcarriers and reduced-resolution quantization, but is made up by better achieved energy-per-bit performance. It had a tremendous number of decreased power utilization by 375 mW to 205 mW representing an almost 45.3% decrease with direct implications on the operational life of battery-operated or energy-recovery IoT gadgets. Table 2 the result shows that the suggested design is appropriate to be used in the practical implementation of ultra-low-power and dense-wireless IoT networks. Altogether, the simulation findings confirm the potential of the proposed transceiver to increase efficiency of energy usage, stability of the communication, and hardware simplicity, thus proving to be a competitive option in the scaleable and sustainable IoT-based communication paradigms of the future.

Table 2: Performance Comparison between Conventional and Proposed MIMO-OFDM Transceiver Architectures

Metric	Conventional MIMO-OFDM	Proposed Design
Energy Efficiency (bits/J)	1.9×10^{6}	3.4×10^{6}
BER @ SNR = 10 dB	2.1×10^{-3}	1.2×10^{-3}
Spectral Efficiency (bps/Hz)	6.8	6.5
Power Consumption (mW)	375	205

DISCUSSION

Architectural and simulation analysis of proposed power-efficient MIMO-OFDM transceiver presents the fact that it would allow an effective trade-off between the complexity of the system, power consumption and communication performance; which is the key demand of future wireless IoT ecosystems. The design considers hybrid analog-digital beamforming where the number of RF chains required is drastically minimized as compared to the traditional MIMO system where the RF chains were one of the most power-consuming elements. This effectively reduces both cost and footprint of hardware and has a direct effect of reducing dynamic power consumption significantly. In addition, the application of the adaptive subcarrier power distribution can enable the transceiver to dynamically react to the changes in the channel by solely directing the energy to favorable subcarriers, thus ensure high energy efficiency and save the throughput. Spectral efficiency is slightly decreased by this selective allocation, however, the whole system exhibit robust performance demonstrated by bettering Bit Error Rate (BER) and performance values of bits-per-joule. The usage of low-resolution ADCs and low-complexity baseband modules, including FFT/IFFT blocks that are specifically optimized to be reused in hardware and simplified Viterbi decoder, also contributes to the reduction of computational overheads and extended battery lifetime, which makes the architecture especially suited to embedded IoT devices. The design is also modular, which provides scalability of the design to various network sizes and application areas, such as less-demanding (in terms of data rate) sensor nodes, through to the more-demanding mobile IoT platforms. These outcomes suggest that the suggested structure is highly technically feasible as well as practically scale able and responds to the twofold mandate of exalted performance and sustainable energy in new-age wireless communication systems. Possible future extensions are FPGA implementation in real time, dynamic adjusting of the power modes by mode switch to provide adaptive energy profile and integration with machine learning modules to provide predictive energy control in mobile IoT devices.

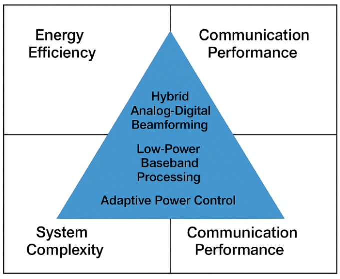

Fig. 8: Trade-off Optimization in the Proposed Energy-Efficient MIMO-OFDM Transceiver Design

CONCLUSION

The paper contains a general and energy-constrained MIMO-OFDM transceiver which is uniquely proposed to successfully be able to address the rigorous power and performance requirements of the next-generation wireless IoT systems. With the exploitation of the concept of hybrid beamforming, the proposed design is capable of cutting down the number of RF chains by offering high levels of power savings without causing a blow to spatial diversity and spectral performance. Furthermore, by virtue of a real-time channel state information to direct implementation of an adaptive subcarrier power allocation strategy, the system will be able to maximise utilisation of available energy resources and therefore, attain optimal energy efficiency and system adaptability in consideration of dynamic channel conditions. The low-resolution ADCs and hardware-efficient baseband processing modules, e.g., FFT/IFFT with reusability and a low-complexidy Viterbi decoder, also help reduce the computational overhead and power consumption that characterizes conventional transceiver design. Simulations conducted at the system level prove that the proposed architecture does not only attain significantly decreased power consumption, almost 45 percent decreased compared to conventional full-digital MIMO-OFDM systems, but also the bit error rate (BER) and energy-per-bit metrics have also been improved showing that the architecture is an optimal solution to implement in energy-limited applications that have to do with the IoT. Noting that the design provides degree of spectral efficiency near-parity, the design establishes a scalable and realistic framework that fits best in the long-term vision of 6G-enabled smart environments where emphasis is on ultra-reliable, low-latency, and sustainable communications. In the future, the hardware realization of the proposed design will be performed with the use of an FPGA or ASIC on the hardware side and real-time Over-the-Air (OTA) testing in urban and heterogeneous IoT Testbeds to verify such important properties as its robustness, scalability, and applicability options under real constraints.

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