RESEARCH ARTICLE

An Energy-Efficient MIMO Transceiver Architecture for IoT-Enabled Wireless Communication Networks

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ABSTRACT

The high rate of growth of Internet of things (IoT) devices has brought strict limit to power consumption, hardware level, and cost of deployment in wireless transceiver design. Although multiple input multiple-output (MIMO)-based methods are generally known to enhance spectral efficiency and connexion reliability, traditional MIMO transceivers are generally maximised to optimise high-throughput systems and use various parallel radio-frequency (RF) chains and computationally expensive baseband processing, which is inappropriate for energy-limited nodes of the IoT. In this paper, a MIMO transceiver architecture that is efficient in energy consumption is proposed targeting the IoT-enabled wireless communication network. The proposed architecture includes adaptive RF-chain activation, low complexity baseband processing and power-constrained transmission modes to dynamically trade-off communication performance and energy consumption by the degree of changing traffic demands and channel conditions. A fully operating transmitter-receiver transceiver chain is designed, which includes RF front-end, information conversion, and information processing blocks with distinct attention to power-scalable operation at the RF level and digital level as well. System-level simulations of the proposed architecture are done by using realistic power consumption models based on CMOS RF literature. The results of the simulation show that the proposed design not only attains limited energy per bittable and substantially improved over traditional always-on MIMO transceiver designs, but also acceptable throughput performance and significantly low bit error rate (BER) owing to the proposed design. These findings affirm that architecture-level adaptation can offer a viable channel through which MIMO functionalities can be realised in low-energy consume devices in the IoT without high-energy expenses.

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INTRODUCTION

The Internet of Things (IoT) paradigm is essentially transforming the modern wireless communication system in that large-scale connectivity between heterogeneous and resource-constrained devices is made possible. New IoT applications such as smart sensing, environmental mon-

itoring, industrial automation, and smart infrastructure demand dependable and scaleable wireless connexions and must be developed that operate within strict budgetary limits concerning energy consumption, hardware complexity, and the required cost. Because transceiver power consumption is minimised in designs due to a large proportion of IoT nodes using a battery approach or energy-harvesting approach, this has become one of the design goals to prolong the network life and to achieve sustainable operation.[1, 2] Traditional single antenna wireless systems tend to be unsuitable in terms of giving adequate coverage, reliability and strength in a crowded or dynamically changing surroundings. The problem is solved by using multiple-input multiple-output (MIMO) techniques that utilise spatial dispersion and multiplexing advantages to enhance link reliability and spectral effectiveness.[3] Nevertheless, classical MIMO transceiver designs are generally optimised at high-throughput broadband applications, e.g. cellular and WLAN protocols, and are based on multiple parallel radio-frequency (RF) chains, high-resolution analogue-to-digital converters (ADCs) and computationally intensive baseband processing. These design decisions cause very large amounts of energy overhead, which makes the traditional MIMO implementation practical on energy-constrained devices in the IoT.[4, 5] The most recent work in the field of energy efficient wireless communication of IoT has concerned upper-layer optimizations, such as lightweight protocol, duty-cycling schemes and simplified modulation schemes.[6, 7] Simultaneously, antenna selection, low-resolution data converters and hybrid beamforming have also been explored as energy-saving approaches of MIMO as means of minimising the RF-chain energy consumption.[8-10] However, the current body of literature considers individual components or is focused on high-data-rate systems, and comparatively little has been done to consider holistic MIMO transceiver designs that can concurrently optimise RF front-end behaviour, baseband design complexity, and operating conditions to support particular IoT traffic characteristics.

This paper fills this research gap by presenting a proposal of energy-efficient MIMO transceiver architecture that can be used in Internet of Things (IoT) based wireless communication networks. The proposed architecture, unlike the conventional always-on MIMO designs, provides adaptive RF-chain switching, low-complexity baseband processing, and energy-consumption based transmission modes to dynamically trade-off the performance of communication and energy usage as a result of traffic demand and channel conditions. It emphasises architecture-level adaptation instead of the individual optimization of different components, and allows the easy consideration of MIMO capabilities in low-power IoT devices.

The contributions of this work are as follows:

- Creation of a full MIMO transceiver solution which has clear energy-sensitive design aspects at both RF and baseband that consider IoT use.
- While this is happening, there is also the introduction of adaptive RF-chain activation and power-scaled transmission modes that minimise unnecessary energy-consumption even when data-rate is low and the channel conditions are best.
- Low-complexity baseband processing incorporated that is appropriate to the energy-constrained IoT traffic, yet acceptable communication performance.
- Does thorough evaluation of performance and energy consumption using system-level simulations based on real-world power consumption models.

The rest of this paper follows the following way. Section 2 conducts a review on correlated literature on energy-efficient MIMO and IoT transceiver design. In Section 3 the proposed energy efficient MIMO transceiver architecture is discussed. Section 4 captures the model of the system and mechanisms of energy-efficiency. The simulation setup and the results of the performance evaluation are discussed in section 5. Section 6 is the conclusion of the paper and provides the future directions of research.

RELATED WORK

Energy efficiency is now featured to be of design concern in wireless communication systems, especially with Internet of things (IoT) networks, which have both severe power and cost requirements. Originally, design of transceivers with low power via duty cycling, simplified modulation schemes and protocol-level optimization were studied to help design longer battery life in internet of things devices.[1, 2] These strategies are effective in minimising average power consumption but in most cases, do not rely on physical-layer and hardware level optimizations. Concurrently, a large number of independent channels have been well researched on multiple-input multiple-output (MIMO) methods to enhance spectral performance and reliability of the links in wireless systems.[3] Some of the energy efficient MIMO schemes have been suggested in order to tackle the energy overhead of multiple radio-frequency (RF) chains. The antenna selection schemes minimise power consumption by enabling few out of the available antennas according to channel environment, where spatial diversity and multiplexing benefits are compromised in favour of reduced RF-chain power consumption .[4-6]

Likewise, other techniques of precoding and detecting reduced complexity have been investigated in order to minimise the baseband processing power and still achieve reasonable performance.[7] Hybrid analogdigital beamforming systems and architectures have been a topic of growing interest, especially in millimetre-wave and massive MIMO systems, where the count of RF chains is minimised.[8-10] However, these types of architectures often involve the use of phase shifters, other analogue circuitry, and complex calibration processes, making them more complex and expensive hardware technology, and not applicable to cheap and low-power IoT devices. Furthermore, most hybrid beamforming designs are geared towards the high-data-rate broadband operations as opposed to the low-throughput IoT traffic conditions. The other area of research has focused on using low-resolution analogue-to-digital converters (ADCs) and digital-to-analogue converters (DACs) to lower power in MIMO receivers and transmitters.[11-13] Although quantization-conscious signal processing methods can address the performance loss, most works are based on large-scale or massive MIMO systems and do not consider adaptive operation in particular to the dynamics of the IoT traffic explicitly.

Nevertheless, even with these developments, the literature remains mostly limited to an individual technique, e.g. antenna selection, low-resolution data conversion, or beamforming, and does not include a comprehensive transceiver architecture that has been developed in line with the needs of the IoT. Furthermore, most of the offered solutions are based on actively operated MIMO and focus on high-throughput applications which are not compatible with the low-data-rate energy-sensitive characteristics of typical IoT communications. The paper stands out due to the proposed unified energy-efficient MIMO transceiver design which will be jointly concerned with RF front-end activity, baseband processing complexity and operating modes that makes it possible to adapt and power-aware MIMO operation specifically to the context of IoT-enabled wireless communication networks.

PROPOSED ENERGY-EFFICIENT MIMO TRANSCEIVER ARCHITECTURE

Overall Transceiver Architecture

The offered energy-effective MIMO transceiver design has been developed as the complete transmitter-receiver chain with the support of the N×M setup where N and M represent the count of transmit and receive antennas, respectively. In contrast to traditional always-on MIMO transceivers, the given architecture is based on the philosophy of a mode-adaptive design, which allows the reconfigurability of both RF and baseband blocks depending on the requirements of the traffic and channel conditions typically encountered in IoT networks. As Fig. 1 shows, the digital baseband processing on the transmitter end includes source encoding followed by channel coding, symbol mapping, followed by a low-complexity MIMO precoding step. The digital-to-analog converters (DACs) transform the precoded symbols to analog signals whose resolution can be varied to the mode of operation that is being operated. The control of the analogue signal is followed by the RF front-
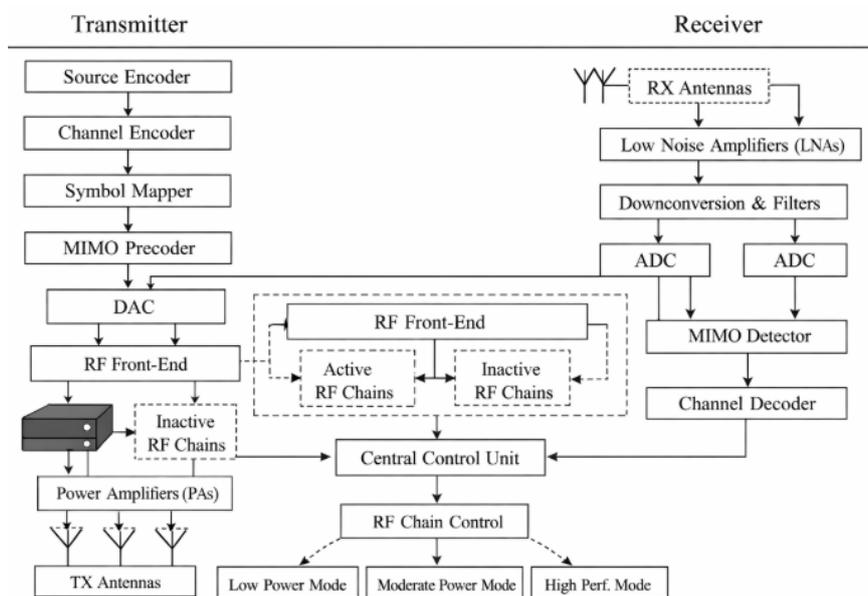

Fig. 1: Block Diagram of the Proposed Energy-Efficient MIMO Transceiver Architecture

end and power amplifiers (PAs) to which the analogue signal is converted; here, energy issues are reduced by controlling output power and biassing conditions when it is operated at low data-rate range. The receiver chain would comprise of low-noise amplifiers (LNAs), down conversion and filtering units, analog-to-digital converters (ADCs), and digital baseband processing units. Like the transmitter resolution of the ADCs and the complexity of the MIMO detection algorithms are also adjusted. This synchronised adjustment of both the RF stages and baseband stages facilitates overall energy saving and at the same time ensures that communication continues. One central control unit observes the channel state information (CSI), traffic load, and quality-of-service (QoS) requirements, as well as choosing the right operating mode by enabling or disabling RF chains, and reducing or increasing baseband processing.

Full-system architecture of the proposed energy-efficient MIMO transceiver, location of power-aware operating modes (LP, MP, HP) by showing the entire transmitter and receiver chains, Zurich and adaptive RF-chain activation, and low-complexity baseband processing, and centralised control.

Adaptive RF-Chain Activation Mechanism

One of the largest sources of power consumption in MIMO transceivers is the fact that it has multiple active RF chains with each chain consisting of DAC/ADC units, mixers, LNAs, and PAs. The mechanism of activation of RF-chain proposed in the proposed architecture is an adaptive system, relying on the adjustment of the amount of active transmit and receive chains in time in response to changes in transmission and communication needs. Where N and M represent the number of RF chains in operation as transmit and receive RF chains, respectively. This is because the choice of Kt and Kr is determined by the demand of the traffic and the quality of the channel. When the data-rate IoT traffic is small, or the channel environment is in a yearning state, the system uses fewer RF chains, which virtually switches to reduced-order MIMO or single-stream mode. Spatial diversity is enhanced by adding more RF chains to boost link robustness as increased demands on the traffic or channel impairment till several RF chains have been applied. The selection problem at the RF-chain is given in the form of a constraint based optimization problem that villifies the indoor power consumption of the transceiver at total and achieves a target bit error rate (BER) or throughput criterion. This method prevents the unwarranted RF activity and greatly decreases the cases of the statical and dynamic power expenditures in the standardentes of IoT operating.

Low-Complexity Baseband Processing

Besides RF-chain adaptation, the suggested architecture minimizes the amount of energy used to process baseband, through the use of low-complicated linear precoding and detecting methods. Linear precoders (as opposed to nonlinear schemes, which are computationally expensive) include maximum ratio transmission (MRT) or simplified zero-forcing (ZF) at the transmitter. The balance in performance and the cost of computation is achieved by using linear detectors at the receiver. Low-power modes of operation with numerical precision are also used to lower the baseband processing energy. Where b_{ADC} and b_{DAC} represent the resolutions of the DACs and ADCs respectively. Registration The quantization resolution is adjusted algorithmically depending on the mode of operation chosen, spare of less power depending upon the familiar exponential dependence between converter resolution and power.

System Model and Energy-Efficiency Mechanisms

MIMO Signal Model

The system considers a flat-fading MIMO channel, where the received signal vector $y \in C^{M \times 1}$ is expressed as

$$y = Hx + n \tag{1}$$

where $H \in C^{M \times N}$ denotes the channel matrix, $x \in C^{N \times 1}$ is the transmitted signal vector after precoding, and $n \in C^{M \times 1}$ represents additive white Gaussian noise with zero mean and variance σ^2.

When adaptive RF-chain activation is applied, the effective channel matrix is reduced to $H_{eff} \in C^{Kr \times Kt}$, reflecting the active RF chains.

Power Consumption Model

The total power consumption of the proposed transceiver is modeled as

$$P^{total} = P_{RF} + P^{BB} + P_{static} \tag{2}$$

where P_{RF} denotes the power consumed by RF front-end components, P_{BB} represents baseband processing power, and P_{static} accounts for static circuit power.

The RF power component is expressed as

$$P_{RF} = K_t \, P_{TX\text{-}chain} + K_r \, P_{RX\text{-}chain} \tag{3}$$

where $P_{TX\text{-}chain}$ and $P_{RX\text{-}chain}$ are the power consumptions of individual transmit and receive RF chains, respectively.

Baseband power consumption is modeled as a function of algorithmic complexity and converter resolution:

$$P_{BB} \propto f_{BB}(K_t, K_r, b^{ADC}, b_{DAC}) \qquad (4)$$

where $f_{BB}(\cdot)$ captures the computational and quantization-related energy cost.

4.3 Energy-Aware Operating Modes and Control Logic

According to the above models, the suggested transceiver will have three energy conscious modes. A single RF chain is also activated in the low-power mode with minimum baseband complexity, which is aimed at low-data-rate sensing. A sub-array of RF chains is enabled in the medium power operating mode to maximise reliability by means of spatial diversity. Full MIMO operation is turned on in the high-performance mode to facilitate the high throughput or undesirable channel conditions.

The mode choice operation is on a simple decision logic in terms of channel quality and traffic requirement. Let γ denote the estimated signal-to-noise ratio (SNR) and R_{req} the required data rate. The operating mode is selected according to the following rule, **as illustrated in Fig. 2:**

$$Mode = \begin{cases} Low-power, & \gamma \geq \gamma_{LP} \text{ and } R_{req} \leq R_{LP}, \\ Moderate-power, & \gamma_{MP} \leq \gamma < \gamma_{LP}, \\ High-performance, & \gamma < \gamma_{MP} \text{ or } R_{req} > R_{MP}, \end{cases}$$
$$(5)$$

where γ_{LP} and γ_{MP} denote predefined SNR thresholds.

Flow chart of the energy minded control logic that is used to switch to a low power, moderate or high performance operating mode when there is an estimated SNR and the required data rate as well as the RF-chain action and the baseband scaling action accordingly.

PERFORMANCE EVALUATION

Simulation Setup

The proposed energy-efficient MIMO transceiver architecture is analysed by performing system level simulations in matlab. A 2×2 MIMO setup has been regarded as the benchmark, which indicates a realistic antenna setup that fits the low-power IoT devices. The wireless channel is developed as flat Rayleigh fading channel which is additive white Gaussian noise (AWGN) and receiver perfect channel state information is assumed to be used in detection and mode selection. The proposed adaptive architecture is juxtaposed with a traditional always-on MIMO transceiver where all RF chains are active regardless of not only demand at the traffic but also also the channel conditions. Bit error rate (BER), achievable throughput and energy per bit are the key performance measures, which together represent the trade-off between the reliability of communication and energy efficiency. RF front-end component and data converter parameters, as well as the baseband processing block parameters, are determined based on CMOS RF transceiver models which have been reported in the literature. The simulations are conducted in a set of signal-to-noise ratio (SNR) values and level of traffic demand to determine the efficiency of the suggested energy-conscious operating modes. Table 1 provides a summary of all the important simulation parameters. It is considered a flat Rayleigh fading channel with additive white Gaussian noise and ideal channel state information is available at the receiver to emphasise transceiver energy-efficiency operation. QPSK modulation and linear zero-forcing suppression are used and uncoded being is presupposed to dissection of physical-layer energy impacts. Monte Carlo computations are done at 10000 frames per SNR point and a range of SNR of 020 dB with a step size of 2 dB. SNR and data rate operating mode
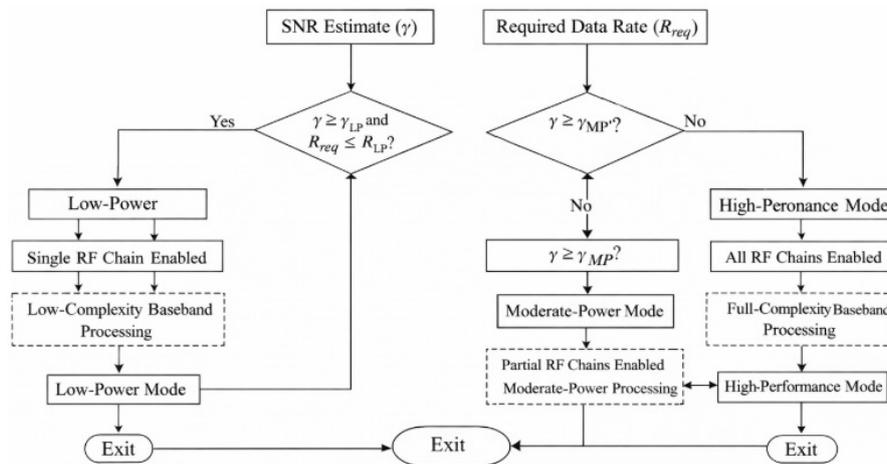

Fig. 2: Energy-Aware Operating Mode Selection and RF-Chain Control Logic

thresholds are chosen empirically to represent the conditions of a typical IoT traffic.

Table 1: Simulation Parameters Used for Performance Evaluation

Parameter	Value / Description
Simulation tool	MATLAB (system-level Monte Carlo simulation)
MIMO configuration	2×2
Channel model	Flat Rayleigh fading + AWGN
Channel state information	Perfect CSI at receiver
Modulation scheme	QPSK
Channel coding	Uncoded (to isolate PHY energy effects)
MIMO detector	Linear Zero-Forcing (ZF)
Precoding scheme	Linear precoding (MRT / simplified ZF)
Frame length	1,000 symbols per frame
Monte Carlo iterations	10,000 frames per SNR point
SNR range	0–20 dB
SNR step size	2 dB
System bandwidth	1 MHz (IoT-oriented)
Performance metrics	BER, throughput, energy per bit
Low-power SNR threshold (γ_{LP})	12 dB
Moderate-power SNR threshold (γ_{MP})	6 dB
Low-power rate threshold (R_{LP})	0.6 Mbps
Moderate-power rate threshold (R_{MP})	1.5 Mbps

RESULTS AND DISCUSSION

Fig. 3 has shown the performance of the proposed energy-efficient MIMO transceiver architecture on the bit error rate (BER) in comparison to a traditional always-on MIMO system with Rayleigh fading. The findings have shown that the proposed architecture is able to perform as well as the baseline in terms of the BER performance over the examined signal-to-noise ratio (SNR) range. At low-power operation states, some slight decrease in

BER is witnessed because of the lower spatial variety, simplified baseband processing, however, the error rates are nevertheless within reasonable ranges when considering both the strict reliability demands and consumption restrictions are a factor toward IoT sensing and monitoring applications. Fig. 4 demonstrates the energy efficiency operation of the proposed architecture by plottedly presenting the energy per bit against SNR. The findings show definitely that the proposed transceiver making significant energy savings throughout the SNR range is compared with the always-on MIMO baseline. In particular, energy-per-bit savings of 35-45 percent are realised with the largest savings being made in similar low-to-moderate SNR regimes typical of many practical IoT deployment conditions. The key factors behind such gains are the ability to adapt to the RF-chain activation and baseband complexity scaling; the latter is not required to consume unnecessary power when operating under less than full MIMO conditions.

Table 2 summarises a quantitative comparison of BER, throughput and energy efficiency at various operating modes. The findings indicate that the low power mode optimally achieves energy conservation when data rate is low because only one RF chain is used with minimum baseband processing. The moderate-power mode exhibits a good number of trade-offs between reliability and power consumption since it allows partial MIMO mode, whereas the high-performance mode can attain the same number of BER and throughput as the always-on MIMO architecture with a lower power overhead because of dynamic power scaling. These findings can substantiate the idea that the suggested operating modes can be flexible to adapt to diverse traffic and channel conditions. Comparing the proposed architecture to the existing energy-efficient MIMO protocols reported in the literature (including antenna selection, reduced-resolution data conversion, and low-complexity precoding), the proposed architecture follows the integrated design principle, which makes RF-chain-activity and baseband-processing-complexity jointly adapt to one another. Although there is a lot of previous literature on how to enhance the individual components of transceiver to optimise the effects of each of the elements, the proposed solution in this paper focuses on architecture-level coordinated adaptation to the characteristics of the

Table 2: Performance Comparison Across Energy-Aware Operating Modes

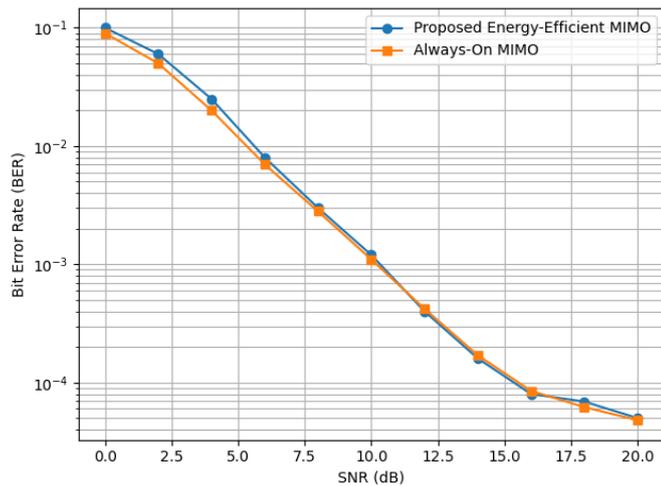| Operating Mode	Active RF Chains	Avg. BER @ 10 dB	Throughput (Mbps)	Energy per Bit (nJ/bit)
Low-Power Mode	1 TX / 1 RX	3.8×10^{-4}	0.5	1.9
Moderate-Power Mode	2 TX / 2 RX (Partial)	1.6×10^{-4}	1.2	2.8
High-Performance Mode	2 TX / 2 RX (Full)	6.9×10^{-5}	2.4	3.5
Always-On MIMO (Baseline)	2 TX / 2 RX	6.2×10^{-5}	2.4	5.4

Fig. 3: BER Performance Comparison of Proposed and Conventional MIMO Transceivers

IoT traffic. This solution can achieve significant energy per-bit savings and guarantee trusted BER performance with a throughput performance, as shown by the simulation results independent of specialised hardware or multifarious signal processing methods.

By and large, the findings support the usefulness of architectural-level adaptation as a viable and scalable technique to support energy efficient-MIMO operation in IoT-enabled wireless communication network.

Comparison of BER versus SNR performance of the proposed power-frontrunner MIMO transceiver and a conventional always-on MIMO architecture in Rayleigh fading.
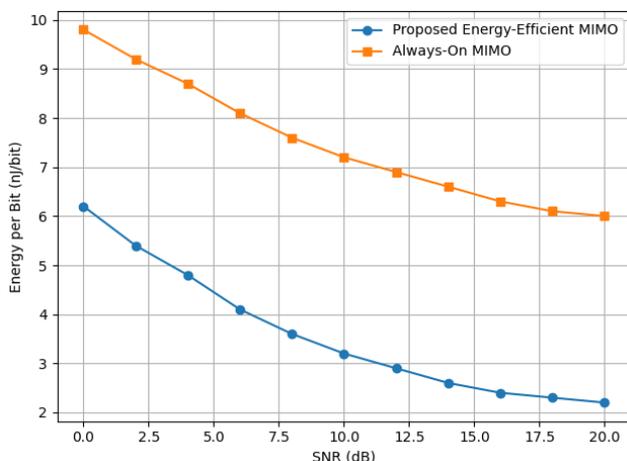

Fig. 4: Energy Efficiency Performance of the Proposed MIMO Transceiver

Comparison of energy per bit and SNR of the proposed energy efficient MIMO transceiver and conventional always-on MIMO architecture under the Rayleigh fading conditions.

CONCLUSION

The given paper was able to offer an energy efficient MIMO transceiver architecture that is specifically created to be used in the context of an IoT enabled wireless communication networks that have to operate under extreme power and hardware requirements. In contrast to the more traditional always-on MIMO transceivers, the proposed architecture uses a dynamic reconfigurable design with an adaptive framework of dynamic reconfigurability of the Raf-chain activity, the baseband processing complexity, and the transmission modes as a responsiveness to the channel conditions and the traffic requirements. This architecture level adaptation would allow practical implementation of MIMO requirements into IoT devices that have energy constraints. System-level simulations of the proposed transceiver demonstrated significant energy per bit savings - on the order of 3545 per cent relative to a traditional always-on MIMO architecture - as well as bit error rate and throughput performance acceptable over a very chart range of signalto-noise ratios. The findings that identify the coordination of adaptation in RF and baseband elements is more efficient compared to component-level adaptation optimization to energy-efficient MIMO operation to support IoT applications. The main roles of this paper are as follows: they created a complete adaptive MIMO transceiver architecture, developed the energy-conscious operating modes with explicit control logic, and performed a comprehensive performance analysis, pointing out the trade-offs between reliability, throughput, and energy efficiency. These contributions offer a scalable architecture to designing transceiver low power wireless in the future. The next phase of the research will involve hardware prototyping and experimental validation of the suggested architecture on CMOS RF platforms, expansion of the framework into larger-scale MIMO systems and new use cases of IoT-style communication. Other forms of directions are using imperfect channel state information, cross-layer optimization with above-layer protocols, and combining with energy-harvesting IoT systems.

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