Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 5, October 2025, pp. 4013~4024
ISSN: 2302-9285, DOI: 10.11591/eei.v14i5.10633

A review on radio-frequency transceiver architectures for low-power wireless sensor networks

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Article Info

Article history:

Received May 7, 2025
Revised Aug 29, 2025
Accepted Sep 11, 2025

Keywords:

Data-rate
Low-power
Radio-frequency
Transceiver
Wireless-sensor-network

ABSTRACT

Wireless sensor networks (WSNs) have garnered significant scientific attention because of their many uses, but their power usage is a fundamental barrier to their deployment. Energy constraints have a direct effect on important design elements including battery capacity, energy harvester effectiveness, and network longevity. To enable sustainable WSN operation, radio-frequency (RF)-based transceiver (TR) design has become a key area of study. A thorough examination of current RF-TR architectures is given in this paper, with a focus on low-power (LP) implementations designed for WSN applications. Amplifier-sequenced hybrid (ASH), superheterodyne (SHD), zero-intermediate frequency (Zero-IF), low-intermediate frequency (Low-IF), sliding-intermediate frequency (Sliding-IF), and super-regenerative (SRG) architectures are among the TR system designs that are categorized, with an emphasis on the performance trade-offs associated with each. Comparative evaluation shows that Zero-IF and SRG architectures are more energy efficient than other designs that were studied, which makes them viable options for ultra-low-power (ULP) WSN installations. Along with outlining important research issues in RF-TR design, such as hardware minimization, security, synchronization, and energy optimization, this review also suggests possible future paths to improve the sustainability and performance of WSN-based RF-TRs.

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1. INTRODUCTION

There has been a rise in interest in wireless sensor networks (WSNs) among scientists in recent years due to a number of theoretical and practical challenges. This state-of-the-art research on WSNs examined numerous new applications made feasible by larger-scale networks of sensor nodes that can collect, process, and transmit data from their environment to a remote location. Most WSN applications have bandwidth and latency tolerance limitations, ranging from commercial and military to environmental and medical surveillance [1]. Current advances in wireless networking, electronic devices, and micro-electro-mechanical systems (MEMS) innovation have made it possible to create multipurpose, inexpensive, and low-power (LP) node sensors that are compact and are able to interact wirelessly across relatively short distances. These small sensor nodes, which are made up of sensing, processing, and communication factors, make use of the concept of WSNs, which rely on the cooperation of many nodes [2]. A WSN is a collection of widely scattered sensor nodes that are linked together. A computer chip known as a sensor node, also known as a mote. The sensor node comprises a central processing unit (CPU), a storage or memory device, a transceiver (TR) module, one or more sensors, an analogue-to-digital converter (ADC), and the source of power, such as a battery. Reliability, precision, adaptability, cost, degree of complexity in advancement, and power usage are the fundamental characteristics of WSN. The most crucial WSN criterion is power usage since all nodes are powered by batteries [3].

There are presently two main developments in the wireless communication sector. A broad variety of sensor-like wireless nodes for purposes including portable medical devices, fitness trackers, and versatile internet of things (IoT) devices are growing more. On the one hand, there is an obvious move regarding the most severe performance data solutions over fifth-generation (5G) networks with Gbps variant data rates. Overall, there will be a significant growth in the need for such sensor nodes.

The high-level-based method's component-based, design-pattern-based, and modern-driven engineering (MDE)-based categories are described in [4], [5]. Nevertheless, the system-on-chip (SoC), system-on-programmable-chip (SoPC), multi-processor system-on-a-chip (MPSoC), field-programmable gate array (FPGA), application specific integrated circuit (ASIC), microcontroller (MC), digital signal processing (DSP), field-programmable analogue array (FPAA), and hybrid architectures are utilized to create the WSN architectures [6]. Most of the mentioned applications handle private information, which requires appropriate security measures to guarantee privacy and integrity. Applications relying on WSNs require robust security measures. Several conditions, including accessibility, authenticity, secrecy, and truthfulness, must be met to ensure the protection of WSNs [7].

Three categories exist for the medium access control (MAC)–based wakeup receiver (WUR) approaches: duty-cycled, non-cycled, and path reservation-based [8]–[10]. These MAC-WUR techniques reduce latency, increase energy efficiency, and prevent collisions in WSNs [11], [12]. The majority of WSNs and IoT-based applications use ultra-low-power (ULP) receivers (RXs), which are similar to nano-watt-WUR, long-range based low-noise-amplifier (LNA)-first RXs, selectivity-based Mixer-first RXs, and universal adoption-based compatibility RXs [13]. There are many LP-based architectures, like LP-cognitive-radio (CR) based approach [14], Bluetooth low energy (BLE) [15], and Zigbee [16] are available in the existing works for WSN and IoT applications. However, the high-performance-radio TRs like long term evolution (LTE), 5G [17], [18], and sixth generation (6G) [19]. However, the high-speed wireless applications are not considered in this article.

WSNs have become an essential technology for smart cities, automated manufacturing, medical, and environmental surveillance activities. However, power usage is the main constraint in WSN implementation, and it has a direct impact on network scalability, dependability, and lifetime. It is difficult to replace or recharge sensor nodes because they are usually battery-powered and frequently placed in inaccessible locations. Since the radio-frequency (RF) based TR is one of the most power-intensive parts of a sensor node, this limitation makes energy-efficient TR topologies imperative. Despite their strong performance, traditional architectures like superheterodyne (SHD) and amplifier-sequenced hybrid (ASH) are not appropriate for ULP WSN applications due to their high-power consumption. However, while other approaches like zero-intermediate frequency (Zero-IF) and super-regenerative (SRG) have the potential to lower power usage, they frequently have issues with sensitivity, selectivity, or interference robustness. A significant research gap is highlighted by the lack of a standardised trade-off analysis between various architectures under practical WSN restrictions.

The primary contributions of this work are presented with a thorough analysis and categorization of RF TR architectures specific to LP WSN applications. A comparison of architectures has been presented according to important performance metrics, such as picture interference ratio, noise figure (NF), power consumption, and sensitivity. Zero-IF and SRG architectures were identified as viable options for attaining ULP operation in WSNs, with an emphasis on the trade-offs between these and alternative architectures. A look ahead at the design opportunities and challenges for creating forthcoming LP RF TRs to improve the scalability and efficiency of WSNs. The article's organization is as follows: section 2 discusses the current TR designs based on system architecture classification. Section 3 outlines the results and discussion considering all, including the performance realization of current LP-TRs, followed by a discussion and research gaps. Finally, it concludes the entire work in section 4, followed by future works.

This section discusses the existing works of the LP TR architectures with merits and limitations from various application viewpoints. The work also highlights the performance metrics from the recent works. Table 1 illustrates the summary of the existing LP TRs below. Sayilir *et al.* [20] explain the wireless TR for LP-insect-based WSNs. The power amplifier (PA), LNA, voltage-controlled oscillator (VCO), and on-off-keying (OOK) modulator with switching activities are integrated to form the wireless TR. The system complexity is reduced drastically with the switching activity of the TX/RX using the same components. The TX and RX utilise the 4.5 mW and 9.5 mW of power using an OOK modulation approach on a 130 nm complementary metal oxide semiconductor (CMOS) process. El-Desouki *et al.* [21] explain the balunless-narrowband (BNB)-based RX frontend (FE) module for short-range wireless applications. The RX-FE comprises the double-balanced down conversion mixer and NB-LNA to achieve the LP and high level of integration in a single chip. The RX-FE offers better performance than other FE designs using single-ended RF inputs. The TX and RX utilize the 1 mW and 67.7 mW power using the OOK modulation method on the 180 nm CMOS process. Liang *et al.* [22] discuss the BLE based TR for WSN. The BLE-TR is integrated with the RX matching network and reusable PA load inductor. Only two inductors minimize the chip area. The integration offers better performance by reusing the PA load inductor. The TX and RX utilize the 9.4 mW and 9.7 mW of power using a gaussian-frequency shift keying (GFSK) based modulation approach on a 110 nm CMOS process. Hou *et al.* [23] present the 2.4 GHz-based CMOS TR for WSNs. The class-E TX and fractional-N based synthesizer, followed by RX, are integrated into a single CMOS chip. Only one off-chip inductor is used in the TX/RX by sharing the same input-output matching network to save chip area. The TX and RX utilize the 4.8 mW and 2.3 mW of power using an OOK/FSK modulation approach on a 180 nm CMOS process. Mustapha *et al*. [24] discuss the V-band TR for near-field IoT applications. The TR is integrated with a resonator and antenna (TX/RX) without using LNA, PA, phase-locked-loop (PLL), and mixers. The V-band offers LP and lower energy/bit in TR. The TX and RX utilize the 1 and 5.2 mW power using the OOK modulation approach on the 65 nm CMOS process. Lee *et al*. [25] present the passive sliding-IF (P-SIF) mixer-based 2.4 GHz RX with ULP features. The ULP-RX has an inverter-based LNA and P-SIF mixer followed by a baseband (BB) PGA and filter. The TX and RX utilize the 1.2 and 0.64 mW of power using the OOK modulation approach on the 28 nm CMOS process. Li *et al*. [26] describe the ZigBee-TR with low-voltage and multi-band features. The TR covers frequency bands from 780 MHz to 2.4 GHz. The RX uses a complex band-pass filter (CBPF) and frequency synthesizer (FS) to minimize the voltage and power on the chip. The TX and RX utilize the 3.5 and 1.42 mW power using the offset-quadrature phase-shift keying (O-QPSK) modulation approach on the 180 nm CMOS process.

Table 1. Summary of the existing LP TRs

Ref	Approach	Advantages	Limitations	Applications
[20]	Wireless TR for WSN	Better sensitivity with less complexity	Moderate data rate and lower BER	WSN
[21]	Balunless NB-RX -FE	LP and offers higher integration capabilities	Issues with IQ balancing	Short-range wireless and WSN
[22]	BLE-based TR	High performance with less chip area	The phase error is more	BLE and WSN
[23]	2.4 GHz-based TR	Lower–chip area	Minimal BER and data rate	WSN
[24]	V-band TR with resonator	LP and better energy efficiency	Lower data rate and lower IIR	Near-field IoT
[25]	ULP-RX with P-SIF mixer	ULP Improves the linearity	Minimal BER and data rate	LP applications
[26]	ZigBee-TR with low-voltage and multi-band features	Low-Voltage and power, multi-band operations	Lower IIR and phase noise are more	Zigbee
[27]	2.4 super regenerative TR	LP and better RX sensitivity	Lower data rate	WSN
[28]	Super regenerative TR	Easy integration	Complex architecture	Portable imaging system
[29]	OOK-super regenerative TR	LP and high sensitivity, and better RX sensitivity	Stability issues	Wireless body area networks (WBANs)
[30]	4-GHz BASED Zero-IF FM-UWB TR	Offers LP and better RX sensitivity	DC-offset issues, minimal data rate	IoT
[31]	Low-intermediate frequency (Low-IF) receiver	Better RX sensitivity	Complex architecture	Bluetooth LE applications
[32]	CMOS RF BeiDou-1 TR	Easy integration	Complex architecture	SMS and positioning applications
[33]	Low-IF-based architecture	LP and less complex architecture	Minimal data rate	BLE applications
[34]	BLE RX	LP and reusable current architecture	Minimal BER and data rate	LP-IoT applications
[35]	Sub-milliwatts TR chip	The better data rate and LP	Complex architecture in TX and RX	Medical implant devices

The SRG-TR with improved selectivity features was designed by Kim *et al*. [27] using a dual-Q enhancement model and digital frequency-locked-loop (FLL). The generation of quench signals using PLL generates voltage-controlling issues, and is overcome with FLL with super-regenerative oscillator (SRO). The SRG-RX with coupled-oscillator networks (CON) is designed by Ma *et al*. [28] to improve the gain with minimal NF. The CON with SRR improves the gain significantly and reduces the NF with the help of a serial resonator. The performance results meet the portable imaging system requirements per the frequency calibration process. The OOK-SRG RX is designed by Fu and El-Sankary [29] for WBAN applications. The RX uses automatic negative transconductance (ANT) with the 2-step periodic-based quenching controller to enhance the sensitivity. The SRO with an adaptive bulk-biasing approach is incorporated to reduce the power in RXs. The FM-UWB TR with Zero-IF architecture is designed by Kopta and Enz [30] with a multi-user approximation for IoT devices. The FM-UWB TR operates in two modes, namely: LP and multi-user mode. The TR can tolerate the frequency offset without additional off-chip components. Pereira *et al*. [31] present the Low-IF RX architecture for BLE applications to improve sensitivity. The inverter-based LNA improves Low-IF-RX's gain and NF. The RF-BeiDou-1 TR is designed by Wang *et al*. [32] to improve the IRR. The TR uses Low-IF RX and BPSK TX to realize the full-duplex communication between users and control stations. The TR is suitable for use in short message service (SMS) and regional positioning (RP) for two-way communications. The quadrature-LO buffer (QLOB) with Low-IF RX is designed by Song *et al*. [33] for BLE applications. The Low-IF RX with QLOB model reduces the additional circuitry for quadrature path generation in LO and saves the utilization of the DC current. The BLE RX architecture is designed by Park and Kwon [34] for LP IoT applications. The BLE RX combined with quadrature RF to BB current reusable model reduces the IRR and improves the gain factor with minimal power consumption. Omisakin *et al*. [35] explain the sub-milliwatt TR chip for medical implantable devices. The implanted TR uses impulse radio (IR)-ultra-wide band UWB with OOK for uplink TX and BPSK with a detection circuit for downlink RX. The RX uses an oscillator, and IR from TX offers better tenability and fully on-chip integration. The TX and RX utilize 0.3 mW and 0.2 mW of power using OOK and BPSK modulation approach on 180 nm CMOS process.

2. METHOD

The TR design-based system architectures are covered in this section. The sensitivity, adjacent/alternate channel selectivity (ACS), highest acquired signal, co-channel obstacles, image interference ratio (IIR), elimination or prevention, and other factors make up a receiver's system-level parameters. The WSN protocols and network framework determine certain system-wide parameters, which are influenced by each submodule's efficiency, including gain, NF, third-order input intercept point (IIP3), and other factors. The primary responsibility of the system designers is to give every single submodule the system-level requirements. The TR designs are classified based on the system architecture and are illustrated in Figure 1. The TRs are classified according to the system architecture design, including the SHD, Zero-IF, Low-IF, sliding-intermediate frequency (Sliding-IF), SRG, and ASH–based architectures. The typical TR has (ADC, filters, mixers, PLL, PA, LNA, and digital-to-analogue converters (DAC), antennas for transmitter (TX) and receiver (RX)-end. The digital BB system provides the signals to perform the TX operation and receives similar signals after the RX operation in the BB system. The DAC converter converts the digital data to analogue signals, followed by a filtering operation to filter out the interferences and harmonics. The mixers generate In-phase (I) and quadrature (Q)-phase up-conversion followed by modulation. The PLL provides the phase difference of the local oscillation (LO) and is input to the mixer. A PA adds and amplifies the I and Q signal. The amplified signals are emitted through the TX antenna on the TX side. On the RX side, the received signals are amplified by LNA and later down-converted by mixer to generate the IQ signals. The IQ signals are filtered using a filter followed by ADC conversion. The received digital signals are moved to the BB RX to perform the decoding mechanism. The WSN TR needs only a few analogue circuits based on requirements to offer low-cost, data rate, and power features. The most popular type of TR architecture uses frequency transformation, changing the signal being processed to a lower frequency to make it easier to employ signal handling units like gain and filtering for demodulating data signals. The BB signal is changed to a higher frequency to modulate data signals with carrier signals. To achieve frequency conversion and selectivity, narrowband responses are combined with high-purity oscillators and mixers.

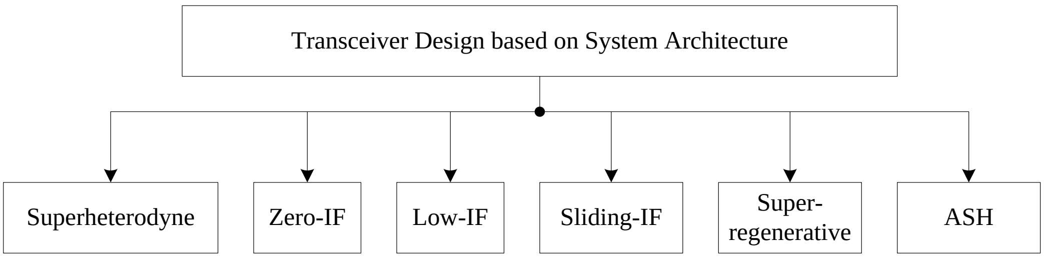

Figure 1. Classification based on system architecture

2.1. Superheterodyne architecture

For instance, the SHD architecture employs two distinct up/down-conversion techniques. To reduce the noise demands on the rest of the receiver chain, the LNA first amplifies the input RF signal in the case of RX. The RF signal is then transformed into IF using a very accurate, adjustable LO. This IF signal gets amplified and filtered with a fixed frequency filter to get rid of the image and erroneous signals. A second mixer transforms the signal to DC using a fixed frequency LO at the IF frequency. The benefit of this approach is that just a tiny subset of frequencies, chosen via RF and IF filters, must be responsive to most of the radio's transmission path. As a result, this TR has the benefit of having great sensitivity. Additionally, TX and RX isolation is achieved via RF filters. The frequency mixing-produced visual response is eliminated using IF filters. In some circumstances, several IF stages can address the undesirable image response with two IFs of differing values. When used with a PLL FS, the SHD approach also provides good stability. The SHD approach uses power-hungry elements like mixers and FS, which results in significant power usage even though it has better frequency features than more straightforward TR kinds. As a result, despite their sensitivity and stability attributes, this architecture is inadequate for the software-defined radio (SDR) system's goal of creating a LP TR. The bass-pass filter (BPF) is designed for SHD RXs to improve charge sharing [36]. The surface acoustic wave (SAW)-less SHD-RX is modelled to mitigate the multistage harmonics [37]. The discrete-time (DT)-SHD RX with fully integrated features to improve the IF image rejection [38]. Similarly, the DT-based SHD RX [39] is modelled for BLE applications. The 28 GHz RF-TR [40] is modelled for 5G mmWave transmission usage. The SHD-RX with a millimetre-wave monolithic integrated circuit is introduced to improve the bandwidth and conversion gain in full duplex communication [41]. The SHD-RX front-end module with a passive mixer is designed to mitigate the acoustic filtering impedance at various harmonic frequencies [42].

2.2. Zero-IF, Low-IF, and Slide-IF architecture

The standard components like LNA, mixers, local oscillators (Los), programmable gain amplifiers (PGAs), and filters are used to construct the Zero-IF-TRs. The choice of IF selection is restricted for commercial filters due to IF-selection trade-offs. The incoming data signals from the antenna are directly transformed to the BB system without using any IF in Zero-IF RXs. A specific BB low-pass filter is needed to design the reconfigurable Zero-IF RXs to enhance the performance metrics. The variable gain amplifier (VGA) and PGAs offer steady output power to various input signals. Digital signals control the PGAs, whereas VGAs are controlled by analog signals. The LPFs' filtering operation in the Zero-IF architecture depends on the specific requirement per channel bandwidth. The Zero-IF-TR uses minimal power, easy implementation, and fewer filtering approaches. The DC offset, flicker noise, and IQ demodulation impairments are limitations of the Zero-IF architectures. The Zero-IF CMOS TR is designed to improve the wireless link at higher data rates for mmWave communications [43]. The CMOS TR with Zero-IF [44] is designed to enhance the RX sensitivity for BLE usage. The Zero-IF module is incorporated in many TRs, like wireless TR for medical implantable usage [45], digital calibration and built-in self-test [46], high-density WSNs [47], and mmWave communication usage [48].

The Low-IF TRs avoid image difficulty by multiplying the BB signal directly to the RF signal and the RF signal directly to the BB via quadrature up/down conversion. The mixers must be driven by an LO with great spectral integrity and stability, just like in the case of SHD design. These architectures' power consumption is constrained by the LO and PLL-FS combined with SHD. A resonant LC oscillator, commonly integrated within a PLL, is frequently required to meet the demanding frequency precision and phase noise performance criteria. The power ceiling associated with integrated passives is a few hundred microwatts due to these components' low-quality factor (Q). The Low-IF-based modules incorporate many TRs for various applications, including global system for mobile communication (GSM) [49], gyrator filter design for dual mode-ZigBee/Bluetooth usage [50], IQ mismatch compensation [51], image rejection mechanism using weaver-Hartley module with Low-IF architecture [52], and injection locked ring oscillator with GFSK demodulator for LP usage [53].

The Sliding-IF TRs offer a better trade-off solution between channel selection and image rejection. The FS with PLL generates the RF and IF signals for LOs at various frequencies. The IF mixers receive the carrier signals from the FS-PLL to generate the IQ signals. These IQ signals are used to suppress the image signals. The Sliding-IF-TR offers easy implementation and a lower IIR. The design of the LO is complex in Sliding-IF architectures. The Sliding-IF-based modules incorporate many TRs for various applications, including wideband communications with Gigabits speed usage [54], ZigBee and WBAN usage [55], body area network (BAN), and warless personal area networks (WPAN) [56], IEEE 802.11ad usage [57], 5G usage [58], and mmWave communication [59], [60].

2.3. Super-regenerative and amplifier-sequenced hybrid architecture

A TR suited for OOK modulation can be produced using the SRG RX architecture. The SRG-RX provides the benefits of excellent energy efficiency, minimal power usage, and a low component count that enables high integration. As a result, it is a desirable paradigm for embedded ultra-low power radio TRs. An SRO with a time-varying loop gain and a bandpass feedback system, an envelope detector (ED) for RX, a possible PA, and LO for TX are all components included in the typical architecture. The quenching signal, which has a modulation bandwidth several times that of the SRO bias current, controls it. An SRR has the benefits of ease of use, minimal power usage, high gain, and steady demodulated output over various data signal levels. Still, it also has the disadvantage of built-in frequency instabilities, and the performance of the SRO greatly influences its characteristics. Therefore, a highly stable low-phase noise oscillator is needed for the SRG-RX. Additionally, radiation from the quench oscillator contributes to interference, and placing an oscillator in the receive path increases the TR's overall power use. The SRG-based modules incorporate many TRs for various applications, including sensitivity control with LP usage [61], medical-implant communications [62], [63], healthcare usage [64], burst-mode UWB usage [65], body channel communications [66], and wearables radio usage [67].

A fundamentally new form of RX has been developed to overcome the drawbacks of earlier RX architectures in limited-range RF connection uses. While using time diversity instead of frequency diversity, this innovative RX architecture accomplishes the identical goal as the SHD RX. The SAW BPF, two RF amplifiers, a pulse generator (PG), a delay line, and a detector module are often found in ASH RXs [68].

The existing TRs based on the system architectures are discussed in the above section [36]-[68]. A few advantages and limitations of the mentioned TRs are highlighted and tabulated in Table 2 based on system architectures. The SHD architectures provide higher stability, sensitivity and simple architectures, but this architecture utilizes more power, has a poor level of integration and is difficult to reconfigurable.

Table 2. Advantages and limitations of the existing TRs based on the system architectures

System architectures	Advantages	Limitations
SHD	– Offers higher selectivity	– Higher power utilization
	– Higher sensitivity, stability	– Integration level is poor
	– Simple architecture	– Difficult to reconfigure
Zero-IF	– Integration is easy	– Flicker noise
	– Offers low power	– DC-offset issues
	– Fewer filters	– Impairments in I/Q demodulator
Low-IF	– Low DC offset and flicker noise	– BB design is complex
	– Integration is easy	– Image rejection is more
	– Fewer filters	– Impairments in I/Q demodulator
Sliding-IF	– Integration is easy	– LO design is complex
	– IIR is lower	
SRG	– LP utilization	– Lower stability
	– Higher sensitivity	– Lower data rate
ASH	– LP utilization	– Lower data rate
	– Higher sensitivity	
	– Offer good stability	

The Zero-IF architecture offers LP utilization and better integration using fewer filters. The Zero-IF architectures face the issues of IQ imbalance, DC-offset, and flicker noise. The Low-IF architecture overcomes the issues of the Zero-IF architectures by offering low DC-offset and flicker noise with less usage of filters. Still, the Low-IF architecture faces the issues of IQ imbalance, more IIR and complex BB design. The Sliding-IF provides easy integration with low-IIR with complex LO design. The SRG-based designs utilize less power than other architectures with higher sensitivity but face issues with stability and lower data rate. The ASH module offers higher sensitivity and stability by utilizing LP, but offers a lower data rate.

3. RESULTS AND DISCUSSION

An overview of the findings and a discussion of current architectures are presented in this section. The LP TR designs under examination operate in the frequency range of 0.7–60 GHz and span CMOS nodes from 28 nm to 180 nm. While some use BPSK, GFSK, FSK, and Q-QPSK to balance power and spectral efficiency, most use OOK modulation because of its simplicity and energy-efficiency. The performance summary of the existing LP-TR architectures is illustrated in Table 3.

Fu and El-Sankary [29], transmit power ranges from 0.12 mW to 26 mW, whereas RX power can be as low as 0.39 mW. This indicates that ULP operation is feasible for WSNs and IoT nodes. For battery-powered usage, supply voltages are typically limited to 0.8–1.8 V, which is consistent with low-voltage CMOS technology. Significant diversity exists in receiver sensitivity, which ranges from –27.5 dBm to –93.8 dBm. Long-range transmission might benefit from deeper sensitivity levels (e.g., Li *et al.* [26]), but these frequently come with greater power costs. However, ULP OOK-based designs (Lee *et al.* [25]; Fu and El-Sankary [29]) are perfect for short-range communication since they sacrifice sensitivity for energy savings.

Trade-offs between transmission range and energy efficiency are reflected in the output transmit power, which ranges from –47.3 dBm to +5 dBm. While some designs, like those by Song *et al.* [33], prioritize low energy consumption at the price of range, others, like those by Kim *et al.* [27] and Li *et al.* [26], achieve positive TX power, making them appropriate for robust links. The majority of designs maintain a bit error rate (BER) between 10-3 and 10-5, guaranteeing dependability in common IoT and biomedical transmission scenarios. Interestingly, somewhat greater power use is required to achieve larger data rates (up to 4.08 Mbps, Wang *et al.* [32]) without sacrificing BER performance.

BPSK and Q-QPSK architectures provide improved sensitivity and resilience, making them more appropriate for longer-range or interference-prone settings, whereas OOK-based approaches are generally the best option for energy-constrained design for low power consumption. While BPSK/QPSK alternatives handle high-reliability applications like medical-telemetry and secure transmissions, ULP OOK architectures are best suited for short-range, implantable, and wearable IoT gadgets, according to the performance trade-offs.

Table 3. Performance summary of the existing LP-TR architectures

Ref	CMOS process (nm)	Frequency band (GHz)	Modulation	Data rate (Mbps)	Supply Voltage (V)	TX power (mW)	RX power (mW)	RX sensitivity (dBm)	Output TX power (dBm)	BER
[20]	130	2.2~2.488	OOK	1	1	4.5	9.5	-90	-4.4	10^{-5}
[21]	180	2.4	OOK	1	1.5	1	67.7	-30	-15	10^{-3}
[22]	110	2.4	GFSK	1	1.8	9.4	9.7	-93	0	10^{-3}
[23]	180	2.4	OOK/FSK	0.5	1.8	4.8	2.3	-60	+3	10^{-3}
[24]	65	60	OOK	0.01	1.8	1	5.2	-42	-10	10^{-3}
[25]	28	2.4	OOK	1	0.8	1.2	0.64	-70	-20	10^{-3}
[26]	180	0.78~2.4	O-QPSK	1	1	3.5	1.42	-93.8	+2.67	10^{-5}
[27]	180	0.7~0.9	BPSK	1	1.8	26	18	-85	+5	10^{-3}
[28]	65	3.5	OOK	1	1	7.5	8.1	-42	-84	10^{-3}
[29]	180	2.4	OOK	3.3	1	1.4	0.39	-87	+3	10^{-3}
[30]	65	4	FSK	0.001	1	1.1	0.42	-68	-10	10^{-3}
[31]	130	2.4	O-QPSK	1	1.2	2.2	1.7	-92	-17	10^{-3}
[32]	130	2.4	BPSK	4.08	1.5	4.7	3.9	-39.8	-10 to 5	10^{-5}
[33]	65	2.4	BPSK	1	0.8	2.8	2	-27.5	-47.3	10^{-5}
[34]	65	2.4	OOK	1	0.8	2.1	1.3	-25	-5	10^{-3}
[35]	180	3~5	BPSK	1	1.3	0.3	0.2	-74	0	10^{-6}

3.1. Discussion

The studied research focuses on the trade-offs between power, linearity, scalability, and application area for different receiver architectures. High linearity and selectivity are crucial in situations where SHD designs are still prevalent. Excellent harmonic rejection and SAW-less integration has been demonstrated [36], [37], while Tohidian *et al.* [38] and Ferreira *et al.* [39] revealed that DT processing can significantly save power, with BLE RXs running at just 2.75 mW. SHD has been expanded to 28–319 GHz at higher frequencies [40], [41], and even combined with acoustic filtering [42], demonstrating its capacity to scale for 5G and THz networks. Compact and power-efficient, Zero-IF architectures need to be carefully calibrated. With a throughput of 6 Gb/s at 60 GHz and a sensitivity of −81.4 dBm at 1.1 mW, as demonstrated by Tomkins *et al.* [43] and Masuch and Restituto [44], Zero-IF is a highly suited technology for BLE and IoT. Mismatch and wideband difficulties were handled by UWB versions [47], [48], and calibration techniques [46], whereas biomedical-focused devices achieved 0.33 nJ/bit energy usage [45]. The effectiveness of Zero-IF in dense, LP, short-range wireless networks is demonstrated by these findings.

Low-IF RXs offer a fair compromise between Zero-IF accessibility and SHD robustness. Dual-conversion and gyrator filters helped early GSM and Bluetooth/ZigBee solutions [49], [50], while adaptive I/Q mismatch correction [51] and weaver-Hartley algorithms [52] enhanced image rejection. Recent designs demonstrated Low-IF's versatility for both IoT and broadband applications by achieving 5.4 pJ/bit demodulation [53] and multi-Gbps wideband performance [54]. Sliding-IF RXs have effective LO use and frequency agility. Liu *et al.* [56] used phase-to-digital conversion to achieve 1.2 nJ/bit operation, while Zhang *et al.* [55] made reconfigurable WBAN hubs possible. With its 115-fs jitter PLL efficiency [58] and improved connectivity to 150 GHz CMOS [60] at mmWave, Sliding-IF is a highly desirable option for 5G and multi-band IoT TRs.

SRG RXs operate at extremely low power levels aiming to targete medical implants at 350–400 μW at early research [61], [62]. Subsequent designs adopted entirely on-chip trade-off tuning [67] and decreased energy to 79 pJ/b at 80 Mb/s [66]. These findings support SRG's superiority in body-area and medical applications, where linearity is subordinated to energy conservation. Lastly, a duty-cycled variant combining enhanced sensitivity and SRG-like efficiency has been introduced via the ASH technique [68]. It has promised for biological and IoT sensing, particularly in applications where ultra-low energy is crucial, while being little studied.

The findings demonstrate a definite application-driven selection across all architectures: SRG and ASH are not conflicted in the implantable and biomedical areas, Zero-/Low-IF dominate LP IoT and BLE, while SHD and Sliding-IF have the greatest potential for high-speed mmWave/5G communications. Energy-limited WSNs find Zero-IF designs very appealing since they do away with IF stages, which lowers chip size and power usage. They are more susceptible to flicker noise and DC offset, though, this might impair performance in settings where interference is common. However, despite requiring larger power budgets, SHD-based systems offer superior linearity and improved robustness against DC offset, making them appropriate for deployments in noisy or congested situations. SRG-based TRs are suitable for tasks requiring both efficiency and moderate dependability because they achieve low energy consumption while preserving moderate sensitivity. Modern trends emphasize hybrid or reconfigurable systems to satisfy multi-standard needs, with the trade-off being striking the ideal balance between power, linearity, and integration difficulty.

3.2. Research gaps

In WSNs, wireless communication between mobility sensor nodes is commonly used to convey data across dispersed locations. Because nodes are mobile in these networks, their structure is extremely dynamic and changes quickly. In WSNs, transmission-reception (TR) units commonly function in unstable and uncertain environments with frequent changes in the network structure, node density, and channel environment. Consequently, there are times when sensor nodes become unaware of the best routes, which results in more retransmissions and decreased efficiency. Additional difficulties brought on by node mobility include energy constraints, duplicated signalling, recovery delays, and frequent link failures. Nodes' wireless networks may sporadically break and then reconnect, causing instability in the communication process as a whole. Despite the fact that a large number of methods have been put forth in the literature to reduce energy usage in WSN-based TR systems, the problems of long-term accessibility and effective energy use have not yet been addressed. TR is one of the most power-intensive parts of a sensor node since it uses most of the available energy for node-to-node communication and data transfer. Prior studies have mostly focused on energy optimization from a broad standpoint, without thoroughly examining the precise role that TR modules play in the sensor node's overall energy consumption. As such, there is still a lack of knowledge regarding the relationship between TR design characteristics and the overall energy use pattern of WSNs.

One of the main areas of research in this field is the application of ULP techniques to reduce WSN energy consumption. Power-hungry TRs, unstable connectivity, and limited battery lifespan are some of the challenges that must be overcome to achieve ubiquitous and independent WSNs. Because energy harvesting (EH) technologies allow WSNs to harvest energy from ambient sources, including solar, vibration, or RF energy, they have become known as a possible solution to this problem. The advent of EH based WSNs opens the door for long-term, self-sustaining installations by offering an alternative to traditional networks with finite lifespans powered by batteries. Nevertheless, more research is still needed to integrate EH procedures with ULP TR designs to improve efficiency while preserving dependable communication.

Adding strong yet lightweight safety safeguards to WSN-based TRs is another crucial difficulty. Signals are intrinsically susceptible to malicious assaults, surveillance, and eavesdropping because they are sent across wireless channels. While traditional cryptographic techniques can offer security, they frequently have high computational and energy costs, making them inappropriate for WSN nodes with limited resources. The necessity for innovative security techniques designed especially for WSN TRs is highlighted by this trade-off involving security and energy consumption. In order to guarantee the privacy and integrity of information while consuming the least amount of energy and computational complexity, future research must concentrate on creating lightweight authentication and security techniques.

Another significant restriction on TR design is carrier frequency offset (CFO), particularly for inexpensive devices that are frequently used in WSNs. CFO causes inter-carrier interference (ICI), which raises the BER of RF-based TR platforms and deteriorates signal quality. In intensive and mobile WSN installations, where synchronization mistakes occur quickly, the negative consequences of CFO are increasingly noticeable. More investigation is needed to create TR designs and compensation structures that can reduce CFO-induced ICI while maintaining energy efficiency in order to solve this problem. In this field, methods including adaptive filtering, digital frequency synchronization, and machine learning-based error correction may be investigated.

The greatest enduring problem for WSNs is still limited battery power, especially when nodes are placed in dangerous or remote areas. Because manual battery replacement or recharging is problematic in these situations, effective power control methods are essential to extending the node's lifespan. Numerous studies have looked at ways to maximize energy use through effective routing, adaptive transmission procedures, and duty-cycling. Nonetheless, the TR unit still accounts for the majority of energy use during the transmission

(TX) and reception (RX) phases. Targeted TR module modification is therefore necessary to increase network lifespan without sacrificing performance.

Another important factor in the structure of WSN-based TRs is energy efficiency. Low dissipation, efficiency, and minimal form factors are necessary for LP WSN systems. One possible way to achieve sustainable TR functioning is to integrate EH from the surroundings. The creation of antenna-on-chip (AoC) systems in particular offers a IoT of potential. To improve RF EH and overall TR efficiency, AoCs offer small, low-profile, and reasonably priced antenna arrays that can be coupled with EH-enabled WSN nodes. In order to accomplish substantial energy savings while preserving scalability and affordability, subsequent studies in this field must concentrate on integrating AoC innovation with EH-based WSN TRs.

Lastly, a major research gap is the absence of digital architectures in current TR designs. Most WSN-based TRs mainly rely on analog and RF components, which are more expensive and less scalable due to their larger chip areas and higher power consumption. LOs and VCOs are examples of analog components that are especially power-hungry and restrict the system's overall efficiency. The efficiency of WSN TRs can be increased by substituting digital FSs for these parts, which can drastically lower power consumption and chip space. Developing high-performance, LP, and affordable TR designs appropriate for extensive WSN deployments is made possible by the shift to entirely digital architectures. This drives the research orientation further.

4. CONCLUSION

A thorough analysis of RF-based TR architectures designed for WSN applications is given in this work, with a focus on LP operation. Along with other performance criteria like NF and interference tolerance, the analysis highlights the crucial difficulties of decreasing energy usage while maintaining excellent sensitivity. Numerous architecture-based strategies have been investigated, and the results show that designs based on SRG and Zero-IF provide significant benefits in terms of energy conservation. The urgent need for creative LP TR alternatives that strike a balance between efficiency, dependability, and overall system performance for future WSN deployment is highlighted by the substantial design challenges that still exist despite recent advancements.

WSN-based TR architecture will advance in the future with the creation of AI-powered intelligent designs that can dynamically learn and optimize methods of interaction depending on energy availability, movements, and channel characteristics. To minimize needless retransmissions and increase network lifetime, machine learning techniques integrated into sensor nodes can facilitate real-time modulation adaptation, interference prevention, and energy-aware routing. The incorporation of RF, BB, EH, and security features into a single ultra-compact SoC is known as chip-scale integration (CSI), and it is another exciting trend. In addition to lowering costs and minimizing power loss, this integration improves sustainability for large-scale implementations. AoC arrays and CSI can also be combined to enable small, energy-efficient connectivity to integrated energy-collecting capabilities. Future studies should examine fully digital, adaptable, AI-driven, TR designs with safe connectivity and EH features. With the help of these designs, WSNs will be able to function independently in dynamic, resource-constrained contexts with low latency, high resilience, and long lifespans.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] M. N. Mowla, N. Mowla, A. F. M. S. Shah, K. M. Rabie, and T. Shongwe, "Internet of Things and Wireless Sensor Networks for Smart Agriculture Applications: A Survey," *IEEE Access*, vol. 11, pp. 145813–145852, 2023, doi: 10.1109/ACCESS.2023.3346299.

[2] M. M. Moslehi, "Exploring coverage and security challenges in wireless sensor networks: A survey," *Computer Networks*, vol. 260, pp. 1-16, Apr. 2025, doi: 10.1016/j.comnet.2025.111096.

[3] D. Kandris, C. Nakas, D. Vomvas, and G. Koulouras, "Applications of wireless sensor networks: An up-to-date survey," *Applied System Innovation*, vol. 3, no. 1, pp. 1–24, Feb. 2020, doi: 10.3390/asi3010014.

[4] R. Eskandari and M. Sawan, "Challenges and Perspectives on Impulse Radio-Ultra-Wideband Transceivers for Neural Recording Applications," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 18, no. 2, pp. 369–382, Apr. 2024, doi: 10.1109/TBCAS.2023.3331049.

[5] M. S. Bensaleh, R. Saida, Y. H. Kacem, and M. Abid, "Wireless Sensor Network Design Methodologies: A Survey," *Journal of Sensors*, vol. 2020, pp. 1–13, Jan. 2020, doi: 10.1155/2020/9592836.

[6] Z. Nurlan, T. Zhukabayeva, M. Othman, A. Adamova, and N. Zhakiyev, "Wireless Sensor Network as a Mesh: Vision and Challenges," *IEEE Access*, vol. 10, pp. 46–67, 2022, doi: 10.1109/ACCESS.2021.3137341.

[7] D. T. Nguyen *et al.*, "Security Issues in IoT-Based Wireless Sensor Networks: Classifications and Solutions," *Future Internet*, vol. 17, no. 8, pp. 1-28, Aug. 2025, doi: 10.3390/fi17080350.

[8] G. Moloudian *et al.*, "RF Energy Harvesting Techniques for Battery-Less Wireless Sensing, Industry 4.0, and Internet of Things: A Review," *IEEE Sensors Journal*, vol. 24, no. 5, pp. 5732–5745, Mar. 2024, doi: 10.1109/JSEN.2024.3352402.

[9] F. Mazunga and A. Nechibvute, "Ultra-low power techniques in energy harvesting wireless sensor networks: Recent advances and issues," *Scientific African*, vol. 11, pp. 1-14, Mar. 2021, doi: 10.1016/j.sciaf.2021.e00720.

[10] Q. Huang *et al.*, "Human body communication transceivers," *Nature Reviews Electrical Engineering*, vol. 2, no. 6, pp. 374–389, Mar. 2025, doi: 10.1038/s44287-025-00160-y.

[11] A. Rana, K. Kaur, P. Kaur, and E. Bhatti, "Energy-efficient protocols for environmental monitoring in wireless sensor networks: A review," *Journal of Ambient Intelligence and Smart Environments*, vol. 17, no. 2, pp. 139–163, May 2025, doi: 10.1177/18761364241297221.

[12] Y. Li *et al.*, "RIS-Based Physical Layer Security for Integrated Sensing and Communication: A Comprehensive Survey," *IEEE Internet of Things Journal*, vol. 12, no. 16, pp. 32444–32468, Aug. 2025, doi: 10.1109/JIOT.2025.3567553.

[13] T. Sanislav, G. D. Mois, S. Zeadally, and S. C. Folea, "Energy Harvesting Techniques for Internet of Things (IoT)," *IEEE Access*, vol. 9, pp. 39530–39549, 2021, doi: 10.1109/ACCESS.2021.3064066.

[14] A. J. Onumanyi, A. M. Abu-Mahfouz, and G. P. Hancke, "Cognitive Radio in Low Power Wide Area Network for IoT Applications: Recent Approaches, Benefits and Challenges," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 12, pp. 7489–7498, Dec. 2020, doi: 10.1109/TII.2019.2956507.

[15] O. Abdelatty, X. Chen, A. Alghaihab, and D. Wentzloff, "Bluetooth communication leveraging ultra-low power radio design," *Journal of Sensor and Actuator Networks*, vol. 10, no. 2, pp. 1-17, Apr. 2021, doi: 10.3390/jsan10020031.

[16] H. A. H. Alobaidy, J. S. Mandeep, R. Nordin, and N. F. Abdullah, "A review on zigbee based WSNs: Concepts, infrastructure, applications, and challenges," *International Journal of Electrical and Electronic Engineering and Telecommunications*, vol. 9, no. 3, pp. 189–198, 2020, doi: 10.18178/ijeetc.9.3.189-198.

[17] S. Sadjina, C. Motz, T. Paireder, M. Huemer, and H. Pretl, "A Survey of Self-Interference in LTE-Advanced and 5G New Radio Wireless Transceivers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 3, pp. 1118–1131, Mar. 2020, doi: 10.1109/TMTT.2019.2951166.

[18] R. Karim, A. Iftikhar, B. Ijaz, and I. B. Mabrouk, "The potentials, challenges, and future directions of on-chip-antennas for emerging wireless applications - A comprehensive survey," *IEEE Access*, vol. 7, pp. 173897–173934, 2019, doi: 10.1109/ACCESS.2019.2957073.

[19] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjoland, and F. Tufvesson, "6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166–1199, Jul. 2021, doi: 10.1109/JPROC.2021.3061701.

[20] S. Sayilir *et al.*, "A -90 dBm sensitivity wireless transceiver using VCO-PA-LNA-switch- modulator co-design for low power insect-based wireless sensor networks," *IEEE Journal of Solid-State Circuits*, vol. 49, no. 4, pp. 996–1006, Apr. 2014, doi: 10.1109/JSSC.2013.2293022.

[21] M. M. El-Desouki, S. M. Qasim, M. S. BenSaleh, and M. J. Deen, "Toward realization of 2.4 GHz balunless narrowband receiver front-end for short range wireless applications," *Sensors (Switzerland)*, vol. 15, no. 5, pp. 10791–10805, May. 2015, doi: 10.3390/s150510791.

[22] Z. Liang *et al.*, "A low cost bluetooth low energy transceiver for wireless sensor network applications with a front-end receiver-matching network-reusing power amplifier load inductor," *Sensors (Switzerland)*, vol. 17, no. 4, p. 895, Apr. 2017, doi: 10.3390/s17040895.

[23] B. Hou *et al.*, "A 11 mW 2.4 GHz 0.18 μm CMOS transceivers for wireless sensor networks," *Sensors (Switzerland)*, vol. 17, no. 2, pp. 1-14, Jan. 2017, doi: 10.3390/s17020223.

[24] A. Mustapha, D. Cracan, R. Gadhafi, and M. Sanduleanu, "A V-Band Transceiver with Integrated Resonator and Receiver/Transmitter Antenna for Near-Field IoT," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 65, no. 10, pp. 1300–1304, Oct. 2018, doi: 10.1109/TCSII.2018.2850973.

[25] S. Lee, D. Jeong, and B. Kim, "UltraLP2.4-GHz Receiver with All Passive Sliding-IF Mixer," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 5, pp. 2356–2362, May 2018, doi: 10.1109/TMTT.2017.2756622.

[26] Z. Li, Y. Yao, Z. Wang, G. Cheng, and L. Luo, "A low-voltage multi-band Zigbee transceiver," *Electronics (Switzerland)*, vol. 8, no. 12, pp. 1-21, Dec. 2019, doi: 10.3390/electronics8121474.

[27] S. J. Kim, D. Lee, K. Y. Lee, and S. G. Lee, "A 2.4-GHz Super-Regenerative Transceiver with Selectivity-Improving Dual Q-Enhancement Architecture and 102-µ All-Digital FLL," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 9, pp. 3287–3298, Sep. 2017, doi: 10.1109/TMTT.2017.2664826.

[28] S. Ma, H. Yu, Q. J. Gu, and J. Ren, "A 7.52-dB Noise Figure 128.75-132.25-GHz Super-Regenerative Receiver with 0.615-fW/√Hz NEP by Coupled Oscillator Networks for Portable Imaging System in 65-nm CMOS," *IEEE Transactions on Microwave Theory and Techniques*, vol. 66, no. 9, pp. 4095–4107, Sep. 2018, doi: 10.1109/TMTT.2018.2836402.

[29] X. Fu and K. El-Sankary, "A Low-Power, High-Sensitivity, OOK-Super-Regenerative Receiver for WBANs," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, no. 5, pp. 793–797, May 2019, doi: 10.1109/TCSII.2019.2908069.

[30] V. Kopta and C. C. Enz, "A 4-GHz Low-Power, Multi-User Approximate Zero-IF FM-UWB Transceiver for IoT," *IEEE Journal of Solid-State Circuits*, vol. 54, no. 9, pp. 2462–2474, Sep. 2019, doi: 10.1109/JSSC.2019.2917837.

[31] M. S.-Pereira, J. T. De Sousa, J. C. Freire, and J. C. Vaz, "A 1.7-mW-92-dBm Sensitivity Low-IF Receiver in 0.13-µ m CMOS for Bluetooth le Applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 67, no. 1, pp. 332–346, Jan. 2019, doi: 10.1109/TMTT.2018.2876224.

[32] Y. Wang, R. Zhou, X. Yu, and Y. Li, "a CMOS RF BeiDou-1 Transceiver for Regional Positioning and Short Message Service applications," *IEEE Access*, vol. 8, pp. 16248–16258, 2020, doi: 10.1109/aCCESS.2020.2967097.

[33] E. Song, B. Park, and K. Kwon, "2.4-GHz low-power low-IF receiver with a quadrature local oscillator buffer for bluetooth low energy applications," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 68, no. 7, pp. 2369–2373, Jul. 2021, doi: 10.1109/TCSII.2021.3059760.

[34] B. Park and K. Kwon, "2.4 GHz BLE Receiver with Power-Efficient Quadrature RF-to-Baseband-Current-Reuse Architecture for LPIoT Applications," *IEEE Access*, vol. 9, pp. 62734–62744, 2021, doi: 10.1109/ACCESS.2021.3074650.

[35] A. Omisakin, R. Mestrom, G. Radulov, and M. Bentum, "Sub-Milliwatt Transceiver IC for Transcutaneous Communication of an Intracortical Visual Prosthesis," *Electronics*, vol. 11, no. 1, pp. 1-20, Dec. 2021, doi: 10.3390/electronics11010024.

[36] I. Madadi, M. Tohidian, and R. B. Staszewski, "Analysis and design of I/Q charge-sharing band-pass-filter for superheterodyne receivers," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 62, no. 8, pp. 2114–2121, Aug. 2015, doi: 10.1109/TCSI.2015.2437514.

[37] I. Madadi, M. Tohidian, K. Cornelissens, P. Vandenameele, and R. B. Staszewski, "A High IIP2 SAW-Less Superheterodyne Receiver With Multistage Harmonic Rejection," *IEEE Journal of Solid-State Circuits*, vol. 51, no. 2, pp. 332–347, Feb. 2016, doi: 10.1109/JSSC.2015.2504414.

[38] M. Tohidian, I. Madadi, and R. B. Staszewski, "A Fully Integrated Discrete-Time Superheterodyne Receiver," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 25, no. 2, pp. 635–647, Feb. 2017, doi: 10.1109/TVLSI.2016.2598857.

[39] S. B. Ferreira, F. W. Kuo, M. Babaie, S. Bampi, and R. B. Staszewski, "System Design of a 2.75-mW Discrete-Time Superheterodyne Receiver for Bluetooth Low Energy," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 5, pp. 1904–1913, May 2017, doi: 10.1109/TMTT.2017.2668407.

[40] Z. Luo, H. Chen, W. Che, and Q. Xue, "Study of 28 GHz Transceiver Module Integrated with LO Source for 5G mmWave Communication," in *2020 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications, IMWS-AMP 2020 - Proceedings*, Jul. 2020, pp. 1–3, doi: 10.1109/IMWS-AMP49156.2020.9199679.

[41] C. M. Grötsch, I. Dan, L. John, S. Wagner, and I. Kallfass, "A Compact 281-319 GHz LPDownconverter MMIC for Superheterodyne Communication Receivers," *IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 2, pp. 231–239, Mar. 2021, doi: 10.1109/TTHZ.2020.3038043.

[42] H. Seo and J. Zhou, "A Passive-Mixer-First Acoustic-Filtering Superheterodyne RF Front-End," *IEEE Journal of Solid-State Circuits*, vol. 56, no. 5, pp. 1438–1453, May 2021, doi: 10.1109/JSSC.2021.3067664.

[43] A. Tomkins, R. A. Aroca, T. Yamamoto, S. T. Nicolson, Y, Doi, and S. P. Voinigescu, "A zero-IF 60 GHz 65 nm CMOS transceiver with direct BPSK modulation demonstrating up to 6 Gb/s data rates over a 2 m wireless link," *IEEE Journal of Solid-State Circuits*, vol. 44, no. 8, pp. 2085–2099, Aug. 2009, doi: 10.1109/JSSC.2009.2022918.

[44] J. Masuch and M. D.-Restituto, "A 1.1-mW-RX-81.4-dBm sensitivity CMOS transceiver for bluetooth low energy," *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 4, pp. 1660–1673, Apr. 2013, doi: 10.1109/TMTT.2013.2247621.

[45] A. Ba *et al.*, "A 0.33 nJ/bit IEEE802.15.6/proprietary MICS/ISM wireless transceiver with scalable data rate for medical implantable applications," *IEEE Journal of Biomedical and Health Informatics*, vol. 19, no. 3, pp. 920–929, May 2015, doi: 10.1109/JBHI.2015.2414298.

[46] J. W. Jeong, A. Nassery, J. N. Kitchen, and S. Ozev, "Built-In Self-Test and Digital Calibration of Zero-IF RF Transceivers," *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 24, no. 6, pp. 2286–2298, Jun. 2016, doi: 10.1109/TVLSI.2015.2506547.

[47] V. Kopta, D. Barras, and C. C. Enz, "An approximate zero if FM-UWB receiver for high density wireless sensor networks," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 2, pp. 374–385, Feb. 2017, doi: 10.1109/TMTT.2016.2645568.

[48] D. Parveg *et al.*, "An mm-Wave CMOS I-Q Subharmonic Resistive Mixer for Wideband Zero-IF Receivers," *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 5, pp. 520–523, May 2020, doi: 10.1109/LMWC.2020.2980973.

[49] S. Tadjpour, E. Cijvat, E. Hegazi, and A. A. Abidi, "A 900-MHz dual-conversion low-IF GSM receiver in 0.35-µm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 36, no. 12, pp. 1992–2002, 2001, doi: 10.1109/4.972150.

[50] B. Guthrie, J. Hughes, T. Sayers, and A. Spencer, "A CMOS gyrator low-IF filter for a dual-mode Bluetooth/ZigBee transceiver," *IEEE Journal of Solid-State Circuits*, vol. 40, no. 9, pp. 1872–1878, Sep. 2005, doi: 10.1109/JSSC.2005.848146.

[51] I. Elahi, K. Muhammad, and P. T. Balsara, "I/Q mismatch compensation using adaptive decorrelation in a low-IF receiver in 90-nm CMOS process," *IEEE Journal of Solid-State Circuits*, vol. 41, no. 2, pp. 395–403, Feb. 2006, doi: 10.1109/JSSC.2005.862353.

[52] C. C. Meng, T. H. Wu, J. S. Syu, S. W. Yu, K. C. Tsung, and Y. H. Teng, "2.4/5.7-GHz CMOS dual-band low-IF architecture using WeaverHartley image-rejection techniques," *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 3, pp. 552–561, Mar. 2009, doi: 10.1109/TMTT.2008.2012300.

[53] S. Hong, A. K. George, D. Im, M. Je, and J. Lee, "A 1.0 V, 5.4 pJ/bit GFSK demodulator based on an injection locked ring oscillator for low-IF receivers," *IEEE Access*, vol. 8, pp. 185209–185217, 2020, doi: 10.1109/ACCESS.2020.3029863.

[54] F. Vecchi *et al.*, "A wideband receiver for multi-Gbit/s communications in 65 nm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 46, no. 3, pp. 551–561, Mar. 2011, doi: 10.1109/JSSC.2010.2100251.

[55] L. Zhang *et al.*, "A reconfigurable sliding-IF transceiver for 400 MHz/2.4 GHz IEEE 802.15.6/ZigBee WBAN hubs with only 21% tuning range VCO," *IEEE Journal of Solid-State Circuits*, vol. 48, no. 11, pp. 2705–2716, Nov. 2013, doi: 10.1109/JSSC.2013.2274893.

[56] Y. H. Liu, A. Ba, J. H. C. V. D. Heuvel, K. Philips, G. Dolmans, and H. De Groot, "A 1.2 nJ/bit 2.4 GHz receiver with a sliding-IF

phase-to-digital converter for wireless personal/body area networks," *IEEE Journal of Solid-State Circuits*, vol. 49, no. 12, pp. 3005–3017, Dec. 2014, doi: 10.1109/JSSC.2014.2365092.
[57] L. Zhang, J. Luo, W. Zhu, L. Zhang, Y. Wang, and Z. Yu, "A fully integrated CMOS 60-GHz transceiver for IEEE802.11ad applications," *Journal of Communications and Information Networks*, vol. 1, no. 2, pp. 45–61, 2016, doi: 10.1007/bf03391557.
[58] S. Ek *et al.*, "A 28-nm FD-SOI 115-fs Jitter PLL-Based LO System for 24-30-GHz Sliding-IF 5G Transceivers," *IEEE Journal of Solid-State Circuits*, vol. 53, no. 7, pp. 1988–2000, Jul. 2018, doi: 10.1109/JSSC.2018.2820149.
[59] N. Ebrahimi and J. F. Buckwalter, "A high-fractional-bandwidth, millimeter-wave bidirectional image-selection architecture with narrowband LO tuning requirements," *IEEE Journal of Solid-State Circuits*, vol. 53, no. 8, pp. 2164–2176, Aug. 2018, doi: 10.1109/JSSC.2018.2828855.
[60] X. Meng, B. Chi, Y. Liu, T. Ma, and Z. Wang, "A Fully Integrated 150-GHz Transceiver Front-End in 65-nm CMOS," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, no. 4, pp. 602–606, Apr. 2019, doi: 10.1109/TCSII.2018.2870926.
[61] N. Joehl, C. Dehollain, P. Favre, P. Deval, and M. Declercq, "A LP1-GHz super-regenerative transceiver with time-shared PLL control," *IEEE Journal of Solid-State Circuits*, vol. 36, no. 7, pp. 1025–1031, Jul. 2001, doi: 10.1109/4.933457.
[62] J. L. Bohorquez, A. P. Chandrakasan, and J. L. Dawson, "A 350 µW CMOS MSK transmitter and 400 µW OOK super-regenerative receiver for medical implant communications," *IEEE Journal of Solid-State Circuits*, vol. 44, no. 4, pp. 1248–1259, Apr. 2009, doi: 10.1109/JSSC.2009.2014728.
[63] T. Copani *et al.*, "A CMOS LPtransceiver with reconfigurable antenna interface for medical implant applications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 5, pp. 1369–1378, May 2011, doi: 10.1109/TMTT.2011.2116036.
[64] M. Vidojkovic *et al.*, "A 2.4 GHz ULP OOK single-chip transceiver for healthcare applications," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 5, no. 6, pp. 523–534, Dec. 2011, doi: 10.1109/TBCAS.2011.2173340.
[65] Y. Zheng, Y. Zhu, C. W. Ang, Y. Gao, and C. H. Heng, "A 3.54 nJ/bit-RX, 0.671 nJ/bit-TX burst mode super-regenerative UWB transceiver in 0.18-µ m CMOS," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 61, no. 8, pp. 2473–2481, Aug. 2014, doi: 10.1109/TCSI.2014.2332244.
[66] H. Cho *et al.*, "A 79 pJ/b 80 Mb/s full-duplex transceiver and a 42.5µW 100 kb/s super-regenerative transceiver for body channel communication," *IEEE Journal of Solid-State Circuits*, vol. 51, no. 1, pp. 310–317, Jan. 2016, doi: 10.1109/JSSC.2015.2498761.
[67] V. D. Rezaei and K. Entesari, "A Fully On-Chip 80-pJ/b OOK Super-Regenerative Receiver with Sensitivity-Data Rate Tradeoff Capability," *IEEE Journal of Solid-State Circuits*, vol. 53, no. 5, pp. 1443–1456, May 2018, doi: 10.1109/JSSC.2018.2793533.
[68] C. Musolff, A. Neuberger, and R. Kronberger, "Amplifier sequenced hybrid receiver," *IEEE Microwave Magazine*, vol. 12, no. 1, pp. 94–98, Feb. 2011, doi: 10.1109/MMM.2010.939317.

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