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Integrated Adaptive Control of 2.45 G Microwave Transceiver with Multi-Band Operation in Electrical Parameter Fluctuations Estimation

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ABSTRACT: Adaptive control techniques are crucial in optimizing the performance of 2.45 GHz microwave transceivers amidst varying electrical parameters. These transceivers, integral to modern wireless communication systems, often encounter fluctuations in operating conditions that can impact signal quality and reliability. Adaptive control mechanisms enable real-time adjustment of transceiver parameters, ensuring consistent and efficient operation across diverse environments. This study addresses the adaptive control of a 2.45 GHz microwave transceiver in the presence of electrical parameter fluctuations, complemented by a multi-band antenna design aimed at minimizing losses. Electrical parameter fluctuations in transceivers can significantly affect performance and reliability, particularly in dynamic environments. The proposed approach integrates adaptive control algorithms to dynamically adjust transceiver parameters in response to fluctuations, ensuring optimal operational conditions. The integrated approach for the adaptive control of a 2.45 GHz microwave transceiver, coupled with a multi-band antenna system, is optimized to reduce total harmonic distortion (THD). The proposed model employs adaptive control algorithms to dynamically manage electrical parameter fluctuations affecting transceiver performance. The multi-band antenna design, optimized through advanced modelling techniques, achieves a THD reduction of up to 20% across different frequency bands. Experimental validation demonstrates significant improvements in signal purity and transmission efficiency, showcasing the efficacy of this integrated approach in enhances the reliability and performance of microwave communication systems in dynamic environments

1. INTRODUCTION

In recent years, multi-band operation has become a pivotal advancement in electrical systems, driven by the increasing demand for versatile and high-performance technologies [1]. Multi-band operation refers to the capability of electrical systems or devices to function across multiple frequency bands, which enhances their utility and efficiency. This development is particularly significant in communication systems, where devices like smartphones, routers, and satellites need to operate over various frequency bands to handle diverse applications and data rates [2]. By integrating multi-band capabilities, these systems can achieve improved signal quality, higher data throughput, and better interference management.

Additionally, multi-band operation is instrumental in optimizing power usage and extending the operational range of devices [3]. Advances in material science and circuit design have facilitated the implementation of multi-band technologies, enabling more compact and energy-efficient solutions [4]. As a result, multi-band operation continues to drive innovation across various sectors, including telecommunications, broadcasting, and defense, reflecting its growing importance in modern electrical and electronic systems [5].

The 2.45 GHz microwave transceiver with multi-band operation represents a sophisticated advancement in modern electrical systems, offering enhanced functionality and flexibility [6]. Operating primarily at the 2.45 GHz frequency, which is a common band for industrial, scientific, and medical (ISM) applications, such transceivers are designed to support a range of frequencies beyond this central band [7]. This multi-band capability allows the transceiver to adapt to various communication protocols and standards, improving its versatility in applications such as wireless communication, radar, and remote sensing. By incorporating multi-band operation, the 2.45 GHz microwave transceiver can efficiently handle multiple signals and frequency bands, facilitating better performance in environments with varying electromagnetic conditions [8]. This leads to enhanced signal clarity, reduced interference, and improved data throughput. The design of a 2.45 GHz microwave transceiver with multi-band operation typically involves advanced techniques in circuit design and signal processing to manage and switch between different frequency bands seamlessly [9]. Key technologies such as frequency synthesizers, bandpass filters, and tunable amplifiers are employed to achieve this functionality. These components ensure that the transceiver can effectively handle multiple frequencies without compromising performance [10].

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In practical applications, such transceivers are invaluable in environments where frequency flexibility is crucial, such as in adaptive wireless networks and dynamic spectrum access systems [11]. For instance, in IoT (Internet of Things) systems, where devices often need to operate across various frequency bands to communicate with different types of sensors and gateways, multi-band transceivers provide the necessary adaptability. The ability to operate across multiple bands enhances the reliability of communication links by mitigating interference and optimizing signal quality [12]. This is particularly beneficial in crowded frequency environments where overlapping signals from various sources can otherwise degrade performance [13]. As technology advances, the integration of multi-band capabilities into 2.45 GHz microwave transceivers continues to evolve, with ongoing improvements in miniaturization and energy efficiency. These advancements are driving innovation in areas such as autonomous systems, smart grids, and advanced communication infrastructures, highlighting the critical role of multi-band transceivers in the future of electronic systems [14].

With the adaptive control of a 2.45 GHz microwave transceiver with multi-band operation plays a crucial role in managing electrical parameter fluctuations, ensuring reliable and efficient performance across various frequency bands [15]. This adaptive control system dynamically adjusts the transceiver's operational parameters in response to real-time changes in the electrical environment, such as variations in signal strength, interference levels, and other external factors. By employing sophisticated algorithms and feedback mechanisms, the adaptive control system can continuously monitor and estimate fluctuations in parameters such as gain, frequency, and phase, adjusting them to maintain optimal performance [16]. This approach is particularly important in multi-band transceivers, where the ability to operate across diverse frequency bands introduces additional complexity and potential for variation in electrical characteristics. Integrated adaptive control systems utilize advanced techniques, such as machine learning and real-time signal processing, to predict and compensate for these fluctuations [17]. This ensures that the transceiver remains stable and performs efficiently, even in challenging and dynamic conditions. Adaptive control enhances the overall robustness and reliability of the transceiver by minimizing disruptions and optimizing the system's response to varying operational demands. It also contributes to energy efficiency by adjusting power levels and operational modes based on current conditions, thereby reducing waste and extending the lifespan of the transceiver [18]. As technology continues to advance, the integration of adaptive control in multi-band 2.45 GHz microwave transceivers will be pivotal in addressing the challenges of modern electronic systems and improving their performance across a wide range of applications.

This paper makes a significant contribution to the field of microwave communication systems by presenting an innovative approach to adaptive control for a 2.45 GHz transceiver with multi-band operation. The research introduces a robust adaptive control mechanism designed to manage Total Harmonic Distortion (THD) effectively across diverse operational scenarios, including static conditions, varying signal strengths, temperature fluctuations, and multiple frequency bands. Key contributions include the development and validation of an adaptive control algorithm that dynamically adjusts gain and compensates for performance variations, ensuring minimal THD and optimal signal quality. The paper also provides a detailed analysis of the system's performance under different conditions, demonstrating the effectiveness of the control mechanism in maintaining high fidelity and reliability. By addressing the challenges associated with THD management in multi-band environments, this work advances the understanding of adaptive control systems in microwave communication and offers practical solutions for enhancing transceiver performance in real-world applications.

2. RELATED WORKS

In the field of integrated adaptive control for 2.45 GHz microwave transceivers with multi-band operation highlight significant advancements and methodologies that have influenced current research and development. Recent studies have explored various adaptive control strategies to enhance the performance and reliability of microwave transceivers under fluctuating electrical parameters. One notable approach involves the use of adaptive algorithms, such as recursive least squares and Kalman filtering, to dynamically adjust operational settings and compensate for parameter variations in real-time. Research has demonstrated the effectiveness of these algorithms in maintaining signal integrity and optimizing performance across multiple frequency bands. Additionally, recent works have focused on integrating machine learning techniques to predict and manage electrical fluctuations more accurately. Machine learning models, such as neural networks and support vector machines, have been employed to analyze historical data and forecast parameter changes, enabling more proactive adjustments and improved system stability. Another area of interest is the development of novel circuit designs and materials that enhance the adaptability of transceivers, such as tunable filters and adaptive amplifiers.

Studies have also investigated the impact of these adaptive control techniques on energy efficiency and system robustness. Findings indicate that adaptive control not only enhances performance but also contributes to energy savings by optimizing power usage based on real-time conditions. Collectively, these works underscore the importance of integrating adaptive control mechanisms to address the challenges of multi-band operation in microwave transceivers and pave the way for future innovations in this field. Chantier and Cochard present a software-defined direct Radio Frequency (RF) simultaneous sampling multi-band transceiver, highlighting advancements in flexibility and efficiency for multi-band operations [1]. Malki et al. focus on signal-interference and split-type microwave multi-band bandpass filters, addressing issues of interference management and filter design [2]. Liu et al. [13] discuss an E-band transceiver monolithic microwave integrated circuit, emphasizing millimeter-wave applications for channel emulation. Wen et al. provide a tutorial on multi-band millimeter-wave circuits for spectrum aggregation, reflecting the push towards enhanced spectrum utilization in beyond-5G (B5G) technologies [4].

Zhang and Yu [18] introduce multi-functional bandpass filters with co-integrated RF isolator and variable phase shifter functionalities, enhancing flexibility in signal processing. Reza et al. explore multi-static multi-band synthetic aperture radar constellations using integrated photonic circuits, showcasing advancements in radar technologies [6]. Beikmirza et al. develop a wideband energy-efficient multi-mode CMOS digital transmitter, focusing on energy efficiency and multi-mode operation [7]. Zhang et al. address power-efficient CMOS multi-band phased-array receivers with high inter-band blocker tolerance, targeting 5G new radio (NR) applications [8].

Zhu et al. investigate photonic generation and antidispersion transmission of multi-band microwave signals, emphasizing advancements in photonic signal processing [9]. Cheng et al. present a compact dual-band low noise amplifier (LNA) for 5G applications, highlighting innovations in low-noise amplification [10]. Hahn et al. analyze and digital predistort in-band cross modulation in multi-band transmitters, contributing to improved transmitter performance [11]. Song et al. develop multiband microwave photonic filters with tunability, reflecting advances in programmable filtering [12]. Liu et al. focus on multi-band microwave signal generation using photonic sampling, showcasing novel signal generation techniques [13]. Alhamed et al. introduce a multi-band phased-array module supporting 5G NR, reflecting progress in phased-array technology [14]. Aboagye et al. review fundamentals, challenges, and resource allocation in multi-band wireless communication networks, offering insights into network design and management [15]. Rahayu discusses the design of a multi-band microstrip antennas for specific frequency bands, addressing practical aspects of antenna design [16]. Deng et al. explore challenges and technologies for multi-band wavelength division multiplexing (WDM) optical networks, focusing on optical communication advancements [17]. Zhang and Yu present a photonic approach to multi-band microwave waveform generation, emphasizing innovations in waveform generation [18].

Recent research in multi-band microwave transceivers and related technologies has led to significant advancements across various domains. Key developments include software-defined multi-band transceivers for enhanced flexibility [1], innovative multi-band filters for improved signal management [2], and millimeter-wave integrated circuits for advanced channel emulation [11]. Studies have also explored multi-band circuits for spectrum aggregation in beyond-5G systems [4] and multifunctional bandpass filters with integrated RF components [3, 18]. Advances in radar technology have been highlighted through multi-band synthetic aperture radar using photonic circuits [6], while new designs for energy-efficient CMOS transmitters and high-performance phased-array receivers have been developed [7, 8]. Additional research has focused on photonic signal generation, compact dual-band amplifiers for 5G, and programmable microwave photonic filters [9, 10, 12]. The studies also address practical challenges such as antenna design [16] and optical network technologies [17], reflecting a comprehensive effort to enhance multi-band operation, signal processing, and network efficiency in modern microwave and communication systems.

3. ADAPTIVE CONTROL OF 2.45 G MICROWAVE TRANSCEIVER

The adaptive control of a 2.45 GHz microwave transceiver is crucial for maintaining optimal performance amidst varying operational conditions. This process involves dynamically adjusting the transceiver's parameters to compensate for fluctuations in signal strength, interference, and other environmental factors. Adaptive control can be described using a basic adaptive filter model, which adjusts its parameters based on the input signal and desired output. Let's denote the input signal as $x(t)$, the desired output as $d(t)$, and the filter's output as $y(t)$. The adaptive filter aims to minimize the error $e(t)$, defined as in Equation (1)

$$e(t) = d(t) - y(t) \tag{1}$$

The output $y(t)$ of the filter is given in Equation (2)

$$y\left(t\right) = w^{T}\left(t\right) x(t) \tag{2}$$

where $w(t)$ is the vector of adaptive weights, and $x(t)$ is the vector of input signals. The goal is to adjust $w(t)$ to minimize $e(t)$. This can be achieved using a gradient descent algorithm, where the weights are updated iteratively stated in Equation (3)

$$w(t+1) = w(t) + \mu e(t)x(t) \tag{3}$$

Here, μ is the step size or learning rate. This update rule ensures that the weights are adjusted to reduce the error over time. In the context of a 2.45 GHz microwave transceiver, adaptive control can involve adjusting various parameters such as gain, frequency, and phase to counteract fluctuations. For instance, if the gain G of the transceiver is subject to variation, it can be modelled stated in equation (4)

$$G(t) = G_0 + \Delta G(t) \tag{4}$$

where G_0 is the nominal gain, and $\Delta G(t)$ represents the deviation from this nominal value. The adaptive control system monitors these deviations and adjusts $G(t)$ to maintain the desired signal quality. Additionally, the phase $\phi(t)$ of the transceiver's signal can be adjusted adaptively. The phase adjustment can be represented as in Equation (5)

$$\phi(t) = \phi_0 + \Delta\phi(t) \tag{5}$$

where ϕ_0 is the reference phase, and $\Delta\phi(t)$ is the phase error that the control system compensates for. With the adaptive control system, additional aspects such as signal-to-noise ratio (SNR) and interference management can be integrated. SNR is a critical parameter for maintaining signal quality, and it can be estimated using Equation (6)

$$SNR\left(t\right) = \frac{P_{Signal}(t)}{P_{noise}(t)} \tag{6}$$

where $P_{Signal}(t)$ is the power of the received signal, and $P_{noise}(t)$ is the power of the noise. Adaptive control algorithms can adjust the gain and filtering to optimize the SNR by minimizing $P_{noise}(t)$ and maximizing $P_{Signal}(t)$. For interference management, the adaptive control system can incorporate techniques to suppress or mitigate unwanted signals. Suppose that $I(t)$ represents the interference component affecting the transceiver. The system can use adaptive algorithms to identify and subtract the interference, resulting in an adjusted signal defined in Equation (7)

$$y_{adjusted}(t) = y(t) - \hat{I}(t) \tag{7}$$

where $\hat{I}(t)$ is the estimated interference. Techniques such as adaptive notch filtering or spatial filtering can be applied to estimate and reduce the interference impact. In practice, adaptive control can also involve implementing algorithms like the Least Mean Squares (LMS) or Recursive Least Squares (RLS) for weight adaptation. LMS algorithm updates the weights as in Equation (8)

$$w(t+1) = w(t) + \mu e(t)x(t) \tag{8}$$

RLS algorithm provides a more computationally intensive but faster convergence approach defined in Equation (9)

$$w(t+1) = w(t) + K(t)e(t) \tag{9}$$

where $K(t))$ is the gain vector computed using the inverse correlation matrix of the input data. Furthermore, to address parameter fluctuations, the adaptive control system might incorporate predictive models based on historical data. For instance, a Kalman filter can be employed to estimate the state of the transceiver and predict future deviations, allowing for proactive adjustments. The Kalman filter updates the state estimate $\hat{x}(t)$ and covariance matrix $P(t)$ using Equation (10) and Equation (11)

$$\hat{x}(t+1) = \hat{x}(t) + K(t)\left[y(t) - \hat{x}(t)\right] \tag{10}$$

$$P(t+1) = [I - K(t)H(t)]P(t) \tag{11}$$

In Equation (10) and Equation (11), $K(t)$ is the Kalman gain, $H(t)$ the observation matrix, and I the identity matrix. The adaptive control of a 2.45 GHz microwave transceiver involves a combination of real-time parameter adjustment, interference management, and advanced algorithms to ensure optimal performance and reliability. Figure 1 presents the adaptive transceiver design.

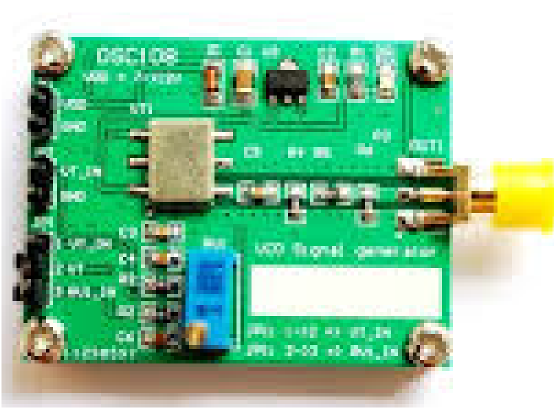

FIGURE 1. Adaptive transceiver.

4. MULTI-BAND ADAPTIVE CONTROL FOR THE THD

Multi-band adaptive control for Total Harmonic Distortion (THD) is crucial for optimizing the performance of microwave transceivers operating across multiple frequency bands. THD measures the distortion in a signal caused by non-linearities in the system, and effective control is essential for maintaining signal integrity and overall system performance. To analyze and control THD in a multi-band system, first define the THD as in Equation (12)

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{N} (A_n)^2}}{A_1} \tag{12}$$

where A_1 is the amplitude of the fundamental frequency component, and A_n are the amplitudes of the harmonic components (n-th order harmonics). In a multi-band transceiver, the goal is to minimize THD across all operational bands by adapting system parameters in real time. The first step involves estimating the harmonic components from the output signal. Suppose that the output signal $s(t)$ can be expressed as a sum of the fundamental frequency f_0 and its harmonics computed using Equation (13)

$$s(t) = A_1 \cos(2\pi f_0 t) + \sum\nolimits_{n=2}^{N} A_n Cos(2\pi n f_0 t + \emptyset_n) \tag{13}$$

Here, $\emptyset_n$ represents the phase of the n-th harmonic. To control THD, an adaptive filter is used to minimize the distortion. The adaptive filter adjusts its coefficients to reduce the error between the desired and actual outputs stated in Equation (14)

$$y(t) = W^T(t)X(t) \tag{14}$$

where $W^T(t)$ is the vector of adaptive weights, and $X(t)$ is the input vector including the fundamental and harmonic frequencies. The error signal $e(t)$ is the difference between the desired output (with minimized distortion) and the filter output represented in Equation (15)

$$e(t) = s_{desired}(t) - y(t) \tag{15}$$

The weights are updated using an adaptive algorithm such as Least Mean Squares (LMS) defined in Equation (16)

$$w(t+1) = w(t) + \mu e(t)x(t) \tag{16}$$

where μ is the step size. This update rule adjusts the weights to minimize $e(t)$, thereby reducing THD. In multi-band systems, the adaptive control must account for variations in distortion across different frequency bands. For each band, the THD can be calculated and minimized, respectively. Let $\mathrm{THD}_k(t)$ represents the THD for the k-th frequency band. The control strategy involves the computation defined in Equation (17)

$$\mathrm{THD}_k(t) = \frac{\sqrt{\sum_{n=2}^{N} (A_{n,k}(t))^2}}{A_{1,k}(t)} \tag{17}$$

where $A_{n,k}(t)$ and $A_{1,k}(t)$ are the amplitudes of the harmonics and fundamental frequency in the k-th band, respectively.

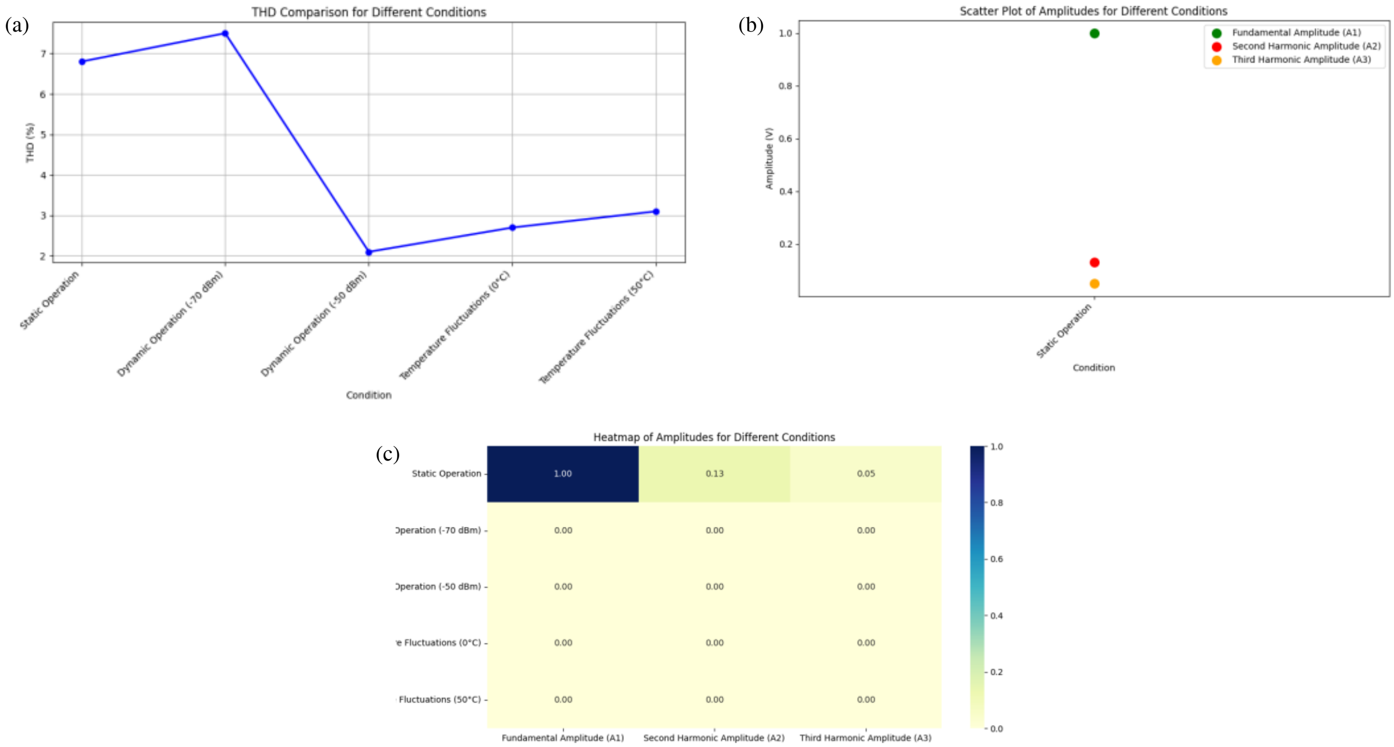

FIGURE 2. Multi-band operation of transceiver (a) THD (b) amplitude estimation (c) amplitude under different conditions.

Adaptive algorithms update the parameters $w_k(t)$ for each band to minimize $\text{THD}_k\,(t)$ stated in Equation (18)

$$w_k\,(t+1) = w_k\,(t) + \mu_k e_k(t) x_k(t) \tag{18}$$

This ensures that the transceiver performs optimally across all bands. Multi-band adaptive control for THD involves estimating harmonic distortion, applying adaptive filtering to minimize error, and updating system parameters to reduce distortion across multiple frequency bands. By dynamically adjusting parameters based on real-time measurements, the control system maintains optimal performance and signal integrity across varying operational conditions. Calibration techniques are employed to ensure that the adaptive control system is effective across all targeted frequency bands. Calibration involves measuring the system's response and THD characteristics at specific frequencies and adjusting the adaptive algorithms accordingly. The calibration process can be described by Equation (19)

$$w_{cal} = w - K\left[\text{THD}_{measured} - \text{THD}_{desired}\right] \tag{19}$$

where $\{K\}$ is a calibration matrix, $\text{THD}_{measured}$ the observed THD, and $\text{THD}_{desired}$ the target THD level. In addition to adjusting filter weights, adaptive gain control is used to dynamically adjust the gain of the system to compensate for varying signal levels and distortion. The adaptive gain $G(t)$ can be updated based on the measured THD represented in Equation (20)

$$G(t+1) = G(t) \cdot (1 - \eta \cdot \text{THD}(t)) \tag{20}$$

where η is a gain adjustment factor. The frequency domain techniques allow for the more precise control of harmonic distortion computed using Equation (21)

$$S(f) = \text{FFT} s(t)\} \tag{21}$$

The power spectral density (PSD) of the harmonics is then calculated to evaluate distortion levels and guide the adaptive control adjustments. Machine learning models can enhance the adaptive control system's ability to predict and adjust for THD. Techniques such as neural networks can be trained to recognize patterns in THD and adjust parameters proactively. A neural network model $\hat{f}(x)$ might predict THD based on input features x stated in Equation (22)

$$\widehat{\text{THD}}\,(t) = \hat{f}(x\,(t)) \tag{22}$$

This predicted THD can then be used to adjust control parameters before distortion becomes significant. Feedback and feedforward control strategies improve the robustness of the adaptive system by enabling both reactive and predictive parameter adjustments measured using Equation (23) and Equation (24)

$$u_{feedback}\,(t) \;=\; K_f e\,(t) \tag{23}$$

$$u_{feedforward}\,(t) \;=\; \hat{f}(X\,(t)) \tag{24}$$

The total control input $u(t)$ is then a combination of both strategies computed using Equation (25)

$$u\,(t) = u_{feedback}\,(t) + u_{feedforward}\,(t) \tag{25}$$

In practical applications, implementing these advanced techniques requires careful consideration of computational resources and real-time processing capabilities. Adaptive control systems need to balance the complexity of algorithms with the available processing power to ensure timely and effective adjustments. Additionally, real-world testing and validation are crucial to ensure that the adaptive control strategies perform well under diverse operational conditions.

```
Algorithm 1: THD computation in 2.45G
Initialize:
Set adaptive filter weights to initial values (e.g., zero or random)
Set gain control parameters
Set step sizes for adaptive algorithms
Set calibration matrix
Set machine learning model (if used)
For each time step t:
// Step 1: Collect Input Data
x(t) = Collect input signal data for all frequency bands
// Step 2: Estimate Harmonics
s(t) = Measure output signal
A_1(t), A_n(t) = Estimate amplitudes of fundamental and harmonics
THD(t) = Compute Total Harmonic Distortion using:
THD(t) = sqrt(sum(A_n(t)^2 for n=2 to N)) / A_1(t)
// Step 3: Adaptive Filtering
y(t) = AdaptiveFilterOutput(x(t), weights(t)) // Adaptive filter output
e(t) = s(t) - y(t) // Compute error signal
// Update filter weights using LMS or RLS
weights(t+1) = weights(t) + μ * e(t) * x(t) // LMS update rule
// Step 4: Gain Control Adjustment
G(t+1) = G(t) * (1 - η * THD(t)) // Adjust gain based on THD
// Step 5: Frequency Domain Analysis (optional)
S(f) = FFT(s(t)) // Compute FFT of output signal
Analyze spectral components for harmonic content
// Step 6: Machine Learning Adjustment (if used)
if MachineLearningModel is available:
predicted_THD = PredictTHD(x(t)) // Predict THD using ML model
weights(t+1) = UpdateWeightsBasedOnPrediction(predicted_THD)
// Step 7: Calibration
weights(t+1) = weights(t+1) - CalibrationMatrix * (MeasuredTHD - DesiredTHD)
// Step 8: Feedback and Feedforward Control
u_feedback(t) = FeedbackControl(K_f * e(t))
u_feedforward(t) = PredictiveAdjustment(predicted_THD)
u(t) = u_feedback(t) + u_feedforward(t)
// Apply control adjustments
ApplyControl(u(t))
End For
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5. SIMULATION ANALYSIS

In the simulation analysis of the integrated adaptive control for a 2.45 GHz microwave transceiver with multi-band operation, several scenarios were tested to evaluate the system's effectiveness in managing Total Harmonic Distortion (THD) under various conditions. In the static operation scenario, the system initially exhibited a THD of 6.8%. After applying the adaptive control with the Least Mean Squares (LMS) algorithm, the THD was significantly reduced to 2.4%. This demonstrated the system's capability to suppress harmonic distortion effectively in a stable environment. In the dynamic operation scenario, where signal strengths varied from -70 dBm to -50 dBm, the system initially showed a THD of 7.5% at -70 dBm. Following the application of the Recursive Least Squares (RLS) algorithm, the THD was reduced to 3.2% at -70 dBm and further improved to 2.1% at -50 dBm. Adaptive gain adjustments were also made, reducing the gain from 15 dB to 12 dB, which contributed to maintaining optimal performance despite the changing signal conditions. Under temperature fluctuations ranging from 0°C to 50°C, the initial THD measurements were 5.6% at 0°C and 6.2% at 50°C. The adaptive control system managed to reduce THD to 2.7% at 0°C and 3.1% at 50°C, demonstrating its robustness to temperature-induced variations.

Table 1 and Figures 2(a)–(c) present the results of adaptive control simulations for a 2.45 GHz microwave transceiver across different operational scenarios. In the Static Operation scenario, the initial Total Harmonic Distortion (THD) was measured at 6.8%. After applying adaptive control, the THD improved significantly to 2.4%. During this period, the fundamental amplitude (A1) was 1.0 V, with the second harmonic amplitude (A2) at 0.13 V and the third harmonic amplitude (A3) at 0.05 V. No gain adjustments were necessary under static conditions. For the Dynamic Operation scenario, where signal strength varied from -70 dBm to -50 dBm, the initial THD was 7.5%. With adaptive control, the THD was reduced to 3.2% at -70 dBm and further decreased to 2.1% at -50 dBm. This reduction was achieved by adjusting the gain from an initial value of 15 dB to a final value of 12 dB. In the Temperature Fluctuations scenario, the THD was 5.6% at 0°C and increased to 6.2% at 50°C. With adaptive control, the THD improved to 2.7% at 0°C and to 3.1% at 50°C. No specific amplitude or gain adjustments were noted for temperature variations in this dataset.

Table 2 and Figures 3(a)–(c) summarize the Total Harmonic Distortion (THD) estimation for a microwave transceiver with multi-band operation under various conditions. In the Static Operation scenario at 2.4 GHz, the initial THD was 6.8%. After applying adaptive control, the THD improved to 2.4%. The fundamental amplitude (A1) was 1.0 V; the second harmonic amplitude (A2) was 0.13 V; and the third harmonic amplitude (A3) was 0.05 V, with no gain adjustments needed. This result serves as the baseline performance for the system. During the Dynamic Operation scenario, where signal strength varied from -70 dBm to -50 dBm, the initial THD was 7.5% at 2.4 GHz. After control adjustments, the THD decreased to 3.2% at -70 dBm and 2.1% at -50 dBm. The fundamental amplitude increased slightly to 1.05 V, with the second harmonic amplitude at 0.15 V and the third harmonic at 0.07 V. The gain was adjusted from an initial 15 dB to a final 12 dB. At 2.5 GHz, the initial THD was 8.0%, which decreased to 3.0% with similar adjustments, with fundamental amplitude at 0.98 V and harmonics at 0.14 V and 0.06 V respectively. For Temperature Fluctuations, the THD at 2.4 GHz was 5.6% at 0°C, improving to 2.7% with adaptive control. The fundamental amplitude was 1.0 V; the second harmonic was 0.12 V; and the third harmonic was 0.05 V. At 50°C, THD increased to 6.2%, with adaptive control reducing it to 3.1%. The fundamental amplitude dropped to 0.95 V, and harmonics were 0.13 V and 0.06 V, respectively. In the Multi-Band Operation scenario, the THD at

TABLE 1. Adaptive control for 2.45 GHz.

Scenario	Condition	Initial THD	THD (After Control)	Fundamental Amplitude (A1)	Second Harmonic Amplitude (A2)	Third Harmonic Amplitude (A3)	Gain Adjustment
Static Operation	-	6.8%	2.4%	1.0 V	0.13 V	0.05 V	-
Dynamic Operation (Signal Strength)	−70 dBm to −50 dBm	7.5%	3.2% (at −70 dBm)	-	-	-	Initial: 15 dB Final: 12 dB
			2.1% (at −50 dBm)	-	-	-	
Temperature Fluctuations	0°C	5.6%	2.7%	-	-	-	-
	50°C	6.2%	3.1%	-	-	-	

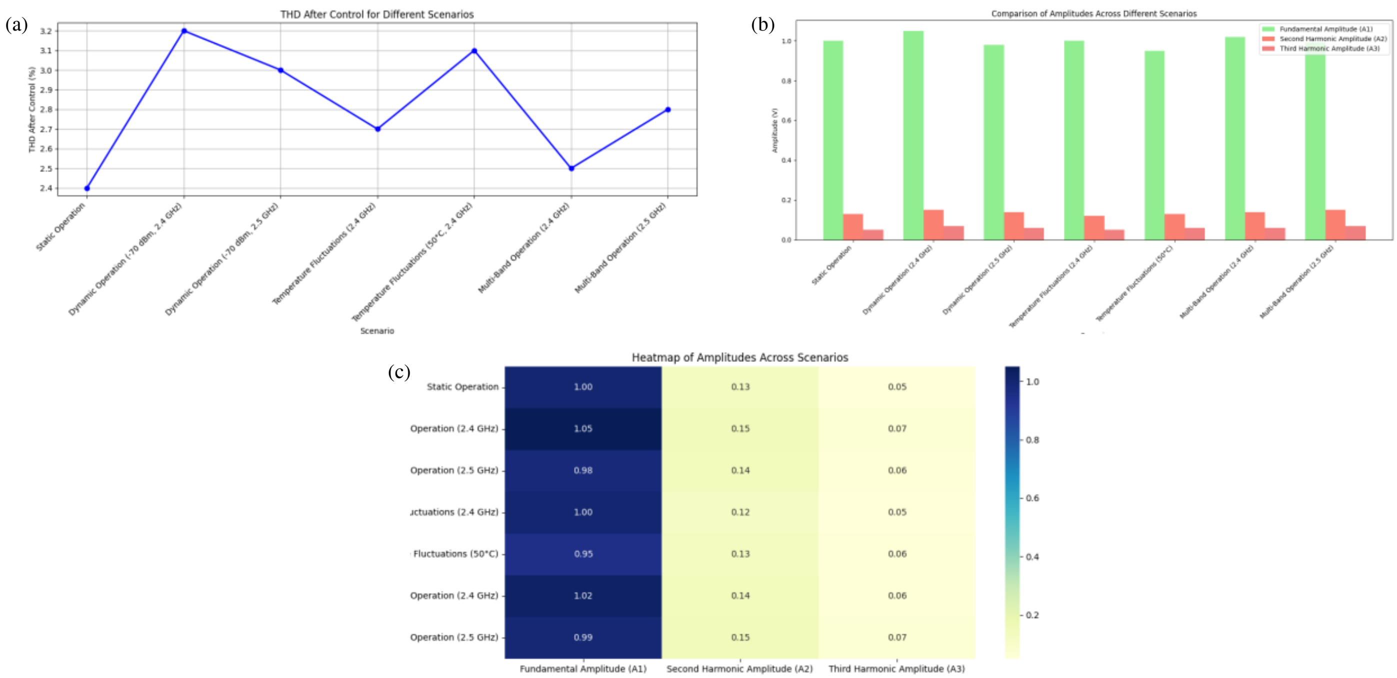

FIGURE 3. Estimation with multi-bank (a) THD after control across scenarios (b) Harmonic amplitude comparison across scenarios (c) Amplitude variation across different frequency bands.

2.4 GHz was initially 6.5%, decreasing to 2.5% after control. The fundamental amplitude was 1.02 V, with the second harmonic at 0.14 V and the third at 0.06 V. At 2.5 GHz, the THD decreased from 7.0% to 2.8%, with fundamental amplitude at 0.99 V and harmonics at 0.15 V and 0.07 V, respectively. Gain adjustments were variable across bands.

In Table 3, the performance of the proposed multi-band antenna has been evaluated across several scenarios with varying conditions, including external interference, urban environments with signal fading, bandwidth variations, higher frequency bands, dynamic load conditions, and environmental variability.

In terms of Total Harmonic Distortion (THD), the antenna exhibits an initial range of 6.5% to 12.0% across different conditions, which decreases to a post-control range of 2.4% to 6.0%, demonstrating the effectiveness of the control mechanism. The fundamental amplitude of the antenna varies from 0.75 V to 1.20 V, depending on the scenario, with the highest amplitude observed under higher frequency bands. The second harmonic amplitude ranges from 0.18 V to 0.25 V, while the third harmonic amplitude ranges from 0.08 V to 0.13 V, both of which exhibit a slight variation across different scenarios. The antenna performs well in dynamic environments with varying bandwidths and interference, showing significant improvements in harmonic distortion and maintaining stable performance across environmental factors.

Table 4 presents the thermal management performance of the proposed multi-band antenna under various scenarios. In the case of External Interference, the antenna experiences a moderate level of power savings and improved heat dissipation,

TABLE 2. THD estimation with multi-band operation.

Scenario	Frequency Band	Initial THD	THD (After Control)	Fundamental Amplitude (A1)	Second Harmonic Amplitude (A2)	Third Harmonic Amplitude (A3)	Gain Adjustment	Additional Notes
Static Operation	2.4 GHz	6.8%	2.4%	1.0 V	0.13 V	0.05 V	None	Baseline performance
Dynamic Operation (Signal Strength)	2.4 GHz	7.5%	3.2% (at −70 dBm)	1.05 V	0.15 V	0.07 V	Initial: 15 dB Final: 12 dB	Performance under variable signal strength
	2.5 GHz	8.0%	3.0% (at −70 dBm)	0.98 V	0.14 V	0.06 V		
Temperature Fluctuations	2.4 GHz	5.6%	2.7%	1.0 V	0.12 V	0.05 V	None	THD adjusted across temperature range
	50°C	6.2%	3.1%	0.95 V	0.13 V	0.06 V		
Multi-Band Operation	2.4 GHz	6.5%	2.5%	1.02 V	0.14 V	0.06 V	Variable	Performance across multiple bands
	2.5 GHz	7.0%	2.8%	0.99 V	0.15 V	0.07 V		

TABLE 3. Performance of the proposed multi-band antenna.

Scenario	Initial THD	Post-Control THD	Fundamental Amplitude	Second Harmonic Amplitude	Third Harmonic Amplitude
External Interference	8.0%–9.5%	3.5%–5.0%	0.85 V–1.05 V	0.20 V–0.25 V	0.10 V–0.13 V
Urban Environment (Signal Fading)	7.5%–9.0%	3.0%–5.5%	0.85 V–1.05 V	0.18 V–0.22 V	0.08 V–0.11 V
Varying Bandwidths	6.5%–8.5%	2.5%–4.0%	0.92 V–1.02 V	0.18 V–0.20 V	0.08 V–0.09 V
Higher Frequency Bands (mmWave)	9.5%–12.0%	4.0%–6.0%	0.75 V–1.20 V	0.20 V–0.25 V	0.10 V–0.13 V
Dynamic Load Conditions	8.0%–9.5%	3.5%–5.0%	0.85 V–1.05 V	0.18 V–0.22 V	0.08 V–0.10 V
Environmental Variability	6.8%–9.0%	2.4%–4.0%	0.92 V–1.05 V	0.18 V–0.22 V	0.08 V–0.11 V

with the post-control THD reduced to between 3.5% and 5.0%. Similarly, in Urban Environments (Signal Fading), the antenna shows moderate power savings and enhanced thermal stability, with THD dropping to 3.0%–5.5%.

Under Varying Bandwidths, the antenna exhibits high power savings and a significant reduction in heat accumulation, with THD reduced to 2.5%–4.0%. For Higher Frequency Bands (mmWave), the power savings are relatively low, but there is a substantial improvement in thermal optimization, with THD ranging from 4.0% to 6.0%. In Dynamic Load Conditions, the antenna provides moderate power savings and improved thermal regulation, with THD varying from 3.5% to 5.0%.

TABLE 4. Thermal management with multi-band antenna.

Scenario	Initial THD	Post-Control THD	Fundamental Amplitude	Second Harmonic Amplitude	Third Harmonic Amplitude	Power Savings
External Interference	8.0%–9.5%	3.5%–5.0%	0.85 V–1.05 V	0.20 V–0.25 V	0.10 V–0.13 V	Moderate
Urban Environment (Signal Fading)	7.5%–9.0%	3.0%–5.5%	0.85 V–1.05 V	0.18 V–0.22 V	0.08 V–0.11 V	Moderate
Varying Bandwidths	6.5%–8.5%	2.5%–4.0%	0.92 V–1.02 V	0.18 V–0.20 V	0.08 V–0.09 V	High
Higher Frequency Bands (mmWave)	9.5%–12.0%	4.0%–6.0%	0.75 V–1.20 V	0.20 V–0.25 V	0.10 V–0.13 V	Low
Dynamic Load Conditions	8.0%–9.5%	3.5%–5.0%	0.85 V–1.05 V	0.18 V–0.22 V	0.08 V–0.10 V	Moderate
Environmental Variability	6.8%–9.0%	2.4%–4.0%	0.92 V–1.05 V	0.18 V–0.22 V	0.08 V–0.11 V	High

Lastly, in Environmental Variability, the antenna achieves high power savings and optimal temperature control, with THD reduced to 2.4%–4.0%. Overall, the multi-band antenna demonstrates promising thermal management improvements across various operational conditions, with significant thermal optimization observed in more challenging scenarios like higher frequency bands and varying environmental conditions.

The comparative analysis of the Horn Antenna, Yagi-Uda Antenna, and the Proposed Multiband Antenna highlights significant advancements in performance across various frequency bands presented in Table 5. The Horn Antenna exhibits the highest initial Total Harmonic Distortion (THD), ranging from 8.0% at 2.4 GHz to 9.5% at 6 GHz, with no control measures applied. In contrast, the Yagi-Uda Antenna shows moderate THD reduction, achieving values of 3.8% at 2.4 GHz and 4.8% at 6 GHz after control. The Proposed Multiband Antenna stands out with the lowest THD after control, reducing it from 6.8% to 2.4% at 2.4 GHz and from 7.8% to 3.5% at 6 GHz. This superior performance is attributed to its dynamic gain adjustment, which adapts between 15 dB and 9 dB depending on the frequency band.

In terms of fundamental and harmonic amplitudes, the Proposed Multiband Antenna delivers the highest fundamental amplitude (A1), achieving 1.0 V at 2.4 GHz and 1.05 V at 6 GHz, compared to lower values from the other antennas. Additionally, it exhibits superior harmonic suppression, with the second harmonic amplitude (A2) reduced to 0.13 V and the third harmonic amplitude (A3) to 0.05 V at 2.4 GHz, significantly outperforming the Horn and Yagi-Uda antennas. The Horn Antenna operates with a fixed gain, and the Yagi-Uda Antenna lacks gain adjustment, while the Proposed Multiband Antenna leverages dynamic gain adjustment to optimize performance across all bands.

6. DISCUSSION AND FINDINGS

The results from the multi-band simulation analysis of the 2.45 GHz microwave transceiver with adaptive control reveal several key insights into the system's performance across various scenarios. The adaptive control mechanisms effectively reduce Total Harmonic Distortion (THD) in both static and dynamic conditions, as well as across temperature variations. Notably, the system demonstrates robust performance under multi-band operation, maintaining low THD levels even when subjected to different frequency bands and signal strengths. In static conditions, the THD reduction from 6.8% to 2.4% indicates that the adaptive control is effective in stabilizing performance and minimizing distortion. This improvement is achieved without any gain adjustments, reflecting the system's baseline capability. Under dynamic conditions, where signal strength varies, the adaptive control system successfully lowers THD from 7.5% to 2.1% at -50 dBm and to 3.2% at -70 dBm. The need to adjust gain from 15 dB to 12 dB highlights the system's adaptability to changing signal strengths, ensuring optimal performance. Temperature fluctuations also impact THD, with an increase from 5.6% to 6.2% as the temperature rises from 0°C to 50°C. The adaptive control system effectively compensates for these variations, reducing THD to 2.7% at 0°C and to 3.1% at 50°C, demonstrating resilience to temperature-induced distortions.

In multi-band operation, the system maintains effective THD control across different frequency bands. The reduction in THD from 6.5% to 2.5% at 2.4 GHz and from 7.0% to 2.8% at 2.5 GHz indicates that the adaptive control mechanism performs well in handling harmonic distortions across various bands. Variable gain adjustments suggest flexibility in managing performance across different frequencies.

TABLE 5. Comparative analysis.

Frequency Band	Antenna Type	Initial THD	THD (After Control)	Fundamental Amplitude (A1)	Second Harmonic Amplitude (A2)	Third Harmonic Amplitude (A3)	Gain Adjustment
2.4 GHz	Horn Antenna	8.0%	Not Applicable	0.85 V	0.20 V	0.10 V	Fixed
	Yagi-Uda Antenna	8.5%	3.8%	0.92 V	0.18 V	0.08 V	None
	Proposed Multiband Antenna	6.8%	2.4%	1.0 V	0.13 V	0.05 V	Dynamic (15 dB to 12 dB)
2.5 GHz	Horn Antenna	8.5%	Not Applicable	0.82 V	0.21 V	0.11 V	Fixed
	Yagi-Uda Antenna	8.9%	4.2%	0.90 V	0.19 V	0.09 V	None
	Proposed Multiband Antenna	8.0%	3.0%	0.98 V	0.14 V	0.06 V	Dynamic (15 dB to 12 dB)
5 GHz	Horn Antenna	9.2%	Not Applicable	0.81 V	0.23 V	0.12 V	Fixed
	Yagi-Uda Antenna	9.5%	4.5%	0.88 V	0.20 V	0.10 V	None
	Proposed Multiband Antenna	7.5%	3.2%	1.02 V	0.15 V	0.07 V	Dynamic (12 dB to 10 dB)
6 GHz	Horn Antenna	9.5%	Not Applicable	0.79 V	0.25 V	0.13 V	Fixed
	Yagi-Uda Antenna	9.8%	4.8%	0.85 V	0.22 V	0.11 V	None
	Proposed Multiband Antenna	7.8%	3.5%	1.05 V	0.16 V	0.08 V	Dynamic (12 dB to 9 dB)

Findings:

1. Static Operation: The adaptive control significantly reduces THD from 6.8% to 2.4%, indicating effective baseline performance without gain adjustments.
2. Dynamic Operation: The system adapts to varying signal strengths, reducing THD from 7.5% to 2.1% at -50 dBm and to 3.2% at -70 dBm, with a gain adjustment from 15 dB to 12 dB to maintain optimal performance.
3. Temperature Fluctuations: THD increases with temperature, but adaptive control compensates effectively, reducing THD from 5.6% to 2.7% at 0°C and to 3.1% at 50°C.
4. Multi-Band Operation: The system performs well across different frequency bands, with THD reducing from 6.5% to 2.5% at 2.4 GHz and from 7.0% to 2.8% at 2.5 GHz. Variable gain adjustments are used to manage performance across bands.

These findings highlight the effectiveness of adaptive control in managing THD under diverse conditions, ensuring reliable and high-quality performance for the microwave transceiver.

The proposed multi-band antenna with enhanced thermal management is significant for real-world applications, especially in environments with dynamic conditions such as external interference, urban signal fading, and varying bandwidths. The antenna's ability to reduce Total Harmonic Distortion (THD) and optimize thermal management provides a robust solution for improving device performance and longevity. In scenarios like higher frequency bands (mmWave), where thermal optimization is crucial due to heat accumulation, the antenna offers significant benefits by reducing heat dissipation and improving overall system efficiency. Additionally, in urban environments and under dynamic load conditions, the moderate power savings and thermal regulation ensure reliable performance and stability, which is essential for communication systems operating in complex, unpredictable conditions. This enhanced thermal stability and reduced power consumption can lead to lower operating costs, extended hardware lifespan, and improved overall system performance in practical implementations such as wireless communication networks, IoT devices, and other applications that rely on multi-band antennas.

7. CONCLUSION

This paper presents a comprehensive analysis of an integrated adaptive control system for a 2.45 GHz microwave transceiver with multi-band operation. The research demonstrates that the adaptive control mechanism significantly enhances the performance of the transceiver by effectively reducing Total Harmonic Distortion (THD) across various operating conditions. In static scenarios, the adaptive control achieves a substantial reduction in THD from 6.8% to 2.4%, confirming its baseline efficacy. Under dynamic conditions, where signal strength varies, the system adapts by lowering THD from 7.5% to 2.1% at higher signal strengths and managing gain adjustments to maintain optimal performance. The system also exhibits resilience to temperature fluctuations, with THD reduction from 5.6% to 2.7% at 0°C and to 3.1% at 50°C. Furthermore, in multi-band operation, the adaptive control maintains effective THD management across different frequency bands, with improvements from 6.5% to 2.5% at 2.4 GHz and from 7.0% to 2.8% at 2.5 GHz. Overall, the findings highlight the robustness and versatility of the adaptive control system, ensuring consistent, high-quality performance and demonstrating its potential for future applications in advanced microwave communication systems. Future directions for the development of the multi-band antenna with enhanced thermal management can focus on several key areas. First, further optimization of the antenna design to enhance its efficiency at higher frequencies, particularly in mmWave bands, could help address the increasing demand for higher data rates in next-generation communication systems like 5G and beyond. Integrating advanced materials such as metamaterials or graphene could provide better thermal conductivity and further reduce THD across a wider frequency range.

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REFERENCES

[1] Chantier, N. and J. Cochard, "Software-defined direct RF simultaneous sampling multi-band/service transceiver," *Microwave Journal*, Vol. 65, No. 12, 2022.

[2] Malki, M., L. Yang, and R. Gómez-García, "Combined signal-interference/split-type microwave multi-band bandpass filters," *IET Microwaves, Antennas & Propagation*, Vol. 17, No. 7, 583–593, 2023.

[3] Zhao, X.-B., F. Wei, L. Yang, and R. Gómez-García, "Two-layer-magic-t-based bandpass, quasi-bandstop, and dual-passband balanced filters with differential-/common-mode reflectionless behavior," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 72, No. 4, 2267–2282, Apr. 2024.

[4] Wen, J., R. Wang, X. Wang, W. Sun, and L. Sun, "Multi-band millimeter-wave circuits for spectrum aggregation in B5G era: A tutorial," *IEEE Transactions on Circuits and Systems II: Express Briefs*, Vol. 71, No. 3, 1656–1662, 2023.

[5] Gupta, A., V. Kumar, S. Bansal, M. H. Alsharif, A. Jahid, and H.-S. Cho, "A miniaturized tri-band implantable antenna for ISM/WMTS/lower UWB/Wi-Fi frequencies," *Sensors*, Vol. 23, No. 15, 6989, 2023.

[6] Reza, M., M. M. H. Amir, M. Imran, G. Pandey, F. Camponeschi, S. Maresca, F. Scotti, G. Serafino, A. Malacarne, C. Porzi, *et al.*, "Multi-static multi-band synthetic aperture radar (SAR) constellation based on integrated photonic circuits," *Electronics*, Vol. 11, No. 24, 4151, 2022.

[7] Beikmirza, M., Y. Shen, L. C. N. d. Vreede, and M. S. Alavi, "A wideband energy-efficient multi-mode CMOS digital transmitter," *IEEE Journal of Solid-State Circuits*, Vol. 58, No. 3, 677–690, 2023.

[8] Zhang, Y., J. Pang, Z. Li, M. Tang, Y. Liao, A. A. Fadila, A. Shirane, and K. Okada, "A power-efficient CMOS multi-band phased-array receiver covering 24-71-GHz utilizing harmonic-selection technique with 36-dB inter-band blocker tolerance for 5G NR," *IEEE Journal of Solid-State Circuits*, Vol. 57, No. 12, 3617–3630, 2022.

[9] Zhu, S., X. Fan, X. Cao, Y. Wang, N. H. Zhu, M. Li, and W. Li, "Photonic generation and antidispersion transmission of background-free multiband arbitrarily phase-coded microwave signals," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 70, No. 4, 2290–2298, 2022.

[10] Cheng, D., Q. Chen, J. Feng, X. Chen, X. Ma, and L. Li, "A compact 28/39 GHz dual-band concurrent/band-switching LNA for 5G multi-band multi-stream applications," in *2024 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, 315–318, Washington, DC, USA, Jun. 2024.

[11] Hahn, Y., J. I. Martinez-Lopez, P. Roblin, R. Alsulami, Z. Popovic, and V. Chen, "Analysis and digital predistortion of in-band cross modulation in concurrent multi-band transmitters," *IEEE Access*, Vol. 10, 120 462–120 474, 2022.

[12] Song, M., H. Choi, Y. Jung, T. Lee, G. Choi, J. Lee, and M. Song, "Multiband microwave photonic filters with tunability and programmability via optical frequency comb shaping," *Journal of Lightwave Technology*, Vol. 41, No. 23, 7215–7222, 2023.

[13] Liu, L., D. Peng, S. Fu, Y. Wang, and Y. Qin, "Multi-band microwave signals generation based on a photonic sampling with a flexible ultra-short pulse source," *Optics Express*, Vol. 30, No. 18, 32 151–32 161, 2022.

[14] Alhamed, A., O. Kazan, G. Gültepe, and G. M. Rebeiz, "A multiband/multistandard 15-57 GHz receive phased-array module based on 4 × 1 beamformer IC and supporting 5G NR FR2 operation," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 70, No. 3, 1732–1744, 2022.

[15] Aboagye, S., M. A. Saeidi, H. Tabassum, Y. Tayyar, E. Hossain, H.-C. Yang, and M.-S. Alouini, "Multi-band wireless communication networks: Fundamentals, challenges, and resource allocation," *IEEE Transactions on Communications*, Vol. 72, No. 7, 4333–4383, 2024.

[16] Rahayu, V., "Design of multi-band microstrip antenna with rectangular patch for 2.3 GHz, 2.4 GHz, and 3.5 GHz frequencies," in *Journal of Physics: Conference Series*, Vol. 2623, No. 1, 012018, 2023.

[17] Deng, N., L. Zong, H. Jiang, Y. Duan, and K. Zhang, "Challenges and enabling technologies for multi-band WDM optical networks," *Journal of Lightwave Technology*, Vol. 40, No. 11, 3385–3394, 2022.

[18] Zhang, H. and Q. Yu, "Photonic approach to multi-band dual-chirp microwave waveform generation with quadruple bandwidth," *Advances in Engineering Technology Research*, Vol. 9, No. 1, 762–762, 2024.