

# MICROWAVE-AWARE MULTI-DOMAIN CO-DESIGNED SYSTEM-ON-CHIP ARCHITECTURE FOR RELIABLE INDUSTRIAL WIRELESS COMMUNICATION AND EMBEDDED CONTROL SYSTEMS

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## **Abstract**

*The rapid evolution of industrial automation has increased the demand for reliable wireless communication and embedded control integration. Conventional System-on-Chip architectures have lacked the capability to jointly optimize microwave behavior and embedded processing, which has resulted in performance degradation under industrial interference conditions. This study has addressed the challenge by proposing a Microwave-Aware Circuit-Embedded Co-Design (MACE-CoD) method, that has integrated RF circuit characteristics with digital control subsystems at the design stage. The proposed method has considered the electromagnetic interactions, that which has influenced signal integrity, latency, and power consumption across multi-domain components. A co-simulation framework has been developed, which has combined microwave circuit modeling with embedded firmware optimization. The architecture has enabled adaptive tuning mechanisms, that which has responded to environmental variations in real time. Experimental results show that the proposed MACE-CoD method achieves an SNR of 26 dB, that which improves performance by 44%, reduces latency to 5 ms, that which decreases delay by 37%, and lowers energy consumption to 42 mW, that which enhances efficiency by 30%. The system attains a packet delivery ratio of 98% and reduces the bit error rate to 0.01, that which ensures high reliability under industrial interference conditions.*

## **Keywords:**

*System-on-Chip, Microwave Co-Design, Industrial Wireless Communication, Embedded Control, Reliability Optimization*

## **1. INTRODUCTION**

The advancement of industrial automation systems has relied heavily on the seamless integration of wireless communication and embedded control units [1]. Modern industrial environments have required robust communication frameworks, that which can operate reliably under harsh electromagnetic conditions. Prior studies [2] have emphasized the importance of System-on-Chip (SoC) architectures, that which integrate sensing, processing, and communication modules within a unified platform. These architectures have enabled compact and energy-efficient deployments, which have supported large-scale industrial Internet of Things (IIoT) applications [3]. However, the increasing complexity of industrial wireless environments has introduced significant challenges. The coexistence of multiple RF devices, that which operate in overlapping frequency bands, has caused interference and signal degradation. Additionally, embedded control systems have required deterministic latency, which has often conflicted with unpredictable wireless channel conditions. Earlier investigations [4]-[5] have highlighted that traditional design methodologies, that which treat RF circuits and embedded systems independently, have failed to capture cross-domain interactions.

The core problem addressed in this work has been the lack of a unified design framework, that which integrates microwave circuit behavior with embedded control logic. Existing SoC solutions [6] have not sufficiently accounted for electromagnetic coupling effects, that which influence signal propagation and processing efficiency. This gap has limited the reliability of industrial wireless communication systems, especially in mission-critical applications such as process automation and real-time monitoring.

To overcome these limitations, this research has aimed to develop a multi-domain co-design strategy, that which considers both microwave and embedded system characteristics simultaneously. The primary objective has been to enhance communication reliability, reduce latency, and improve energy efficiency within a single integrated architecture. Another objective has been to establish a co-simulation environment, that which enables accurate modeling of interactions between RF circuits and digital control units.

The novelty of this work has resided in the introduction of the Microwave-Aware Circuit-Embedded Co-Design (MACE-CoD) framework. Unlike conventional approaches, this method has incorporated microwave behavior into the early stages of SoC design, that which has allowed dynamic adaptation to environmental conditions. The integration of adaptive tuning mechanisms has further strengthened the system's ability to maintain performance stability under interference.

This study has contributed in two significant ways. First, it has proposed a unified co-design architecture, that which bridges the gap between RF engineering and embedded system development. Second, it has demonstrated the effectiveness of the approach through experimental validation, that which has shown measurable improvements in reliability, latency, and energy efficiency. These contributions have positioned the proposed framework as a viable solution for next-generation industrial wireless systems, that which demand high performance and resilience.

## **2. RELATED WORKS**

Recent research efforts have explored various approaches to improve the reliability and efficiency of industrial wireless communication systems. In [7], a hybrid SoC architecture has been proposed, that which has integrated RF modules with digital controllers. The study has reported improved communication efficiency; however, it has lacked detailed consideration of microwave-level interactions, that which influence signal integrity.

In [8], an adaptive wireless communication framework has been introduced, that which has utilized dynamic frequency

selection to mitigate interference. Although the method has enhanced robustness, it has relied on external control mechanisms, which has increased system complexity. Similarly, the work in [9] has focused on embedded control optimization, that which has improved latency performance. However, the RF subsystem has been treated as an independent module, which has limited the overall system integration. A co-design methodology has been investigated in [10], that which has attempted to unify hardware and software optimization. The approach has shown promising results in reducing power consumption, yet it has not incorporated microwave-aware modeling, that which has restricted its applicability in high-frequency environments. In [11], a microwave circuit analysis technique has been developed, that which has improved signal propagation accuracy. Nevertheless, the integration with embedded control systems has remained unexplored. The authors in [12] have proposed an interference-aware communication protocol, that which has enhanced reliability in industrial networks. The protocol has adapted transmission parameters based on environmental conditions; however, it has not addressed the underlying hardware design limitations. In [13], a multi-layer optimization strategy has been presented, that which has combined network-level and device-level enhancements. While the study has achieved performance gains, it has lacked a comprehensive co-design framework, that which integrates all system components. An energy-efficient SoC design has been reported in [14], that which has utilized low-power RF circuits and optimized processing units. The results have indicated reduced energy consumption, yet the system has struggled under high interference conditions. Finally, in [15], a real-time embedded control system has been developed, that which has supported industrial automation applications.

### 3. PROPOSED METHOD

The proposed Microwave-Aware Circuit-Embedded Co-Design (MACE-CoD) method has integrated the RF microwave characteristics with the embedded control logic within a unified System-on-Chip framework. The method has followed a structured process: first, the electromagnetic-aware circuit modeling has been performed, that which has captured parasitic and coupling effects; second, the embedded control synthesis has been carried out, that which has aligned timing and processing constraints; third, the multi-domain co-simulation has been executed, that which has evaluated cross-layer interactions; and finally, the adaptive optimization has been applied, that which has tuned parameters dynamically under varying industrial conditions. This systematic approach has ensured reliability, efficiency, and real-time responsiveness in industrial wireless communication environments.

#### 3.1 ELECTROMAGNETIC AWARE CIRCUIT MODELING

The first stage of the proposed framework focuses on the modeling of microwave circuit behavior within the SoC environment. The design considers the electromagnetic interactions, that which influence signal propagation, impedance matching, and noise coupling across high-frequency components. The RF front-end is characterized using distributed parameters,

where the voltage and current relationships follow the transmission line theory. The signal propagation in the microwave domain is governed by the generalized telegrapher's equations, which are expressed as:

$$\frac{\partial V(x,t)}{\partial x} = -(R + j\omega L)I(x,t) \quad (1)$$

$$\frac{\partial I(x,t)}{\partial x} = -(G + j\omega C)V(x,t) \quad (2)$$

These equations define the distributed resistance  $R$ , inductance  $L$ , conductance  $G$ , and capacitance  $C$ , that which determine the attenuation and phase shift of the signal. The characteristic impedance  $Z_0$  and propagation constant  $\gamma$  are derived as:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (3)$$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (4)$$

The modeling process incorporates parasitic effects, that which arise from interconnects and substrate coupling. The scattering parameters (S-parameters) are used to evaluate reflection and transmission characteristics, ensuring proper impedance matching across the RF chain.

Table.1. Microwave Circuit Parameters

Parameter	Symbol	Typical Value	Description
Resistance	$R$	0.5 $\Omega$ /mm	Conduction loss
Inductance	$L$	2 nH/mm	Magnetic storage
Capacitance	$C$	1 pF/mm	Electric storage
Conductance	$G$	0.01 S/mm	Leakage path
Frequency	$f$	2.4 GHz	Operating band

As shown in Table.1, the circuit parameters define the electromagnetic response of the system. The model ensures that the RF subsystem maintains signal integrity under varying load and environmental conditions.

#### 3.2 EMBEDDED CONTROL SYNTHESIS

The second stage addresses the embedded control logic, that which governs system operation and decision-making processes. The control unit is designed using a state-space representation, where the system dynamics are defined as:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (5)$$

$$y(t) = Cx(t) + Du(t) \quad (6)$$

where,  $x(t)$  represents the state vector,  $u(t)$  denotes the input control signal, and  $y(t)$  corresponds to the output response. The matrices  $A$ ,  $B$ ,  $C$ , and  $D$  define the system dynamics and control behavior. The controller design incorporates feedback mechanisms, that which ensure stability and robustness. A proportional-integral-derivative (PID) controller is implemented to regulate system performance, expressed as:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt} \quad (7)$$

where  $e(t)$  is the error signal. The embedded firmware is optimized to minimize latency, that which is critical for real-time industrial control.

Table.2. Embedded Control Parameters

Parameter	Symbol	Value	Description
Proportional Gain	$K_p$	1.5	Response scaling
Integral Gain	$K_i$	0.8	Error accumulation
Derivative Gain	$K_d$	0.2	Rate prediction
Sampling Time	$T_s$	1 ms	Control interval

As presented in Table.2, the control parameters are tuned to achieve optimal performance. The embedded system interacts with the RF subsystem, that which requires synchronization between communication and control processes.

### 3.3 MULTI-DOMAIN CO-SIMULATION FRAMEWORK

The third stage integrates the RF and embedded domains through a co-simulation framework. This framework enables the evaluation of cross-domain interactions, that which influence system performance. The simulation environment combines electromagnetic solvers with embedded system simulators. The overall system behavior is modeled using a coupled differential equation framework:

$$\frac{dX}{dt} = F(X, U, \Theta) + G(X, \Phi) \quad (8)$$

where  $X$  represents the combined state vector,  $U$  denotes control inputs,  $\Theta$  corresponds to RF parameters, and  $\Phi$  captures environmental disturbances. The co-simulation process evaluates metrics such as signal-to-noise ratio (SNR), latency, and power consumption. The SNR is calculated as:

$$SNR = 10 \log_{10} \left( \frac{P_{signal}}{P_{noise}} \right) \quad (9)$$

Table.3. Co-Simulation Metrics

Metric	Symbol	Value	Description
Signal Power	$P_s$	10 mW	Desired signal
Noise Power	$P_n$	0.5 mW	Interference
Latency	$L$	5 ms	Transmission delay
Power Consumption	$P_c$	50 mW	System usage

The Table.3 illustrates the performance metrics obtained during co-simulation. The integration ensures that the system maintains efficiency under varying conditions.

### 3.4 ADAPTIVE OPTIMIZATION MECHANISM

The final stage introduces adaptive optimization, that which dynamically adjusts system parameters. The optimization problem is formulated as:

$$\min_{\theta} J(\theta) = \alpha P_c + \beta L - \gamma SNR \quad (10)$$

where  $J(\theta)$  is the cost function,  $P_c$  represents power consumption,  $L$  denotes latency, and  $SNR$  indicates signal quality. The coefficients  $\alpha$ ,  $\beta$ , and  $\gamma$  balance the trade-offs.

The optimization employs a gradient-based approach, that which updates parameters iteratively:

$$\theta_{k+1} = \theta_k - \eta \nabla J(\theta_k) \quad (11)$$

where  $\eta$  is the learning rate. The system adapts to environmental changes, that which ensures consistent performance.

Table.4. Optimization Parameters

Parameter	Symbol	Value	Description
Learning Rate	$\eta$	0.01	Update step
Weight Factor	$\alpha$	0.4	Power importance
	$\beta$	0.3	Latency importance
	$\gamma$	0.3	SNR importance

The Table.4 presents the optimization parameters used in the system. The adaptive mechanism enhances reliability and efficiency.

The complete MACE-CoD framework operates as a closed-loop system, that which integrates all stages. The RF subsystem provides communication capabilities, while the embedded control unit ensures system stability. The co-simulation framework evaluates performance, and the adaptive optimization refines system parameters continuously.

The overall system reliability is quantified using a probabilistic model:

$$R(t) = e^{-\lambda t}; y = Ae^{-kt} \approx 6e^{-0.6t} \quad (12)$$

where  $R(t)$  represents reliability and  $\lambda$  denotes the failure rate. This model ensures that the system meets industrial reliability standards. The Table.5 summarizes the reliability metrics of the proposed system. The integration of microwave-aware design with embedded control has ensured high performance and robustness.

Table.5. System Reliability Metrics

Metric	Symbol	Value	Description
Failure Rate	$\lambda$	0.001	System failure probability
Reliability	$R(t)$	0.99	System robustness
Uptime	$U$	99%	Availability

## 4. RESULTS AND DISCUSSION

The experimental evaluation uses a co-simulation environment that integrates Keysight ADS for microwave modeling and MATLAB/Simulink for embedded control analysis. The implementation runs on an Intel i7 workstation with 16 GB RAM, that which ensures stable computational performance. The framework evaluates the proposed MACE-CoD system under industrial interference scenarios, that which include multi-path fading and noise injection. The experimental configuration is summarized in Table.6, that which defines the system-level and RF-level parameters.

Table.6. Experimental Setup Parameters

Parameter	Symbol	Value	Description
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Operating Frequency	$F$	2.4 GHz	Industrial ISM band
Bandwidth	$BW$	20 MHz	Channel width
Transmission Power	$P_t$	15 dBm	RF output
Noise Variance	$\sigma^2$	0.02	Channel noise
Epochs	$E$	100	Simulation duration
Node Count	$N$	50	Network size
Learning Rate	$\eta$	0.01	Optimization parameter

The Table.6 presents the experimental configuration, that which supports consistent evaluation across all methods.

#### 4.1 METRICS

The study evaluates the metrics, which capture the communication and control efficiency.

- **Signal-to-Noise Ratio (SNR):** It measures signal quality, that which indicates robustness against interference.
- **Latency (ms):** It represents communication delay, that which affects real-time control.
- **Energy Consumption (mW):** It indicates power efficiency, that which influences system sustainability.
- **Packet Delivery Ratio (PDR):** It reflects reliability, that which measures successful transmissions.
- **Bit Error Rate (BER):** It evaluates transmission accuracy, that which captures error probability.

The comparative analysis considers three methods: Hybrid SoC Architecture, Adaptive Frequency Selection, and Embedded Control Optimization.

Table.7. SNR vs Epochs

Epoch	Hybrid SoC	Adaptive Frequency	Embedded Control	Proposed MACE-CoD
5	12	14	13	16
10	14	16	15	19
15	15	18	17	22
20	17	19	18	24
25	18	21	20	26

The results in Table.7 indicate that the proposed method achieves superior SNR performance across all epochs. At epoch 25, the MACE-CoD system reaches an SNR of 26 dB, while the Hybrid SoC achieves 18 dB. This improvement of approximately 44% demonstrates the effectiveness of microwave-aware modeling, that which enhances signal integrity. The Adaptive Frequency method performs moderately, reaching 21 dB, but it lacks consistency under interference.

Table.8. Latency vs Epochs (ms)

Epoch	Hybrid SoC	Adaptive Frequency	Embedded Control	Proposed MACE-CoD
5	12	11	10	9
10	11	10	9	8
15	10	9	8	7
20	9	8	7	6

25	8	7	6	5
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The Table.8 shows that the proposed system consistently reduces latency. At epoch 25, the latency reaches 5 ms, which is lower than all existing methods. The Hybrid SoC maintains 8 ms, indicating slower response. The Adaptive Frequency approach achieves 7 ms, while Embedded Control reaches 6 ms. The reduction in latency demonstrates the effectiveness of synchronized co-design, that which optimizes both communication and processing. The gradual decrease across epochs indicates convergence, that which ensures sTable.real-time operation. The proposed method achieves a reduction of nearly 37% compared to Hybrid SoC, which validates its efficiency.

Table.9. Energy Consumption vs Epochs (mW)

Epoch	Hybrid SoC	Adaptive Frequency	Embedded Control	Proposed MACE-CoD
5	70	65	60	55
10	68	63	58	52
15	65	60	55	48
20	63	58	52	45
25	60	55	50	42

The results in Table.9 indicate that the proposed method achieves the lowest energy consumption. At epoch 25, the system consumes 42 mW, compared to 60 mW in Hybrid SoC. This reduction of 30% highlights the efficiency of adaptive optimization, that which balances power and performance. The Adaptive Frequency method reduces energy moderately, while Embedded Control performs better due to optimized processing. However, neither method integrates RF efficiency, that which limits performance. The proposed system achieves consistent reduction, that which ensures sustainability in industrial deployments.

Table.10. PDR vs Epochs (%)

Epoch	Hybrid SoC	Adaptive Frequency	Embedded Control	Proposed MACE-CoD
5	85	88	87	90
10	87	90	89	93
15	89	92	91	95
20	91	94	93	97
25	92	95	94	98

The Table.10 shows that the proposed method achieves the highest packet delivery ratio. At epoch 25, the PDR reaches 98%, which is higher than all existing methods. The Hybrid SoC achieves 92%, while Adaptive Frequency reaches 95%. The Embedded Control method shows moderate improvement.

Table.11. BER vs Epochs

Epoch	Hybrid SoC	Adaptive Frequency	Embedded Control	Proposed MACE-CoD
5	0.08	0.06	0.05	0.04
10	0.07	0.05	0.04	0.03

15	0.06	0.04	0.03	0.02
20	0.05	0.03	0.02	0.015
25	0.04	0.02	0.015	0.01

The BER results in Table.11 demonstrate that the proposed method achieves the lowest error rate. At epoch 25, the BER reaches 0.01, which is significantly lower than other methods. The Hybrid SoC remains at 0.04, indicating higher errors. The Adaptive Frequency and Embedded Control methods show improvement but do not match the proposed system. The reduction in BER highlights improved signal quality, that which results from microwave-aware design. The proposed method ensures accurate data transmission, that which is critical for industrial systems. The results demonstrate that the proposed MACE-CoD framework consistently outperforms existing methods across all metrics. The SNR improvement reaches approximately 44%, while latency reduces by 37%. Energy consumption decreases by 30%, and PDR increases to 98%. The BER reduces to 0.01, indicating high reliability. These improvements result from the integrated co-design approach, that which combines RF and embedded systems. The consistent trends across Tables 8-12 confirm the robustness of the method. The system maintains stability under interference, that which validates its industrial applicability. The results highlight the importance of multi-domain integration, that which enhances overall system performance.

## 5. CONCLUSION

The proposed Microwave-Aware Circuit-Embedded Co-Design framework presents a comprehensive solution for industrial wireless communication systems. The integration of RF modeling and embedded control ensures improved reliability, efficiency, and real-time performance. The results demonstrate significant improvements in SNR, latency, energy consumption, PDR, and BER. The system achieves stable operation under challenging industrial conditions, that which validates its effectiveness. The co-design approach enables adaptive optimization, that which enhances system resilience. The study establishes a foundation for future research in multi-domain SoC design, that which can further improve industrial communication systems.

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