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BoM Reduction for the 5G Radio Unit

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Abstract

This paper explores strategies for reducing the bill of materials (BoM) in 5G massive MIMO radio units, with a focus on optimizing RF component integration while maintaining performance standards. We examine the architecture of Argo Semiconductors product series "AS0102" RF-sampling companion IC and analyze challenges related to electromagnetic interference (EMI) and crosstalk that arise from passive component coupling. Through comprehensive EM simulations, we identify key factors influencing TX-TX and RX-RX isolation, such as transformer placement and decoupling capacitor positioning. Our findings suggest that carefully managing floor planning and signal integrity can significantly improve isolation, enabling efficient BoM reduction without compromising on system performance. The insights from this study provide valuable guidelines for the design of future 5G radio units.

1 Introduction

Massive Multiple Input Multiple Output (m-MIMO) is a key enabler for the advancement of 5G cellular communications, providing higher capacity, improved coverage, and enhanced spectral efficiency. As the demand for 5G continues to expand, optimizing the infrastructure of m-MIMO systems, particularly in the sub-6GHz band, is crucial for reducing costs and facilitating widespread adoption.

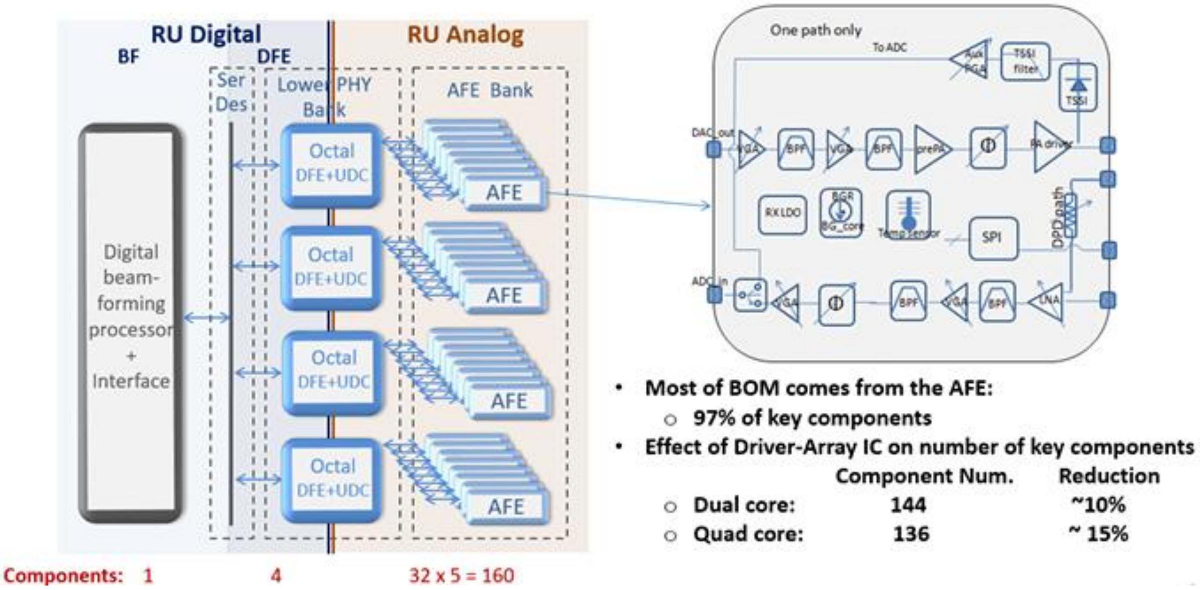
One critical area of optimization is the Bill of Materials (BOM) for the radio unit, where reducing the number of RF components plays a pivotal role in packing a large number of radios into a single radio unit. Achieving this requires sophisticated integration techniques that condense multiple RF functions into fewer integrated circuit (IC) packages or even a smaller number of dies. However, this high level of integration introduces several challenges, such as noise coupling and increased heat dissipation, which can degrade system performance if not properly addressed.

In this paper, we present a novel circuit design that integrates multiple TX/RX paths on a single die. The design is based on advanced CMOS-SOI technology and incorporates various strategies to mitigate the challenges arising from dense integration, including the use of guard bands to reduce crosstalk and interference. The paper will also explore approaches to optimize component layout and improve isolation between transmission paths, enabling a reduction in the total number of key components required in m-MIMO radio units by more than 15%.

The proposed solution demonstrates significant BOM reduction while maintaining performance metrics such as power output and efficiency. The system's modular design, with both two-core and four core configurations, highlights its scalability and adaptability to different deployment scenarios. By optimizing RF integration and system design, this approach contributes to more efficient and cost effective m-MIMO infrastructure for 5G networks.

2 Typical m-MIMO Architecture and Integration Challenges

In a typical massive MIMO (m-MIMO) radio unit, such as the 32T32R configuration, the radio architecture includes both digital and analog components, with most of the BOM originating from the Analog Front End (AFE). In fact, the AFE accounts for approximately 97% of the key components, which significantly impacts the overall complexity and cost of the radio unit.



- **Most of BOM comes from the AFE:**
  - **97% of key components**
- **Effect of Driver-Array IC on number of key components**

	Component Num.	Reduction
Dual core:	144	~10%
Quad core:	136	~ 15%

Figure 1: Typical Architecture of 32T32R massive MIMO Radio

One of the critical factors influencing the BOM is the Driver-Array IC architecture. As shown in our design analysis, using a dual-core or quad-core configuration for the driver array directly impacts the number of key components required for the m-MIMO system:

Component Configuration	Component Number	Reduction
Dual Core	144	~10%
Quad Core	136	~15%

Table 1: Effect of Driver-Array IC on number of key components

By integrating more cores into the design, significant reductions in the BOM are achieved, which is crucial for achieving a more compact and cost-effective radio unit.

3 Integration Challenges: EMI and Crosstalk

As RF components become more densely integrated into smaller IC packages, issues such as Electromagnetic Interference (EMI) and crosstalk become increasingly problematic. These phenomena are particularly prevalent in RF ICs due to the high density of interconnects and close proximity of sensitive components.

EMI can originate from several sources within the IC, including direct radiation from the surface of the IC and conducted noise through signaling ports. The impact of EMI can be severe, leading to synchronization issues, clock misalignment, and signal degradation. One of the most challenging aspects of EMI is the high-frequency noise signals conducted through the power lines, which can interfere with the critical timing and signaling of the system.

Crosstalk occurs when unwanted electromagnetic coupling between interconnects, bonding wires, power pins, or signal pins degrades the performance of the IC. This interference can manifest in several ways, such as signal propagation delays, failures, pulse distortions, and emissions. As IC geometries shrink and the distance between components reduces, the risk of crosstalk increases, posing a significant threat to signal integrity.

The effects of crosstalk and EMI are directly responsible for poor signal integrity and an increase in noise margins, ultimately degrading overall system performance. In the context of m-MIMO systems, where precision and timing are crucial, these issues can severely impact the reliability and efficiency of the radio unit. To address these challenges, several techniques can be applied to the layout and design of the IC: Noise and Signal Separation: Ensuring that noise-generating nets and sensitive signal nets are physically separated on the layout can help to reduce EMI and crosstalk. Careful layout optimization can minimize the parasitic coupling between various nets, reducing the likelihood of signal interference.

Additionally, the use of advanced electromagnetic (EM) modeling is essential to accurately predict and mitigate the risks associated with EMI and crosstalk. As IC designs move towards more advanced process nodes, the complexity of design rules, interconnect parasitics, and wire resistance continues to grow, requiring even more precise modeling and simulation techniques to ensure optimal performance.

4 Case Study: AS0102 Sub-6GHz AFE RF-Sampling Companion IC

The AS0102 Sub-6GHz AFE RF-Sampling Companion IC from Argosemi is a highly integrated solution designed for 5G radio systems, offering both transmit (TX) and receive (RX) paths. The architecture is optimized for sub-6GHz 5G radio units, and it provides high levels of performance and integration for a variety of m-MIMO radio configurations. It supports 4x4 or 2x2 radio configurations, making it ideal for high-throughput applications. Each core in the AS0102 integrates both the 5G-Tx and 5G-Rx paths. This compact design makes it well-suited for high-density integration into massive MIMO radio units, but it also introduces specific challenges in terms of signal integrity and noise management, as explored in the following sections. A critical requirement for this IC is achieving greater than 35 dB of Tx-Tx and Rx-Rx isolation, which is essential for maintaining optimal Error Vector Magnitude (EVM) and Signal-to-Noise Ratio (SNR) performance.

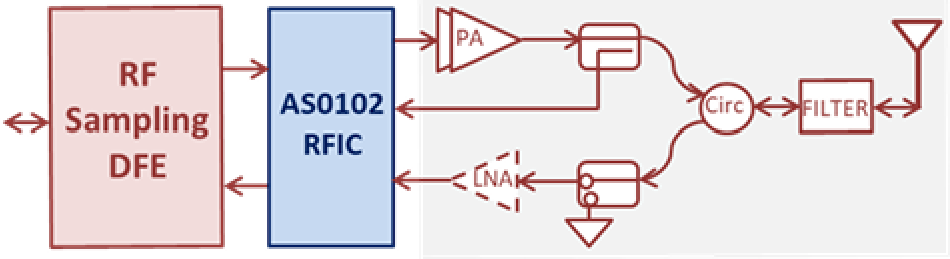


Figure 2: AS0102-Sub-6 GHz AFE RF-Sampling Companion IC

Below, we outline the key features of the AS0102's TX and RX paths.

AS0102 Features	TX	RX
Freq. Range	3.3-4.9 GHz	
Bandwidth	450 MHz	
Gain	25dB	
O1dBCP	28dBm	
Noise Figure	1.8dB	

Table 2: AS0102 Selected Key Metrics

5 Isolation Study

Isolation between signal paths is a critical factor in the design of 5G radio units, especially for m MIMO systems where multiple transmission and reception paths are in close proximity. Electromagnetic (EM) interference between these paths can degrade performance, and the isolation level must be accurately characterized and optimized. We conducted isolation simulations for both TX TX and RX-RX paths in the AS0102 architecture. The goal was to ensure high isolation between paths to minimize interference and cross-talk, thus preserving signal integrity.

5.1. TX Isolation: Identifying Worst Coupling between TX cores

To simulate the isolation between two TX paths, the following workflow was implemented: All passive components, such as PGA, prePA, and PA transformers, were moved to the top hierarchy level. This setup allowed easy switching between different passive models. A secondary TX path (TX2) was added to the top hierarchy, powered on, and sharing the same control logic as the primary TX path (TX1). However, no input signal was applied to the secondary path (TX2). Isolation is defined as the difference in output power (in dB) between TX1 and TX2. This provides a measure of how well TX1 and TX2 are isolated from each other. S-Parameter files generated through EMX were used for the isolation simulation, considering different separations and dimensions. The simulation yielded isolation values of approximately:

- 33.3 dB for 1000 µm separation
- 43 dB for 2500 µm separation
- 52.6 dB for 3000 µm separation

Note: AS0102 package models were included in the simulation but without TX-TX coupling. These models were only used for evaluating TX performance and output matching.

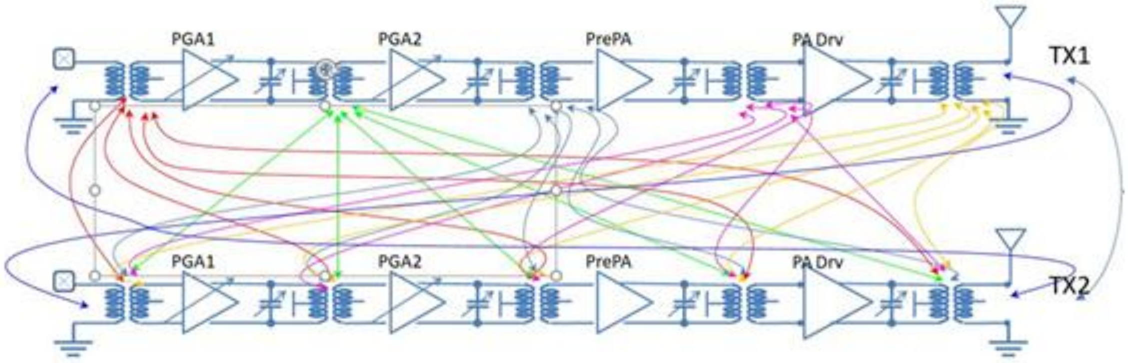


Figure 3: All Cross-talks combinations in 2x2 TX paths

In our design for the AS0102 architecture, understanding and mitigating electromagnetic interference (EMI) and crosstalk between TX paths is essential for maintaining signal integrity. The major contributors to coupling and interference are the passive components in the transmission chain, particularly transformers and inductors. Power Amplifier (PA) transformer act as major contributor. The isolation between TX1 and TX2 slightly improved when moving the "PAC=1" source from the PGA1 output to the PA output. However, it was clear that the PA transformer was the main source of coupling from TX1, primarily due to the significantly larger power it handles compared to other passives. This result was expected and confirmed by several test scenarios, demonstrating that the TX1 PA transformer contributes most to the power observed at the TX2 PA output.

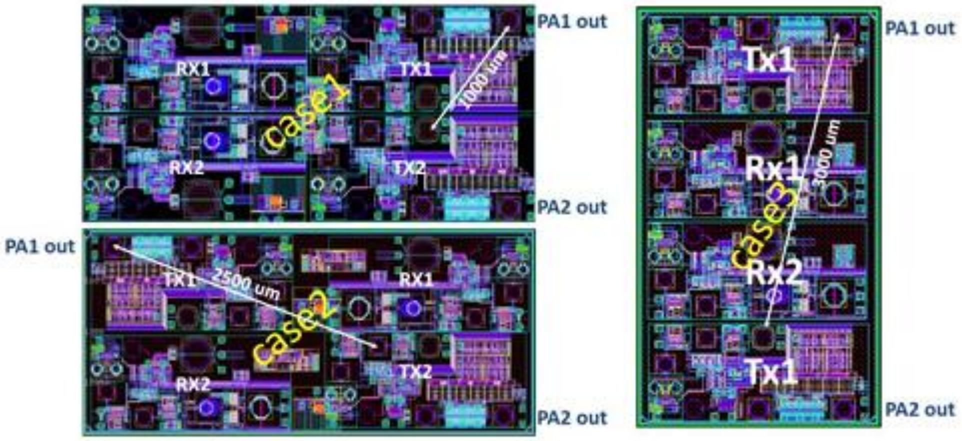


Figure 4: Three different floor plan cases of the 2x2 Transceiver identifying worst coupling combinations between passives

To isolate the worst coupling combinations, we employed a systematic approach: In each test, one passive component was treated as non-coupled by using its standalone S-Parameter model, which had no coupling with the other five passives. The remaining five passives were simulated with coupled S Parameter models. The major improvement in isolation occurred only when the TX1 PA transformer was treated as non-coupled, further emphasizing its significant role in the observed interference.

From the data of our study, it became evident that the major coupling occurs between the TX1 PA transformer and the TX2 PGA1 inductor. When non-coupled models for TX2 prePA and PA transformers were used, only a slight improvement in isolation was observed. However, significant improvement occurred when using a non-coupled TX2 PGA balun, confirming that this inductor-balun interaction is a primary source of interference. Improvements in the prePA transformer coupling were minor, with a maximum possible improvement of only about 3 dB. Thus, further efforts to reduce coupling in the prePA transformer would not yield substantial benefits.

We conducted the study for three different floor plan configurations of the 4x4 transceiver, with results aligning with the previous observations.

Case 1 was selected as the optimal configuration due to its superior isolation performance compared to the other two cases. A general rule of thumb emerged from the simulations: for every 300 µm increase in separation, we observed a 2-3 dB increase in isolation. This trend is consistent for typical inductors with diameters up to 200-250 µm. A 1000 µm pitch distance between the two transmitters was found to be insufficient, with the analysis suggesting that a separation of at least 1500 µm would provide safer isolation levels. The PA1 transformer and its associated bumps were identified as the main sources of interference, particularly affecting the prePA2 and PA2 transformers in the adjacent TX path. As a potential solution, a rearrangement of the AS0102 Tx5G output transformer bumps could be considered to increase separation and reduce coupling. Another solution to consider would be the use of an 8 shaped prePA or PGA transformer, which, while having a lower Q-factor, would help in mitigating crosstalk due to its reduced coupling footprint.

The study of TX-TX isolation revealed that the PA transformers are the main contributors to coupling and EMI, and that significant improvements in isolation can be achieved through floor plan optimization and passive component design. By carefully analyzing different coupling scenarios and floor plan arrangements, we identified key strategies for improving isolation in the AS0102 architecture. Going forward, rearranging the layout of the PA transformers and their bumps as well as exploring alternative transformer designs, such as the 8-shaped transformer, will be critical in minimizing EMI and ensuring optimal performance.

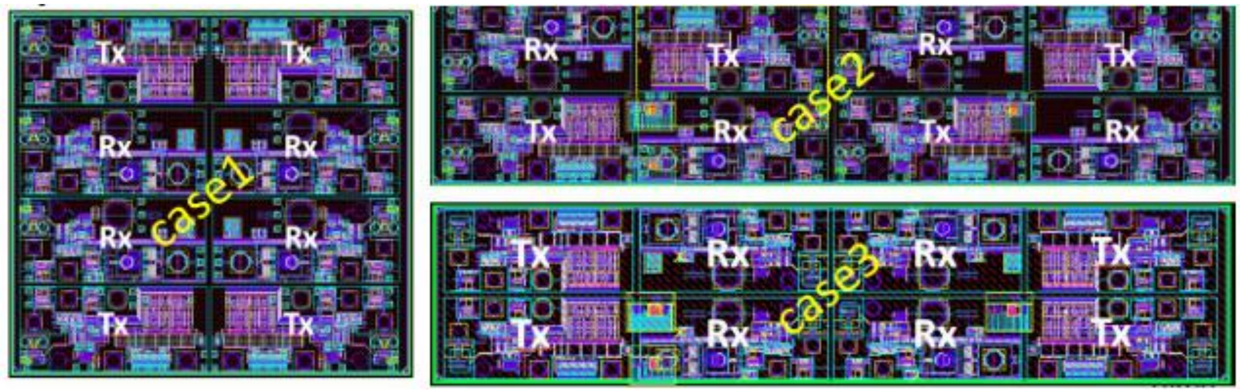


Figure 5: Three different floor plan cases of the 4x4 Transceiver identifying worst coupling combinations between passives

5.2. RX Isolation: Identifying Worst Coupling Combinations

The RX-RX isolation simulation was conducted in a similar manner, with modifications specific to the RX paths. The simulation testbench consisted of two complete RX paths, the aggressor and the victim:

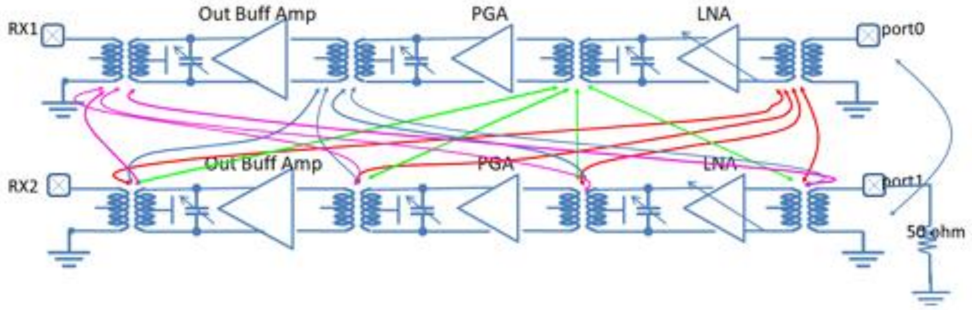


Figure 6: RX coupling combinations between passives on a 2x2

The total RX gain was set to approximately 52 dB, measured at the Output Buffer Amplifier. The input signal to RX core 0 was set at -50 dBm. All passive components (input/output transformers and routings) were moved to the top hierarchy, allowing the sharing of S-parameter models between RX core 0 (RX0) and RX core 1 (RX1). The RX path hierarchy was also modified to allow the connection of the S-parameter files to both RX paths, ensuring a complete and realistic simulation environment. Harmonic Balance simulations were used to assess the performance and isolation levels between the RX paths. Similar to the TX simulation, a secondary 5G-RX path (RX1) was added to the top hierarchy. RX1 shared the same control logic as RX0 but had no input signal. Instead, RX0 received an input signal, while RX1 was terminated with a 50 Ohm load at port 1. The RX-RX isolation was defined as the difference in output power (in dB) between RX0 and RX1, measured at the Output Buffer Amplifier. The simulation results demonstrated the importance of accurate S-parameter modeling and passive component placement in achieving high levels of isolation, particularly as IC designs become more compact and densely integrated.

Through detailed electromagnetic simulations we were able to achieve strong isolation results, demonstrating the effectiveness of the design and the importance of precise EM modeling ensuring that the AS0102 architecture provides the necessary isolation between signal paths and meet performance requirements. As with TX isolation, identifying the worst coupling combinations in the RX path is crucial for maintaining signal integrity, particularly for sensitive reception stages. Our methodology aims to evaluate the effectiveness of the current floor planning, analyze how isolation is affected by different passive components, and provide insights on optimizing the decoupling capacitor setup for better RX-RX isolation. To assess RX-RX isolation, we inject the RF signal from Port 0 and measure the signal level difference at the Buffer Amp outputs of RX Core 0 (aggressor) and RX Core 1 (victim). The isolation is determined by the output power difference between these two cores, with Port 1 terminated using a 50 Ohm to ground configuration. This setup provides a reliable measurement for isolation and enables us to observe how the two cores interact under different coupling scenarios. We utilize harmonic balance simulations to model the non-linear behavior of the circuit and to accurately capture the coupling effects between RX paths. The current floor planning with a 1000 µm spacing between RX cores is used as the baseline for these simulations. We aim to evaluate whether this spacing can achieve the target isolation of 35 dB. To predict the worst-case coupling scenarios, we applied a method similar to the one used for TX isolation. By sweeping the capacitances on the VDD nets, we can observe potential resonances that might degrade isolation. This approach helps us identify problematic points where the impedance of the power nets (surrounding transformers or inductors) affects the isolation between RX cores.

Results from the capacitance sweep indicated that, as seen in the TX case, the impedance characteristics of the VDD nets surrounding the passive components play a significant role in inter-core isolation. Higher capacitance values generally improved RX-RX isolation, as they help to suppress the resonance effects that may arise at specific frequencies.

The value of the decoupling capacitors has a direct impact on RX-RX isolation. In general, larger capacitance values lead to better isolation, as they improve filtering and reduce noise on the power and ground planes. However, in addition to the capacitance value, the position of the decoupling capacitors also plays a critical role. To study this effect, we conducted simulations where the decoupling cap bank was connected between various VDD and VSS ports, positioned at different spots along the power and ground paths. Results showed that the RX-RX isolation is highly dependent on the exact points of connection between the VDD-VSS rails and the decoupling capacitors.

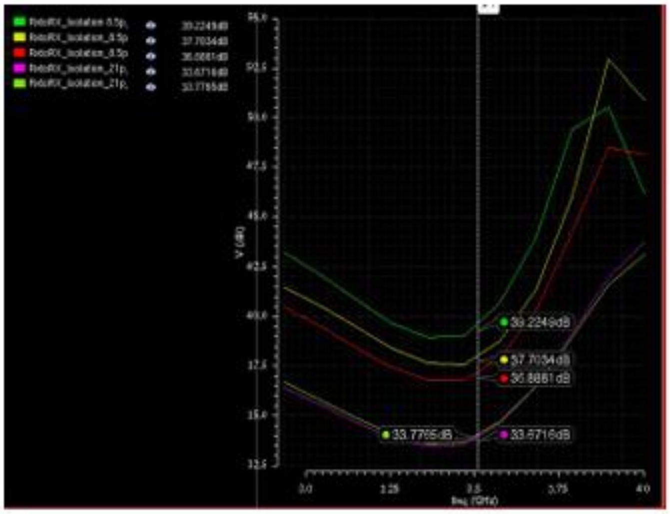


Figure 7: RX resonance vs decoupling capacitance

The optimal placement of these capacitors significantly reduces coupling between RX cores, improving isolation by filtering out the unwanted noise and resonance effects that can degrade signal performance. The results from the RX-RX isolation study showed reasonably consistent behavior when compared to the TX-TX isolation findings. Similar trends were observed, particularly regarding the influence of transformer placement and power net impedance on isolation performance.

As seen in the TX isolation study, spacing between components plays a crucial role, and increasing the spacing beyond 1000 µm is likely to improve isolation significantly.

The study highlights the importance of both decoupling capacitor value and positioning in achieving optimal RX-RX isolation. Increasing the value of the decoupling capacitors and carefully selecting their placement on the power and ground planes can lead to significant improvements in isolation between RX cores. Based on the harmonic balance simulations and capacitance sweep results, we recommend increasing the spacing between RX cores to above 1500 µm where feasible, and optimizing the layout of decoupling capacitors to minimize noise and resonance effects.

6 Conclusion

The development of 5G massive MIMO radio units, particularly in the context of reducing the bill of materials (BoM) while maintaining performance integrity, presents several key challenges related to component integration, electromagnetic interference (EMI), and signal isolation. Through a detailed exploration of both TX and RX paths, this paper has highlighted the critical impact of passive component coupling, floor planning, and decoupling strategies on overall system performance.

The findings show that as RF component densities increase, especially with advanced RF-sampling companion ICs like the AS0102, effective management of EMI and crosstalk is essential for ensuring system reliability and signal quality. Our EMX simulations have demonstrated the importance of passive component separation and optimized decoupling capacitor placement in improving TX-TX and RX-RX isolation, with notable improvements achieved by increasing separation distances and strategically positioning decoupling capacitors.

Moreover, the study reinforces that while component miniaturization and integration are key to BoM reduction, careful attention must be paid to the physical layout of passive elements and power distribution networks to mitigate the risks of EMI, crosstalk, and other forms of interference that can degrade signal integrity.

In conclusion, achieving optimal performance in 5G m-MIMO radio units requires a delicate balance between BoM reduction and the mitigation of signal integrity risks. By applying advanced simulation techniques and focusing on the careful integration of RF components, future designs can continue to push the boundaries of performance while meeting the stringent demands of next-generation wireless communication systems. The ongoing evolution of process technologies, such as the AS0102, offers promising paths for further innovation, but they must be accompanied by equally advanced strategies for addressing the growing complexity of RF system integration.

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