A reconfigurable low-band RF front-end architecture for global smartwatch connectivity

Using the Forefront RF FFM51010 front-end module

The evolving RF landscape in smartwatch design

Smartwatches and other compact wearable devices are rapidly evolving from companion devices into fully connected, standalone products. Cellular connectivity enables features such as independent calling, messaging, health monitoring, safety services, and location tracking without reliance on a paired smartphone. To support these use cases globally, smartwatch platforms increasingly require multi-band low-frequency cellular connectivity while operating under extreme constraints on size, power consumption, and antenna performance.

Traditional RF front-end architectures were not designed with these constraints in mind. Fixed-band duplexers, multiple regional RF variants, and limited antenna tuning margin introduce complexity, add component count, increase the overall PCB space, and heighten development risk. These challenges are amplified in smartwatches, where antenna detuning due to wrist proximity and compact mechanical enclosures is unavoidable.

Figure 1: Smartwatches are increasingly connected to the cellular network

The purpose of this application note is to explain how Forefront RF's reconfigurable low-band front-end architecture, implemented in the FFM51010 Front-End Module (FEM), enables a scalable, software-defined RF solution for global smartwatch platforms.

Connectivity requirements for smartwatches and wearables

Modern smartwatches typically integrate multiple radios, including Bluetooth, Wi-Fi, GNSS, NFC and cellular connectivity. The latter, in particular places stringent demands on the RF front-end due to the need for global coverage, regulatory compliance, and efficient operation from a small battery.

Key low-band cellular requirements for smartwatches include:

- Support for multiple 4G LTE and 5G NR low bands across different regions
- Operation with a single compact antenna
- High transmitter efficiency at moderate output power levels
- Robust receiver sensitivity under antenna mismatch conditions
- Fast band switching and configurability

In addition, compact wearable platforms face unique physical constraints:

- PCB area is limited by compact form factors
- Antenna performance varies significantly depending on wrist position and user interaction
- Mechanical enclosure materials (metal, glass) impact RF behaviour
- Battery capacity places strong limits on average and peak current consumption

These requirements challenge traditional RF front-end solutions that rely on fixed duplexers and band-specific architectures.

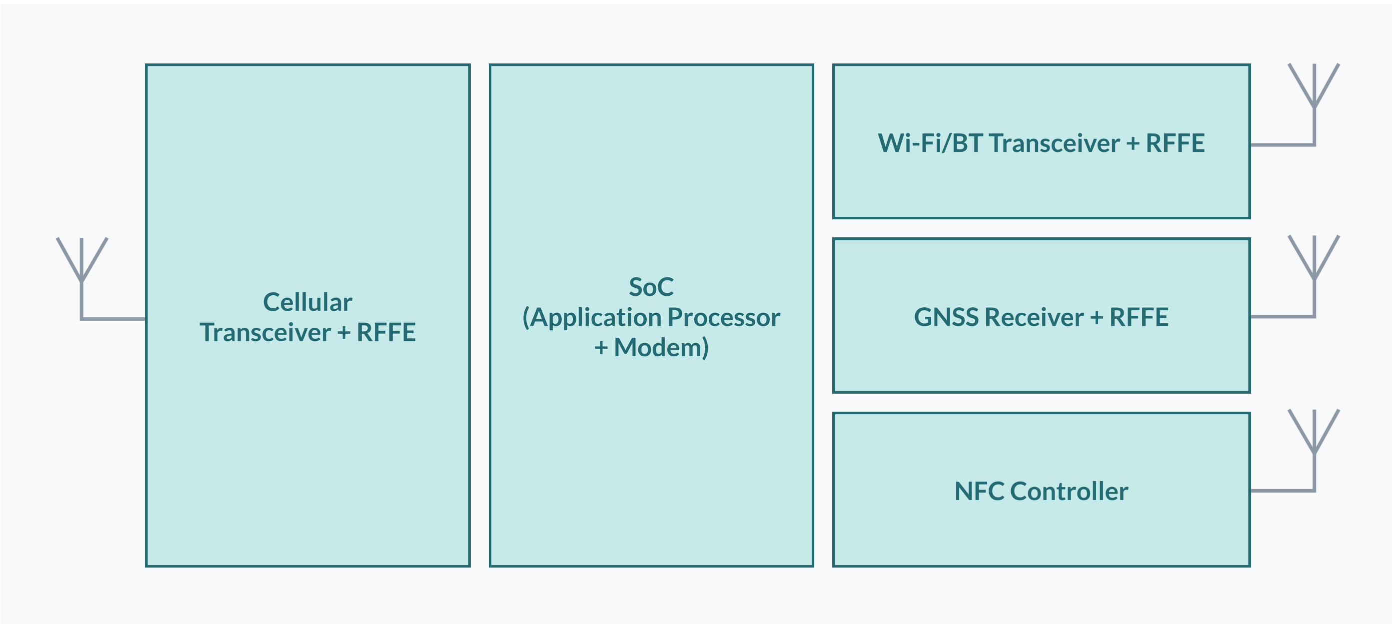

Figure 2: Modern smartwatches typically integrate multiple radios, including Bluetooth, Wi-Fi, GNSS, NFC and cellular connectivity

Forefront RF reconfigurable front-end architecture

The Forefront RF FFM51010 is a low-band Tx-Rx L-PAMiD Front-End Module designed to address the specific challenges of global cellular connectivity in compact and highly integrated devices such as smartwatches. The module supports all major low-frequency cellular bands from 612 MHz to 960 MHz using a single hardware platform, eliminating the need for band-specific RF front-end variants.

Central to the FFM51010 is Forefront RF's patented Foretune™ technology which combines an Electrical Balance n-plexer with Adaptive Passive Cancellation to create a digitally controlled duplexer. Unlike traditional fixed SAW-based duplexers, which are optimized for narrow frequency ranges, the Foretune™ can be dynamically configured across all low band frequency ranges and bandwidths.

The Electrical Balance n-plexer provides intrinsic isolation between the transmit and receive paths by balancing impedance networks rather than relying on high-Q acoustic filtering. This is particularly advantageous in low-band operation, where duplex spacing can be relatively small and where SAW duplexers tend to be physically large and insertion-loss heavy.

Adaptive Passive Cancellation further enhances Tx-to-Rx isolation by compensating for residual leakage paths that vary with frequency, antenna impedance, and operating conditions. In smartwatches, where antenna characteristics change dynamically due to user interaction and proximity effects, this adaptive behaviour provides a significant robustness advantage.

The FFM51010 integrates the following key RF functions into a single module:

- A Foretune™ tunable duplexer covering the full 612–960 MHz range
- A multi-mode power amplifier supporting both 4G LTE and 5G NR waveforms
- A low-noise amplifier optimized for low-band receiver sensitivity
- An integrated bi-directional RF coupler located at the antenna port
- A single MIPI RFFE v3.0 digital control interface

By combining these functions, the FFM51010 replaces multiple discrete RF components, including fixed duplexers, external couplers, and associated matching networks. This high level of integration reduces PCB and simplifies RF system design and verification.

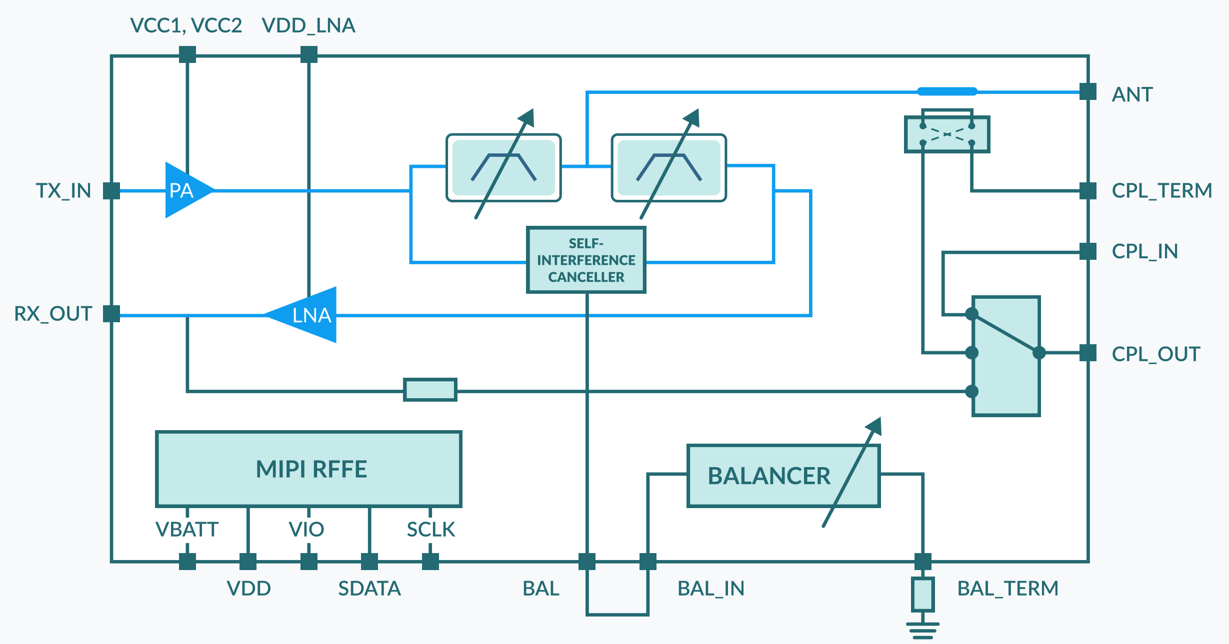

Figure 3: Block diagram of FFM51010

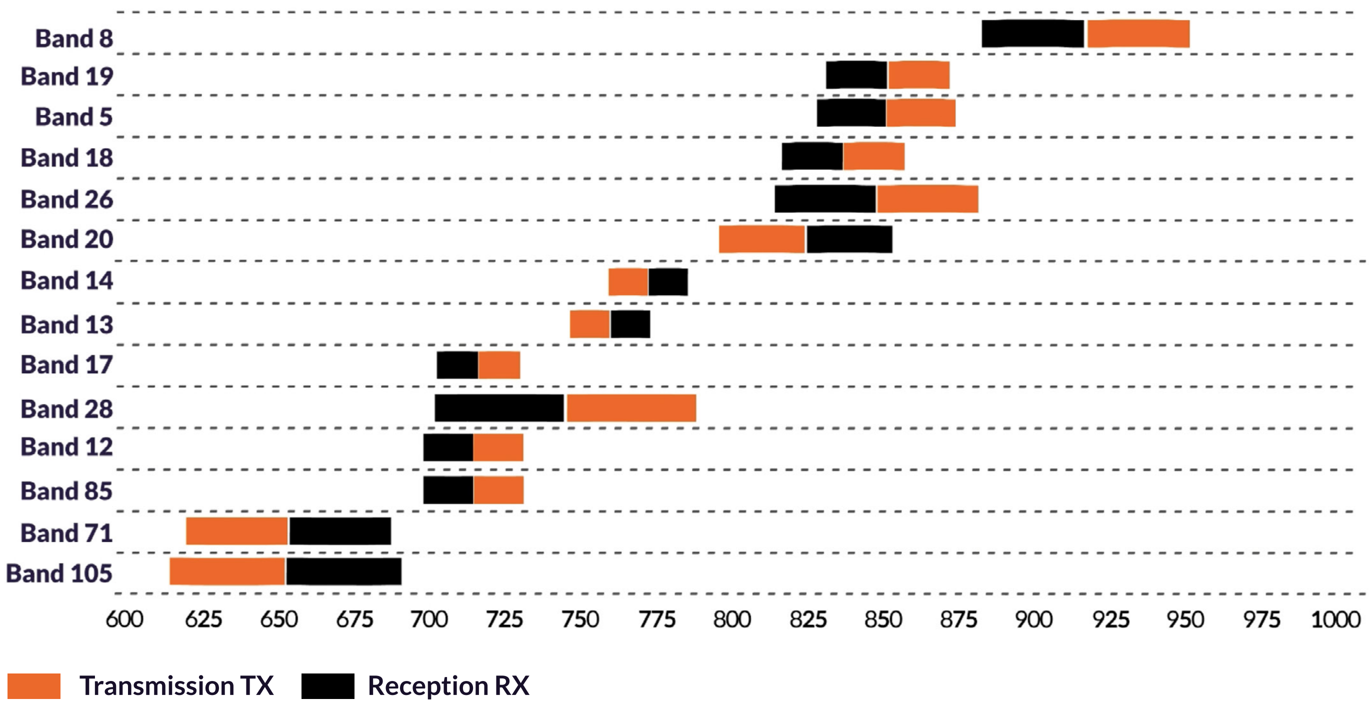

Figure 4: FFM51010 supports all the low-bands between 612 and 960 MHz

Reference smartwatch implementation

Figure 5 illustrates a reference smartwatch RF architecture using the FFM51010 Front-End Module. The cellular baseband connects directly to the module's transmit and receive ports, while a single antenna is shared for both Tx and Rx operation.

The FFM51010 is controlled via a standard MIPI RFFE interface, allowing system software to configure operating band selection, duplexer tuning states and transmit and receive operating modes.

By placing band and duplexer configuration under software control, a single RF hardware design can support multiple regional band configurations. Regional variants are enabled through configuration profiles, without requiring changes to the PCB or RF layouts.

The integrated antenna-port coupler provides a mechanism for monitoring forward and reflected power, enabling advanced system-level features such as antenna diagnostics, antenna impedance matching and adaptive tuning algorithms.

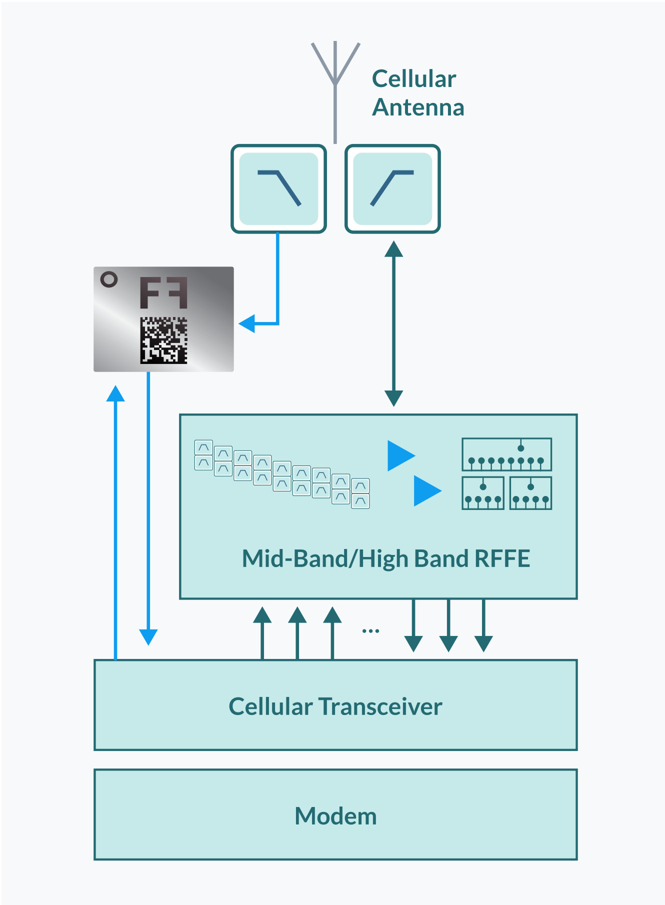

Figure 5: A reference smartwatch RF architecture using the FFM51010 Front-End Module

Tx–Rx isolation mechanics and selectivity considerations

Rethinking isolation in low-band RF front-ends

RF engineers have traditionally achieved transmit-to-receive (Tx–Rx) isolation using highly selective, fixed-frequency SAW duplexers. These components provide steep frequency skirts and high out-of-band attenuation, aligning well with classical RF design practices. However, traditional SAW and BAW filter technologies are typically designed and characterised for ideal 50 Ω source and load impedances. In real-world user conditions, where antenna impedance can vary significantly with hand effects, proximity, and environment, this fixed-impedance optimisation often leads to performance degradation, including increased insertion loss, detuning and requirement for switches. The SAW/BAW filter approach therefore involves trade-offs in size, insertion loss, frequency agility, and scalability across multiple bands.

The Forefront RF FFM51010 adopts a fundamentally different isolation strategy. Instead of relying solely on extreme frequency selectivity, the module combines moderate-selectivity LC-based networks with active and adaptive cancellation techniques to achieve the required Tx–Rx isolation across a wide frequency range.

Selectivity versus isolation: a system-level perspective

It is important to distinguish between frequency selectivity and effective isolation at the receiver input. While SAW duplexers achieve isolation primarily through steep filtering, system-level isolation in a transceiver is influenced by multiple mechanisms, including:

- Impedance balance between Tx and Rx paths
- Cancellation of correlated leakage components
- Receiver linearity and blocker tolerance
- Additional band- and system-level filtering outside the FEM

In the FFM51010, the LC-based tunable networks are not intended to replicate the extreme selectivity of SAW filters. Instead, they establish a controlled, reconfigurable impedance environment that enables the Electrical Balance n-plexer to suppress Tx leakage at the Rx port.

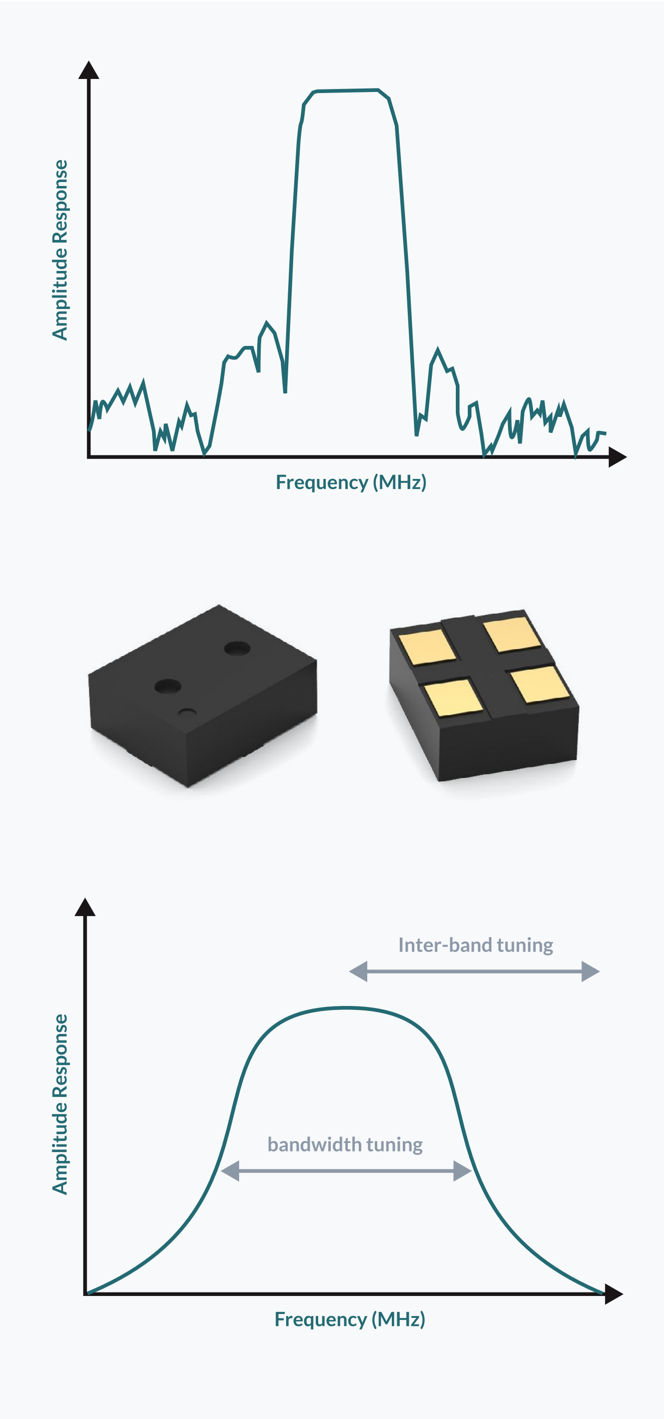

Figure 6: (top) Traditional SAW filter response; (middle) image of a SAW filter package and (bottom) tunable (LC) filter response

Electrical balance and adaptive passive cancellation

The Electrical Balance n-plexer provides the first stage of Tx–Rx isolation by balancing the impedance seen by the transmit and receive paths. When this balance is maintained across frequency and operating conditions, a substantial portion of the transmit signal is inherently prevented from coupling into the receive path.

Residual leakage components, caused by antenna mismatch, parasitics, and frequency-dependent effects, are addressed through Adaptive Passive Cancellation. This technique generates a cancellation signal that is phase and amplitude-aligned with the leakage component, effectively suppressing it at the receiver input.

Crucially, because this cancellation operates on correlated leakage signals, effective suppression can be achieved even when the underlying LC-based networks exhibit significantly lower frequency selectivity compared to SAW-based solutions.

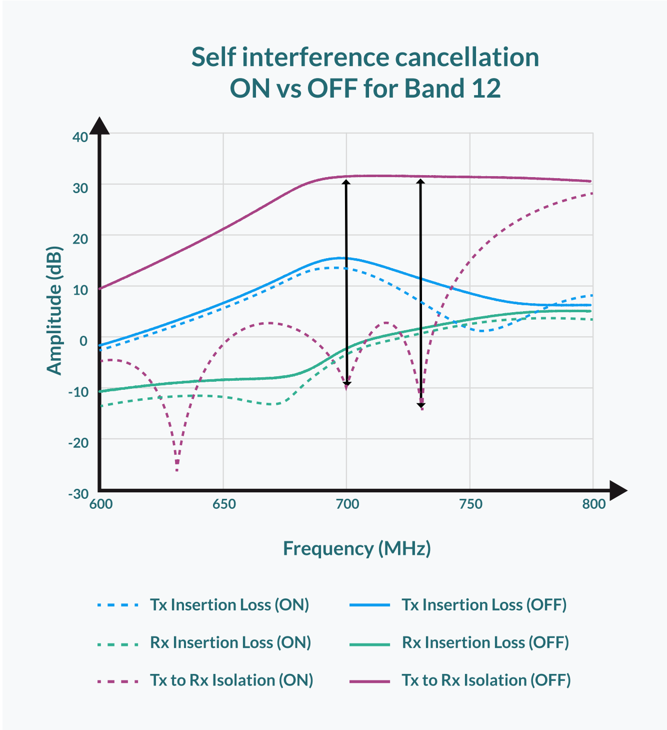

Figure 7: Demonstrating the impact on isolation of the self-interference cancellation technology

Out-of-band blocking and external filtering

In traditional architectures, high-selectivity SAW duplexers also serve a second function: providing strong out-of-band rejection of interferers far removed from the operating band. In the Forefront RF architecture, this function is intentionally decoupled from the duplexing mechanism.

The FFM51010 is designed to work in conjunction with standard, well-understood system-level filtering approaches including:

- Baseband or transceiver-integrated filtering
- Dedicated blocker filters where required by the platform
- Coexistence filters shared across multiple radio paths

By separating the roles of duplexing and out-of-band blocking, the overall RF architecture gains flexibility. The tunable duplexer focuses on efficient Tx–Rx separation across bands, while out-of-band interferer rejection is handled by conventional filtering elements optimized for that purpose.

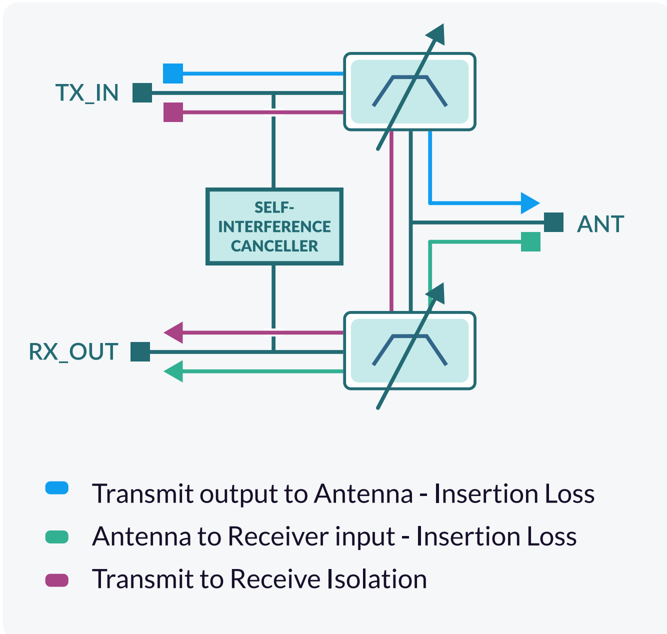

Figure 8a: Signal flow between transmit, receive and the antenna in FFM51010. The colour scheme relates to Figures 8b-8d.

Building engineer confidence

When evaluating the FFM51010, engineers may initially focus on the apparent frequency selectivity of the LC-based networks relative to traditional SAW duplexers. At the system level, however, the combined effects of electrical balance, adaptive cancellation, and standard external filtering deliver the isolation, receiver sensitivity, and robustness required for low-band wearable applications.

This architecture represents a deliberate shift away from fixed, high-Q filtering towards a more adaptive and scalable RF front-end design. It is ideally suited to the realities of multi-band operation, severe space constraints, and software-defined configuration in modern wearable platforms.

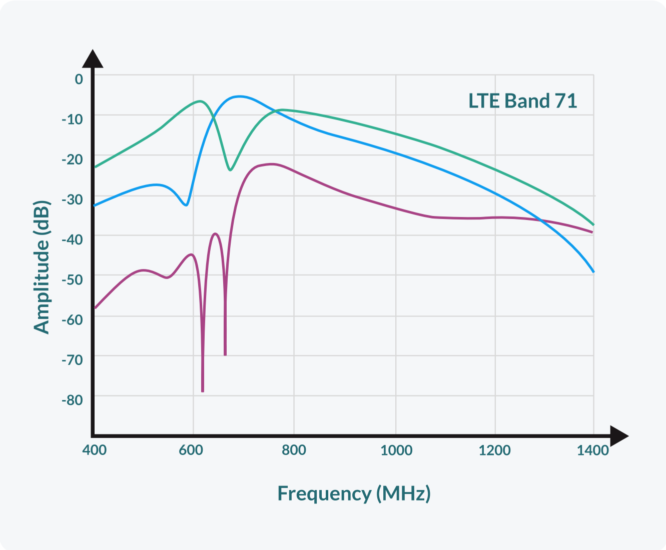

Figure 8b: Demonstrating transmit, receive and isolation of Foretune™ for LTE band 71

RF performance in wearable applications

Transmit path performance

The integrated power amplifier supports transmit output power levels up to approximately 24.7 dBm across all supported low bands, ensuring compliance with regional regulatory requirements while maintaining efficient operation. The PA architecture supports both Average Power Tracking (APT) and Envelope Tracking (ET), allowing system designers to optimize efficiency across different transmit power levels and traffic profiles.

Error Vector Magnitude (EVM) and Adjacent Channel Leakage Ratio (ACLR) performance meet 3GPP requirements for LTE and NR waveforms with channel bandwidths up to 20 MHz. Maintaining linearity at moderate output power levels is particularly important in smartwatches, where sustained high power transmission must be balanced against thermal and battery constraints.

The FFM51010 is designed to meet 3GPP performance requirements for low-band 4G LTE and 5G NR operation while addressing the efficiency, sensitivity, and robustness demands specific to wearable platforms.

Receiver path performance

On the receive side, the integrated low-noise amplifier provides a typical noise figure of approximately 4.8 to 5.2 dB when referenced to the antenna port. This level of sensitivity supports reliable connectivity in challenging coverage scenarios while accounting for additional losses introduced by compact antennas and mechanical enclosures.

Receiver linearity is maintained under strong blocker conditions, which is critical in dense network environments where out-of-band interference can be significant. The tunable duplexer architecture helps maintain consistent receive performance across the full supported frequency range.

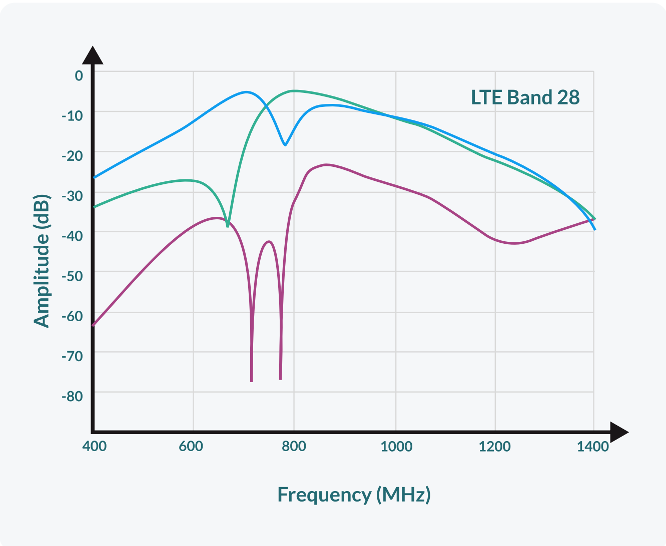

Figure 8c: Demonstrating transmit, receive and isolation of Foretune™ for LTE band 28

Antenna mismatch robustness

Smartwatch antennas are subject to significant impedance variation due to wrist proximity, user movement, and environmental factors. The FFM51010 is specified to operate with antenna VSWR conditions up to 3:1, providing additional margin compared to traditional fixed duplexer solutions.

This robustness reduces sensitivity to antenna detuning, thus helping to maintain both transmit efficiency and receive sensitivity in real-world usage conditions.

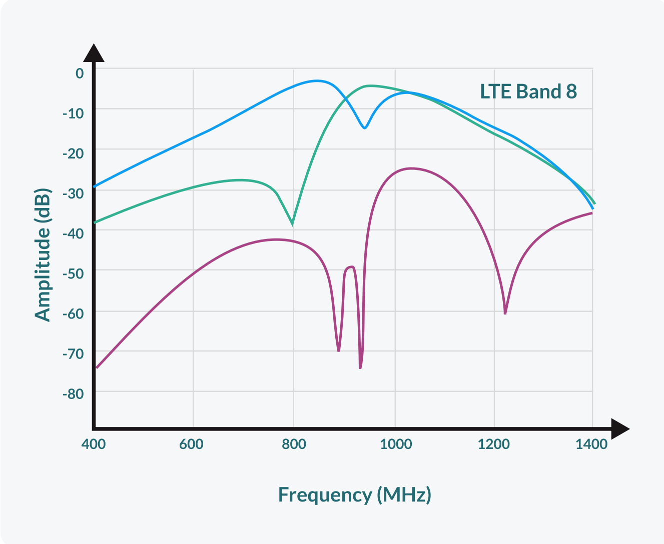

Figure 8d: Demonstrating transmit, receive and isolation of Foretune™ for LTE band 8

Antenna interaction and wrist effects

In smartwatch applications, antenna behaviour is one of the dominant factors influencing overall RF system performance. The close proximity of the antenna to the human body introduces loss, detuning, and impedance variation that change dynamically with wrist position, orientation, and user activity.

Traditional RF front-end architectures assume relatively stable antenna impedance conditions and rely on fixed matching and filtering networks. In wearables, this assumption often breaks down, leading to degraded efficiency, reduced sensitivity, and increased development risk late in the design cycle.

The reconfigurable nature of the Foretune™ duplexer allows the RF front-end to adapt across a wide frequency range, helping to mitigate the impact of antenna detuning. By dynamically adjusting duplexer and balancing states, the system can maintain improved Tx-to-Rx isolation and consistent performance even as antenna conditions change.

The integrated bi-directional RF coupler at the antenna port enables monitoring of forward and reflected power. This capability can be leveraged by system software to implement antenna diagnostics, detect abnormal operating conditions, or support adaptive tuning strategies at the platform level.

Together, these features provide a more resilient RF system that is better suited to the variable operating environment of wearable devices.

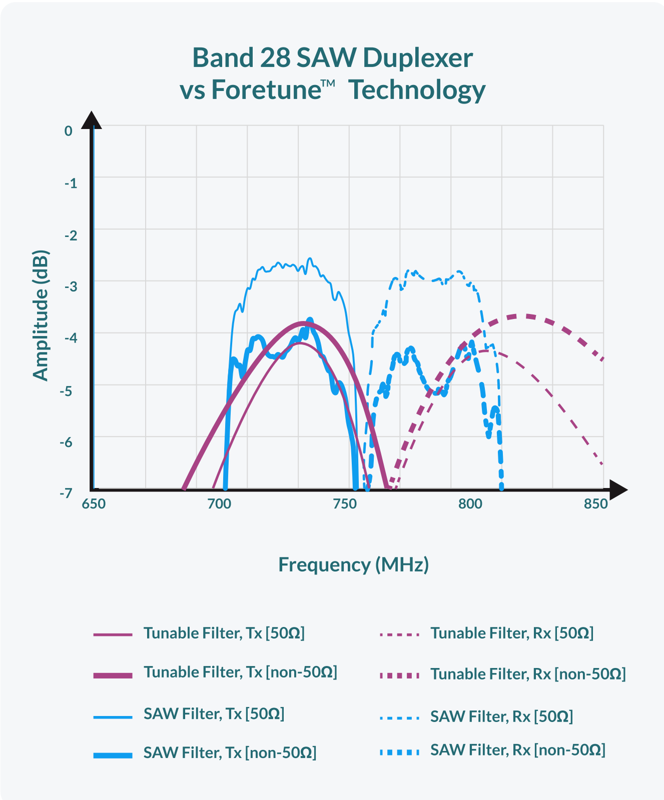

Figure 9: Under non-50 Ohm conditions, FFM51010's tunable filters can match or outperform traditional SAW filters

PCB and mechanical integration considerations

The FFM51010 is housed in a compact LGA module measuring approximately 6.0 × 4.5 × 0.75 mm, making it well suited for space-constrained wearable designs.

Key integration considerations include:

- Placement close to the antenna feed to minimize RF losses
- Careful grounding of the module's ground pads to ensure RF and thermal performance
- Short RF interconnects to the baseband transceiver

By eliminating the need for external duplexers and associated matching networks, the FFM51010 simplifies PCB routing and reduces overall RF layout complexity.

Development flow and time-to-market benefits

Using a reconfigurable RF front-end enables a streamlined development flow for global smartwatch platforms:

- A single RF hardware design supports multiple regional variants
- Software-based band configuration reduces the need for PCB re-spins
- Simplified RF architecture lowers integration and validation effort
- Reduced component count improves manufacturability and yield

These advantages contribute to faster time-to-market and reduced development risk, which are critical factors in competitive wearable product cycles.

Conclusion

Forefront RF's FFM51010 Front-End Module introduces a new approach to low-band cellular connectivity in smartwatches and wearable devices. By combining a reconfigurable duplexer architecture with integrated transmit and receive functions, the module enables global band coverage, improved robustness to antenna variation, and simplified RF design.

This software-defined RF approach aligns well with the evolving requirements of wearable platforms, offering scalability, efficiency, and flexibility as connectivity standards continue to evolve.

For more information, reference designs, or evaluation support, please contact Forefront RF.

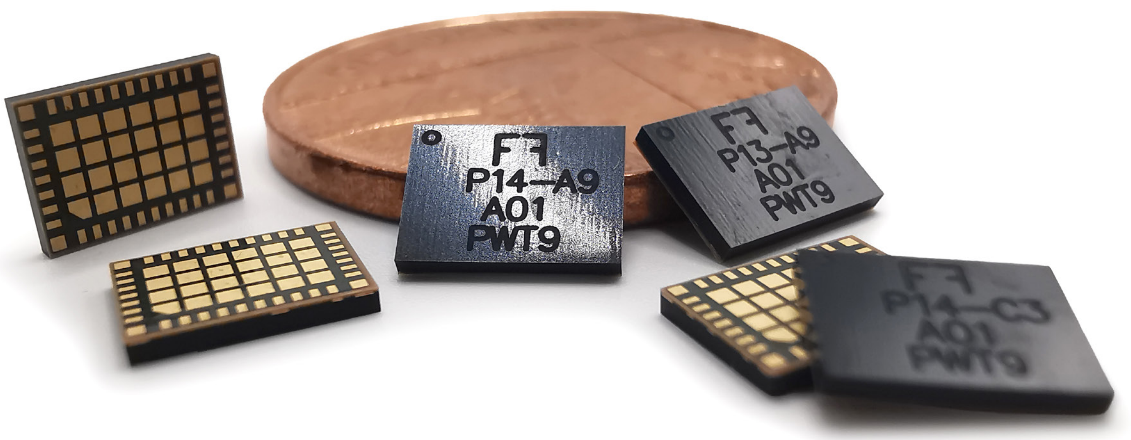

Figure 10: FFM51010 modules are 4 x 6.5 mm in dimension

Contact Information

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