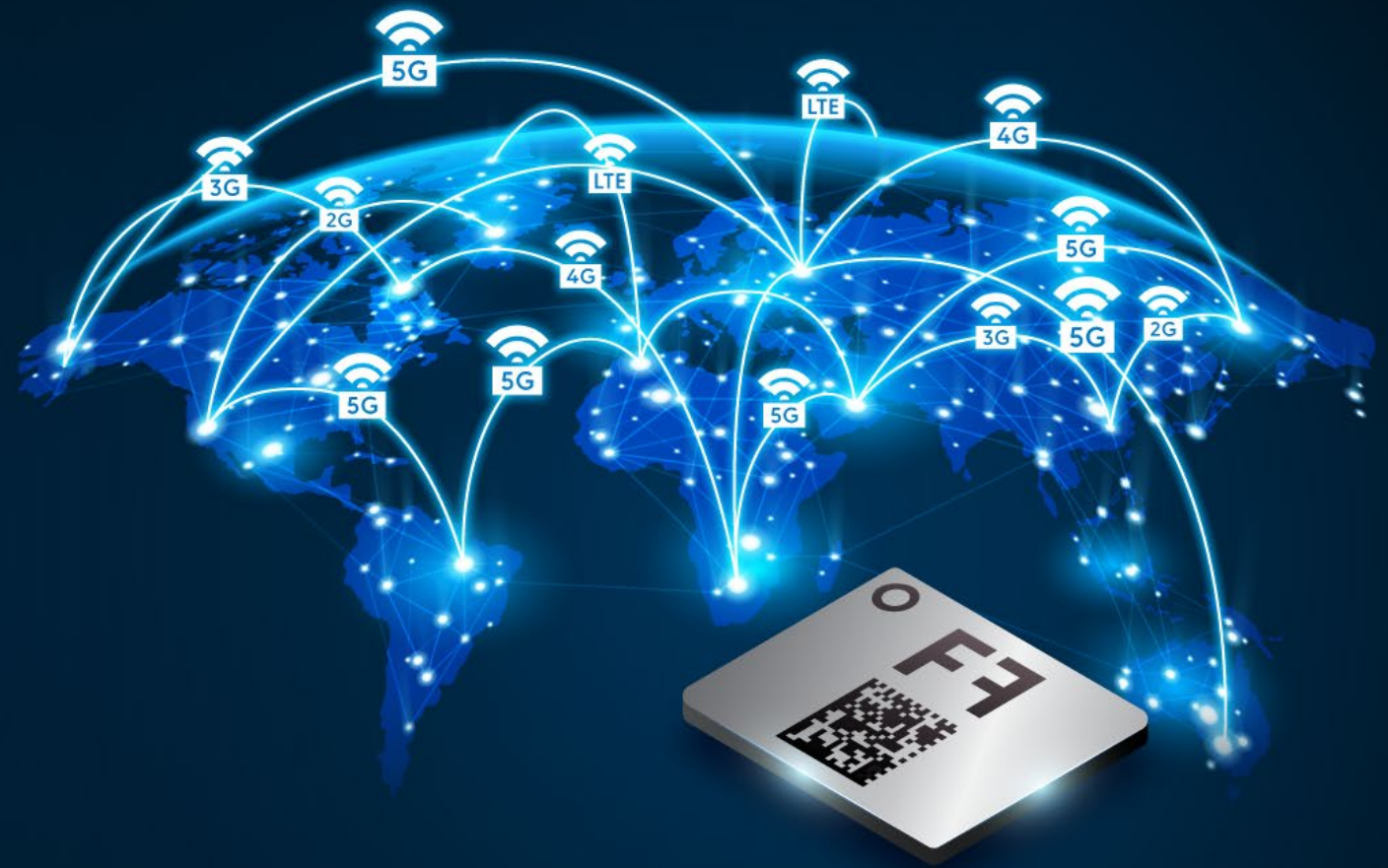




Forefront RF

Technology Briefing Note

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1 Background information

From cellular-enabled smartwatches to next-generation IoT applications and direct-to-device satellite communications, the proliferation of wireless technologies is accelerating demand for scalable RF architectures and globally compatible devices.

Advances in wireless communications technologies and the continued rollout of 5G networks are driving the need for greater interconnectivity and interoperability. Global mobile data consumption is expanding exponentially, with traffic expected to more than double between 2026 and 2030. This growth is being fuelled by video-rich applications, cloud services, AI-enabled devices and the rapid expansion of advanced IoT technologies.

The advent of the smartphone transformed the communications landscape and laid the foundations for 24x7 connectivity. Today, this expectation extends across a diverse ecosystem of products spanning wearables, healthcare, logistics, automotive, consumer electronics and IIoT (Industrial Internet of Things). Billions of devices now rely on seamless wireless connectivity to exchange ever-increasing volumes of data across increasingly complex global networks.

As manufacturers seek to deploy products internationally, they face mounting pressure to support a continually growing number of frequency bands, regional variations and operator requirements within increasingly compact and power-efficient devices. This is creating significant new challenges for wireless system integration and RF front-end architectures.



Current mobile radio front-end architectures are reaching their limits

The evolution of wireless standards has introduced new levels of complexity into RF front-end architectures. The transition from 3G to 4G and now 5G has driven the proliferation of frequency bands, carrier combinations and regional spectrum allocations that devices must support. With 6G on the horizon, this trend is set to accelerate further.

In parallel, today's mobile devices are becoming smaller, more compact and power constrained, creating integration challenges for RF front-ends. Achieving global interoperability requires support for a growing number of RF filters, switches and related components, which increases device size, raises costs and adds further engineering limitations.

Although advances in CMOS technologies have enabled baseband processors to deliver greater performance and efficiency, conventional RF front-end architectures have not advanced at the same pace. Traditional approaches that rely on adding more discrete components are no longer practical due to restrictions in space, power consumption and overall hardware overheads. As wireless connectivity requirements continue to expand worldwide, the industry must embrace more adaptable and scalable RF front-end solutions.

This briefing note explores the technologies and architectural innovations helping address these next-generation RF design challenges.

Topics covered

- RF spectrum challenges and evolving design architectures
- Limitations of current hardware
- The impact of 5G/6G carrier aggregation, MIMO and other emerging technologies
- Mobile Network Operator (MNO) and band compatibility challenges
- The role of tunable and adaptive duplexer technologies
- The importance of global connectivity

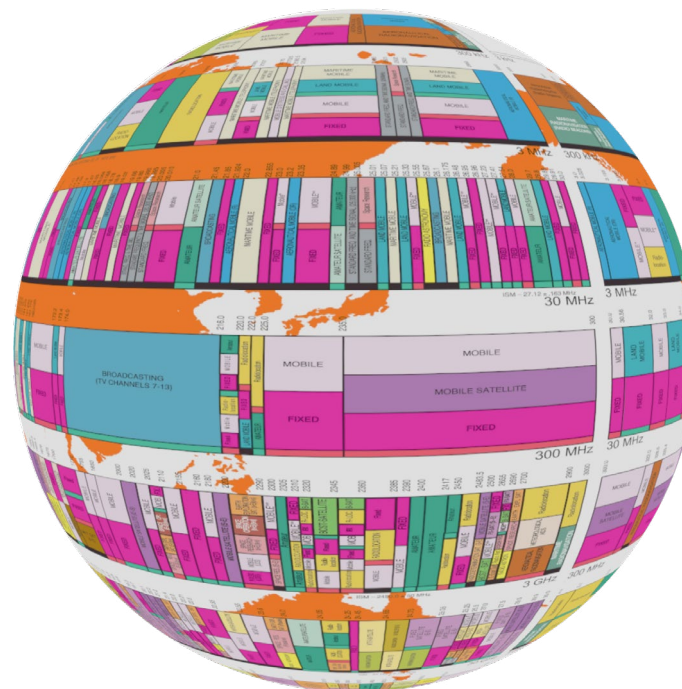


Figure 1: Today's fragmented RF spectrum

2 Making sense of RF signals and the RF spectrum

Mobile radio frequency (RF) signals are the foundation of our interconnected world

Radio signals sit at the low-energy end of the electromagnetic spectrum with wavelengths ranging from 1 mm to more than 100 km, and frequencies spanning 3 kHz to 300 GHz. Collectively they form the RF spectrum which is subdivided into multiple “frequency bands” to simplify classification and spectrum management. Within telecommunications, the 600 MHz to 6 GHz range remains the most widely used portion of the spectrum for mobile communications, broadcast and radar technologies.

These frequencies offer an effective balance of coverage, propagation and data capacity, making them ideally suited to large-scale wireless connectivity. As a result, they continue to form the foundational layer underpinning billions of connected devices and global wireless networks, even as emerging technologies increasingly explore mmWave and satellite-based communications.

RF frequency bands explained

The term “frequency band” refers to a defined range of RF frequencies allocated to specific services, applications or industries. Their usage is tightly controlled through national and international spectrum management frameworks and overseen by country-specific regulatory authorities. These organisations are responsible for co-ordinating spectrum management and licensing frequency bands to a wide range of stakeholders, including mobile network operators.

Escalating mobile data consumption, driven by smartphones and an expanding ecosystem of IoT devices, is driving the need for additional spectrum allocations. As new wireless standards and services emerge, policing the RF spectrum is becoming significantly more difficult, with a growing number of technologies, industries and operators all competing for access to limited licensed and unlicensed spectrum resources.



Low Band
(The backbone of all mobile networks)
600 – 1000 MHz



Mid/High Band
~1.76 – ~2.6 GHz



Ultra High Band
~3.0 – ~6.0 GHz



mmWave
(High speed data for densely populated areas)
>20 GHz

3 RF frequency bands and mobile radio front-end complexity

The global RF spectrum is becoming increasingly fragmented as regulators allocate new frequency bands to support emerging wireless services and growing connectivity demands.

As a result, device manufacturers must design products capable of operating across a broader range of frequencies, bandwidths and international spectrum allocations. This evolution is placing unprecedented demands on mobile radio front-end architectures.

From a network infrastructure perspective, greater densification is needed to maintain coverage and service continuity. At the device level, mobile radio front-ends are growing in complexity and size as additional components, including fixed frequency Bulk Acoustic Wave (BAW) and Surface Acoustic Wave (SAW) filters, duplexers, selector switches, etc are needed to support the growing number of global frequency bands and carrier combinations.

Fixed frequency filters and duplexers explained

Fixed-frequency Bulk Acoustic Wave (BAW) and Surface Acoustic Wave (SAW) filters and duplexers are fundamental components within modern wireless device RF front-ends. They are made of piezoelectric crystals and films and enable frequency selection and signal isolation, ensuring transmitters and receivers can operate simultaneously without interference.

By preventing transmitted RF signals from leaking into the receiver path, usually referred to as self-interference, these components play a critical role in maintaining signal integrity, wireless performance and overall quality of service.

While fixed-frequency architectures have underpinned decades of wireless innovation, their reliance on dedicated filtering hardware for each operating band and bandwidth presents scalability challenges as spectrum allocations become increasingly fragmented. This has driven interest in more adaptable RF front-end architectures capable of supporting multiple frequency bands using fewer configurable components.

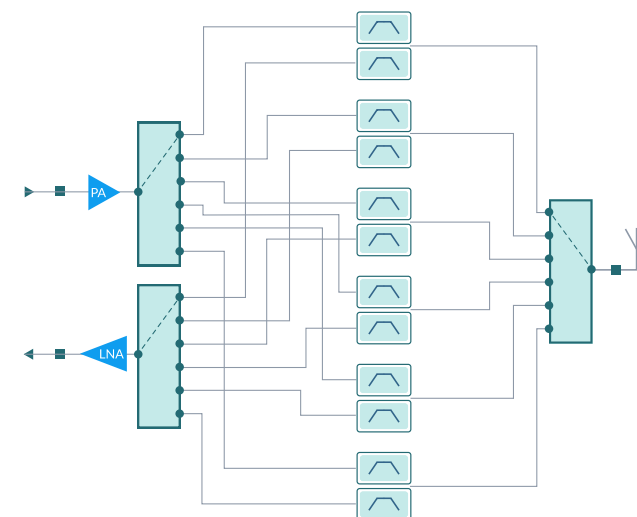


Figure 2: This infographic demonstrates the complexity of a typical RF front-end supporting 6 bands

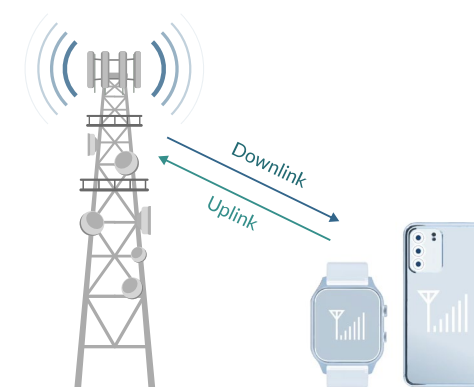


Figure 3: Typical communications between a mobile device and a base station in FDD mode

More bands – more filters

When the first smartphones were launched in the late 1990s/early 2000s, only two frequency bands were in use. At device level this meant four filters were needed, two for transmit (TX) and two for receive (RX). Each TX/RX filter pair forms a single “duplex filter” or “duplexer”. By 2010, support for 8 frequency bands was required. Fast-forward to now and regular wireless devices (smartphones, wearables, etc) must support 32+ bands which equates to 32+ duplex filters and this figure is continuing to rise.

The growth in supported frequency bands has a direct impact on RF hardware requirements. Because each frequency band requires its own dedicated filtering resources, increases in band support translate directly into additional RF components occupying valuable PCB area.

To give this some perspective:

- Each frequency band requires a dedicated fixed-frequency duplex filter supported by selector switches
- Each packaged duplexer measures approximately 1.6 x 1.2 mm
- 30 duplexers alone occupy at least 66 mm² of PCB space. This includes 100 µm spacing between filters, but excludes the required routing

Advanced RF technologies and radio front-end designs

Fuelled by global demand for faster data speeds and greater network capacity, the wireless communications landscape has evolved significantly. Advanced signal processing technologies such as Carrier Aggregation (CA), Multiple-Input Multiple-Output (MIMO) and Diversity are now widely deployed to improve network performance, spectral efficiency and user experience.

While these technologies play a critical role in enabling higher data throughput and supporting increasing mobile network capacity demands, they also add significant complexity to RF front-end architectures. Supporting these advanced capabilities requires additional filters, duplexers, antennas and associated components, increasing hardware requirements and overall component count, and compounding challenges around scalability, efficiency and overall system optimisation.

Understanding Carrier Aggregation

Carrier Aggregation (CA) enables a mobile device to simultaneously access and combine multiple frequency carriers into a single data connection. This approach allows fragmented spectrum resources to be utilised more efficiently while delivering higher peak data rates and improved network performance. However, supporting multiple concurrent frequency bands places additional demands on RF front-end architectures and associated filtering technologies.

Understanding MIMO

Multiple-Input Multiple-Output (MIMO) is a wireless technology that uses multiple antennas to transmit and receive several independent data streams simultaneously. By exploiting spatial diversity within the radio environment, MIMO increases the amount of information that can be carried within a given bandwidth and has become a foundational technology in modern 4G and 5G networks.

Understanding Diversity

Diversity is a wireless communication technique that improves link reliability by providing multiple signal paths between the transmitter and receiver. Rather than increasing capacity, diversity reduces the impact of fading, interference and signal blockage by allowing the strongest or most reliable signal to be selected or combined. This helps maintain stable connectivity and consistent service quality, particularly in challenging radio environments.

As wireless systems continue to evolve, simply increasing the number of RF components is becoming an unsustainable approach. Next-generation filtering technologies must provide greater adaptability and performance while reducing overall hardware requirements and complexity.

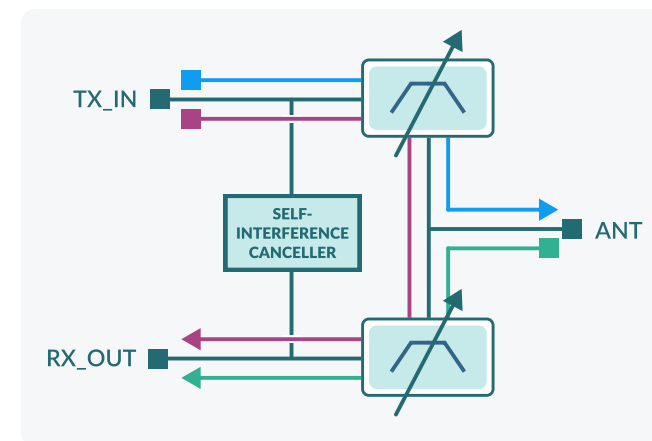
4 The Tunable Duplexer

Tunable RF front-end architectures are becoming essential to enable scalable global connectivity across next-generation wireless devices.

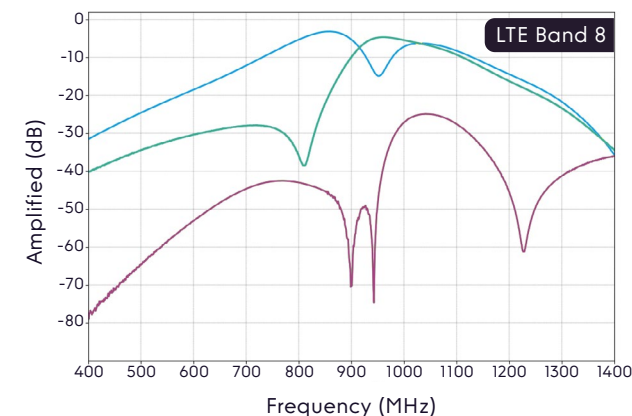
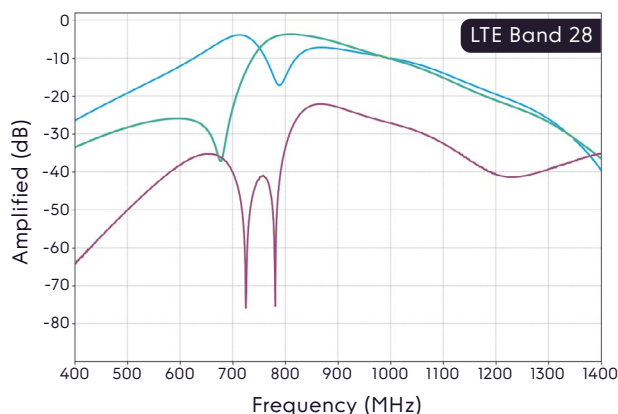
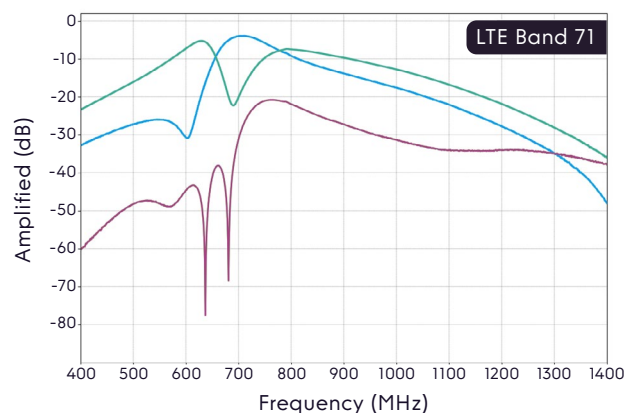
Unlike conventional duplexers, which are designed to operate within a fixed frequency range, tunable duplexers can dynamically adjust their operating characteristics to support different frequency bands using a single hardware platform. This capability is achieved through electronically controlled tuning elements that modify the resonant behaviour of the filtering network, allowing the duplexer to be reconfigured as operating requirements change.

Depending on the implementation, a tunable duplexer may support multiple frequency bands, wireless standards or regional spectrum allocations without requiring dedicated fixed-frequency filtering hardware for each operating band.

As wireless networks continue to evolve, and spectrum utilisation becomes increasingly fragmented, tunable duplexers have emerged as a viable alternative to conventional fixed-frequency RF front-end designs.



- Transmit output to Antenna - Insertion Loss
- Antenna to Receiver input - Insertion Loss
- Transmit to Receive Isolation



Key benefits

- **Flexibility:** Tunable duplexers can dynamically support multiple frequency bands and wireless standards, making them ideally suited to multi-band and multi-mode connected products. This adaptability helps future-proof designs against evolving wireless technologies and regional spectrum requirements
- **Multiband support:** Tunable duplexers can support 20+ frequency bands compared with the four typically supported by switched fixed-filter architectures. This capability is critical for reducing RF front-end complexity and enabling further device miniaturisation
- **Size efficiency:** Reducing the need for fixed-frequency filters, selector switches and associated RF components enables a significantly smaller RF front-end footprint and more efficient system integration
- **Single global SKU enablement:** Greater frequency band coverage minimises the need for multiple regional hardware variants, simplifying RF system design, streamlining supply chains, lowering development costs and accelerating time-to-market
- **Antenna mismatch robustness:** Connected products such as smartwatches are subject to significant antenna impedance variation caused by user interaction, device positioning and surrounding environmental conditions. Tunable duplexer architectures capable of adapting to higher antenna VSWR conditions provide greater tolerance to antenna detuning, helping maintain transmit efficiency and receiver sensitivity in real-world operating environments
- **Sustainability:** Reducing component count and increasing frequency band support helps minimise material usage, manufacturing complexity and overproduction, contributing to lower overall environmental impact and reduced CO₂ emissions

Limitations of conventional tunable duplexers

Conventional tunable duplexers are typically based on technologies such as varactor diodes, MEMS (Micro-Electro-Mechanical Systems) devices and other electronically adjustable tuning elements. These approaches enable the operating frequency of the duplexer to be reconfigured dynamically, reducing dependence on dedicated fixed-frequency filtering solutions.

Despite their flexibility, conventional tunable duplexer implementations have historically struggled to achieve the levels of isolation required by modern RF systems, particularly in demanding cellular applications. Insufficient isolation can allow transmit energy to leak into the receiver path, degrading receiver sensitivity and limiting overall system performance.

Proprietary technology that overcomes the band-specific limitations of BAW/SAW filters for the very first time

Forefront RF is pioneering a new approach to RF front-end design architectures in smartphones, wearables and next-generation IoT devices by replacing fixed-frequency duplex filters with a frequency-agnostic solution that is dynamically tunable according to available frequencies. The company is developing an end-to-end mobile radio front-end module that incorporates:

- Tunable duplexer
- Self-interference canceller
- Power amplifier
- Low noise amplifier
- Bidirectional Coupler

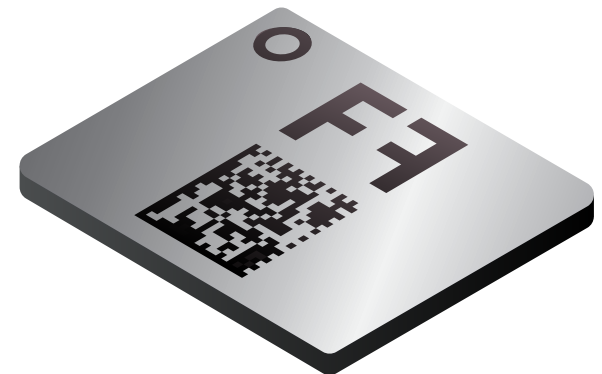
Enabled by patented Foretune™ technology

A milestone in RF signal processing advancement, Forefront RF has overcome the historical transmit-to-receive leakage challenges associated with conventional tunable duplexers. Using advanced self-interference cancellation techniques, Foretune suppresses unwanted transmit signals within the receiver path while maintaining the high levels of isolation needed for modern wireless systems. The principle is comparable to noise-cancelling headphones, which improve audio clarity by detecting external noise, inverting the signal and cancelling unwanted interference.

Foretune technology allows Forefront RF to integrate a high-performance tunable duplexer within a microminiature RF front-end module capable of supporting 3G, 4G and 5G applications. By replacing multiple fixed-frequency components with a dynamically tunable alternative, the company's proprietary Foretune technology reduces RF front-end size and complexity while supporting a significantly broader frequency range. As connectivity requirements continue to evolve, tunable RF architectures offer a more efficient path to simplifying hardware design and enabling globally deployable products.

This gives OEMs and ODMs greater flexibility to simplify RF front-end design, reduce component count and develop more compact connected products with broader frequency support.

By supporting multiple frequency bands within a simplified architecture, Forefront RF's technology reduces the need for multiple regional hardware variants and supports the development of single global SKU products. This helps manufacturers streamline worldwide product deployment while reducing supply chain complexity, overall system cost and material waste.



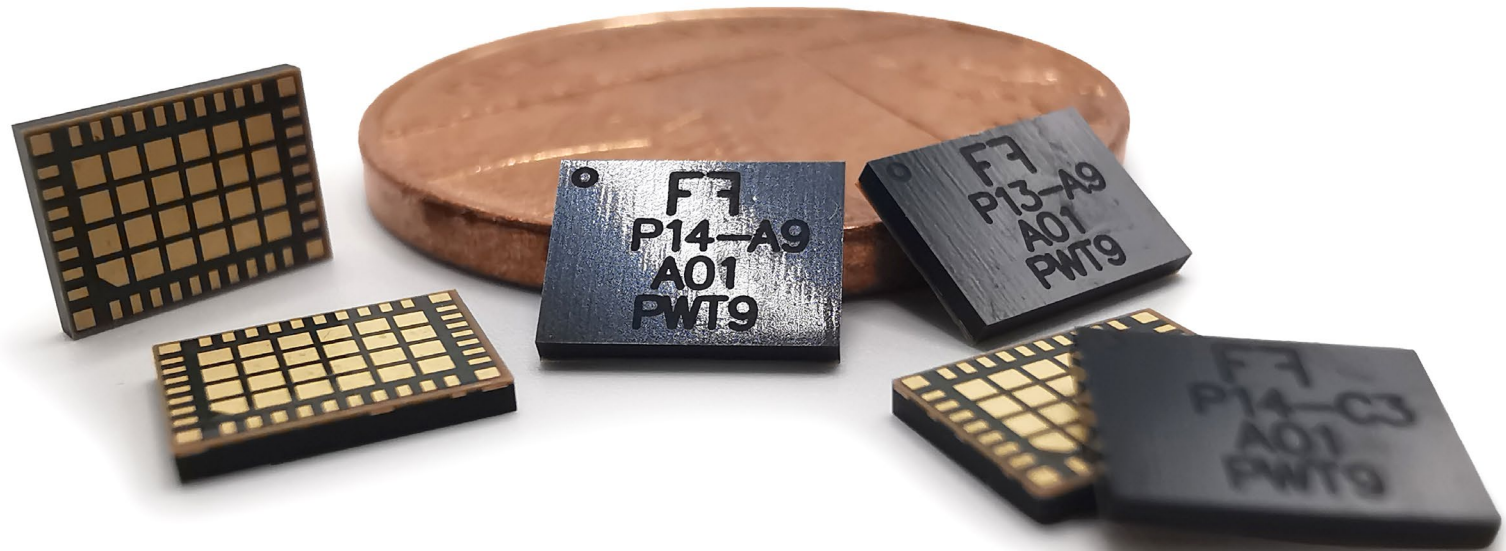
Based on award winning research

Forefront RF's patented Foretune™ technology is based on award-winning research conducted at the University of Bristol. The underlying innovation addresses the long-standing challenge of self-interference cancellation, a critical barrier that has historically limited the performance and commercial viability of tunable duplexer technologies.

Today, Forefront RF is combining advanced RF research with industry expertise to develop a reconfigurable RF front-end technology designed to simplify global wireless connectivity by supporting broader frequency coverage within a single RF module.

The company's first-generation product, the FFM51010, has a footprint of 4.5 x 6mm, and has been developed for operation across frequency bands in the 600–1000 MHz range. The underlying technology is protected by a broad international patent portfolio and is marketed under the Foretune trademark.

The same technology is also allowing Forefront RF to develop solutions for satellite-to-device applications and for solving co-existence solutions.



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Conclusion

Forefront RF's Fortune™ technology addresses the growing RF front-end challenges associated with expanding frequency band support, increasing spectrum fragmentation and the evolution of global wireless connectivity requirements.

By replacing multiple fixed-frequency components with a dynamically tunable architecture, Fortune simplifies RF front-end design, reduces component count and offers multiband support for compact connected products. This helps manufacturers reduce hardware complexity, streamline global product deployment and support single global SKU strategies across multiple markets and operator requirements. As wireless devices continue to evolve, Fortune technology represents a more flexible and scalable approach to RF front-end design, supporting the development of next-generation connected products designed for efficient worldwide deployment.

About Forefront RF

Founded in 2020, Forefront RF is a fabless semiconductor company poised to transform the way multi-band smartphones, wearables and other connected devices are designed. Based on award-winning academic research, the company is developing a groundbreaking technology that reduces PCB space through fewer components and increases the number of supported frequency bands. With the mobile phone and adjacent markets embracing miniaturization and simplification, Forefront RF's next-generation solution empowers OEMs and ODMs to incorporate a range of advanced features into their designs while reducing the overall cost, size and weight of the end-product. The company is headquartered in Cambridge UK, with a subsidiary office in the Netherlands.



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