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Self-Interference Cancellation for Co-Located TDD Radios Sharing the Same Band

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A self-interference canceller on a chip enables real-time software programmable suppression of the interference a transmitter presents to a co-located receiver, even if the two radios operate with zero guard band between them. This allows unprecedented densification and spectrum utilization in every RF environment.

A Boeing 787 Dreamliner has more than 20 antennas protruding from its fuselage, with multiples operating in the HF, VHF and UHF bands (see ***Figure 1***). To minimize interference between radios using the same band, their antennas are spread around the airplane to maximize the isolation among them.[1] Nowadays, nearly every military platform packs multiple radios and antennas: satellites, planes, ships, ground vehicles, drones—even the backs of soldiers, which carry tactical manpack radios. The smaller the platform, the closer the antennas and the stronger the interference.

The conventional solution is to use RF filters to block the transmission of one radio from affecting the receiver of another. However, filters are plagued with many problems: they are in the RF path of the receiver, affecting its noise figure. The sharper the desired frequency response, the larger and heavier the filter. On moving platforms, weight and size are at a premium, especially if the "platform" is a soldier's back. The filter is static; it can never adjust its passband or stopband, which represents an impossible problem for frequency-hopping radios that share the same band and hop across the entire band. As good as a filter might be, it still requires a certain guard band, since the cutoff response is never perfect, resulting is some unutilized channels near the transmitter.

This problem affects every RF environment. In the 2.4 GHz ISM band, Wi-Fi transmissions often desensitize the receivers of co-located IoT radios, such as Zigbee or Bluetooth Low Energy (BLE) or co-located Bluetooth receivers for audio streaming applications.[2] This, for example, is why Bluetooth speakers typically do not share the same enclosure as Wi-Fi access points. Similarly, in the 5 GHz ISM band—and soon the 6 GHz band—multiple co-located Wi-Fi radios never share the same frequency segment. The so-called Wi-Fi mesh devices always ensure that one Wi-Fi radio is limited to the lower part of the 5 GHz band (UNII-1 and UNII-2a), while the other is con-

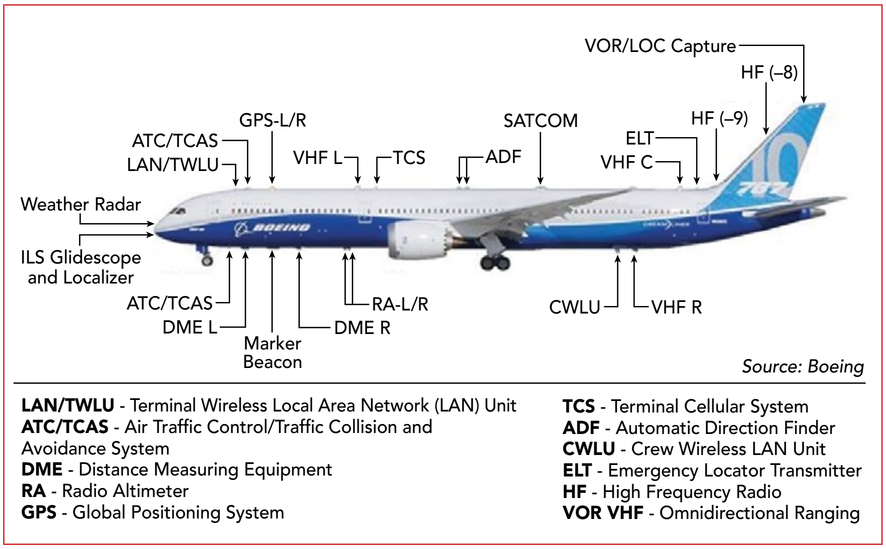

Fig. 1 **Antennas on a Boeing 787.**

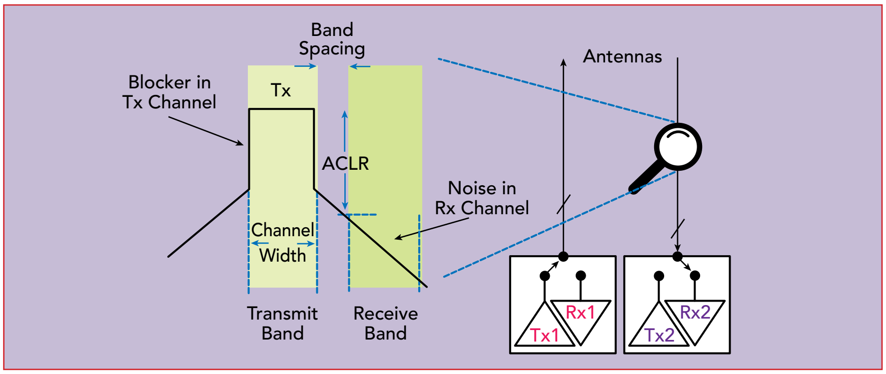

Fig. 2 **Adjacent channel interference.**

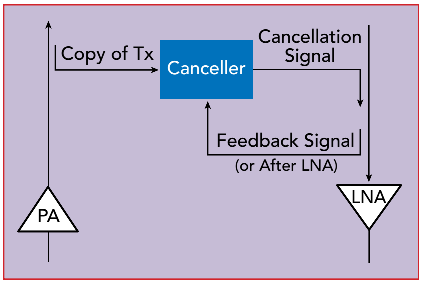

Fig. 3 **Architecture for self-interference cancellation.**

fined to the upper part of the band (UNII-2c and UNII-3). This scheme works by using the 160 MHz gap in the middle of the 5 GHz band. With the projected release of UNII-4 and higher frequencies in the 6 GHz band, this approach is likely to fall apart.

As 5G networks migrate from FDD to TDD, they will suffer self-interference from co-located radios. An AT&T radio operating in physical and frequency proximity to a Verizon Wireless radio will interfere with each other unless the radios are synchronized to transmit and receive at the exact same time, all the time.

This article describes a self-interference cancellation solution to the co-existence challenges of co-located radios operating on nearby frequencies.[3]

THE TECHNICAL CHALLENGE

A transmitting radio obviously emits a large amount of energy in its intended channel. This energy is a "blocker" for a nearby receiver, even if the receiver is listening on a different channel. The transmitter also leaks noise into the adjacent channels where nearby receivers may be listening, a phenomenon known as the "noise skirt" of the transmitter (see ***Figure 2***). Both sources of interference must be suppressed for a receiver to operate normally in the presence of a nearby transmitter.[4]

Filters are only useful when the transmitter and receiver are sufficiently far away in frequency to ensure a sufficient guard band between them. Since filters are static and passive, any change in the desired response between the interfering and interfered radios requires a different filter. In practical systems, this results in large filter banks that are undesirable.

In highly regulated environments, the interference problem is typically solved through predefined frequency allocations, large guard bands—with enormous spectrum waste—and strict spectral masks and output power limitations. That is obviously not the case in the defense space, nor is it true in the unlicensed spectrum bands allocated to ISM and used for Wi-Fi, IoT, Bluetooth and other consumer applications.

SELF-INTERFERENCE CANCELLATION

Self-interference cancellation technology offers a superior solution to some of the most challenging radio filter applications, promising dramatic size, weight and performance benefits. While conventional radio filters have changed little since vacuum tube days, self-interference cancellation brings radio filtering into the software-controlled, IC era. Instead of blocking certain frequencies, cancellation directly addresses the source of interference by "cancelling" it.[5] Fundamentally, self-interference cancellation is similar to noise-cancelling headphones. Noise-cancelling headphones sample the noise, measure key parameters and create a cancellation signal 180 degrees out of phase with the noise. When the cancellation signal is combined with the noise, the two signals cancel each other. Likewise, self-interference cancellation samples the interference, measures key parameters and creates a cancellation signal. When the cancellation signal is combined with the interfering signal, the two signals cancel each other (see ***Figure 3***).

While conceptually simple, implementing a canceller is challenging. The transmitter noise seen by the receiver is not static: it is affected by channel effects like fading

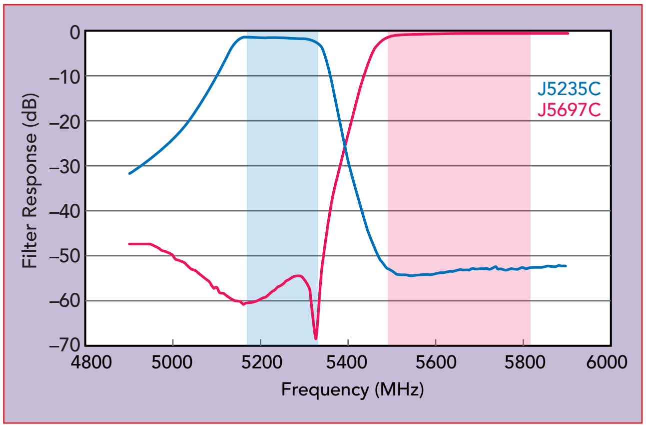

Fig. 4 **Frequency response of Cirocomm Wi-Fi filters.**

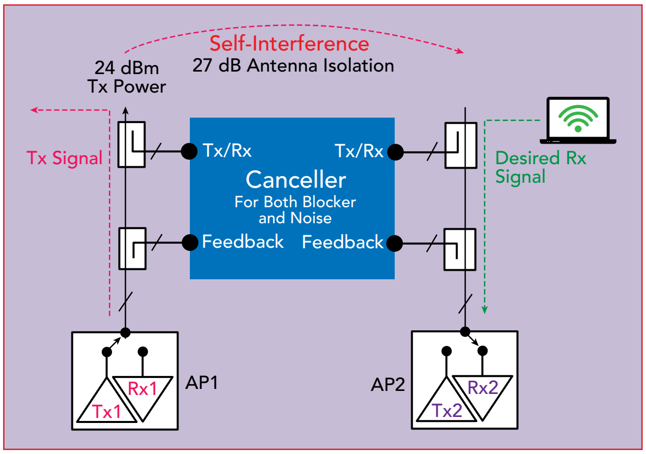

Fig. 5 **Dual 5 GHz radio test setup.**

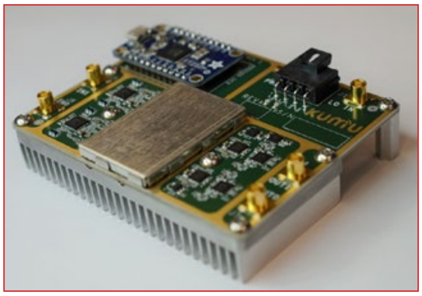

Fig. 6 **Kumu Networks' RFIC evaluation board.**

and by dynamically varying multipath due to reflections off moving objects near the radio. As such, the canceller must track the changing self-interference channel with a speed and accuracy to achieve the amount of desired cancellation. Further, the solution must not introduce noise that decreases the receiver sensitivity, meaning it must handle the large blocking signal while not introducing noise above the receiver's sensitivity level. This translates to a very large dynamic range where the circuit must be linear.

TEST SETUP FOR RADIO CO-EXISTENCE

A class of consumer and enterprise products commonly known as tri-band Wi-Fi routers—tri-band because such products integrate one 2.4 GHz and two 5 GHz radios —typically use filters to isolate one 5 GHz radio from the other. Within the FCC allocation, one 5 GHz radio always selects a channel between 5170 and 5330 MHz, while the other radio picks a channel between 5490 and 5835 MHz. The unallocated 160 MHz gap between the two bands is used as the transition band for the filter. ***Figure 4*** shows the response of commonly used filters.[6] A smaller gap would be an impossible challenge for the filter, as its roll-off would not be sharp enough to handle the narrower guard band.

To test the performance of cancellation in a live environment, a test setup in the unlicensed 5 GHz ISM band was constructed. The goal was to operate the two radios anywhere in the band, even with no guard band between them (see ***Figure 5***). Unlike a filter, the cancellation technology is tunable for the desired frequency of operation, so it allows the two 5 GHz radios to operate anywhere in the band, not requiring them to be at opposite ends of the spectrum. The setup included two radios using the standard Qualcomm 802.11ax reference design based on the recently introduced IPQ8074 SoC. To represent a practical use case, instead of randomly placing the antennas, the setup used the antenna configuration of a Cisco Aironet 3800 enclosure. The self-interference canceller used Kumu Networks' MIMO-capable KU1500 RFIC, tuned using patented, real-time tuning algorithms (see ***Figure 6***).

The challenge is to transmit from one of the Wi-Fi radios, operating at its maximum output power of 24 dBm and maximum bandwidth of 80 MHz, while receiving on the other Wi-Fi radio. The critical metric is the sensitivity degradation of the receiving radio. Commonly used Wi-Fi filters affect receiver sensitivity by approximately 2.5 dB due to their insertion loss, even when the radios operate 160 MHz apart. Unlike filters, the self-interference cancellation is not in the RF path; it is only connected to the RF path using couplers, which negligibly contribute to the insertion loss.

MEASURED PERFORMANCE

A spectrum analyzer measured the transmitter's interference at the input of the "victim" receiver's LNA. The analyzer screen shots in ***Figures 7, 8*** and ***9*** show the noise the transmitter makes in its intended channel (i.e., the blocker) and the noise leaking to the adjacent channels, where the receiver operates (i.e., the noise skirt). In each, the self-interference is measured with the canceller off (yellow) and on (purple).

To establish a baseline and ensure that cancellation is not worse than using the filter, the initial test used a 160 MHz gap between the interfering transmitter and co-located receiver (see Figure 7). Markers 7 and 8 represent the interfering transmitter and markers 9 and 10 the co-located receiver. This 160 MHz gap is the minimum supported by commercial off-the-shelf filters used in current tri-band Wi-Fi designs. With a transmit noise level in the receive channel of approximately −81 dBm, the canceller suppresses it to around −99 dBm, very close to the noise floor. While this is only 18 dB cancellation, the amount is limited by the noise floor, and the new noise level of −99 dBm represents a noise figure hit lower than the insertion loss of the Wi-Fi filters. Even if the radios are using separated channels where traditional filters are effective, the cancellation circuit provides better performance. Simultaneously, the canceller suppresses the Tx channel blocker by 33 dB to avoid saturating the receiver LNA.

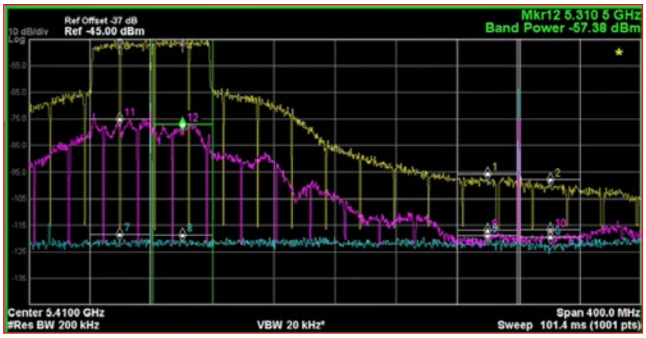

Fig. 7 Two 5 GHz radios with 160 MHz gap.

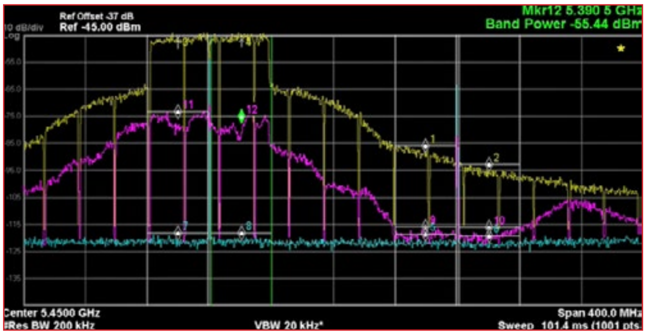

Fig. 8 Two 5 GHz radios with 80 MHz gap.

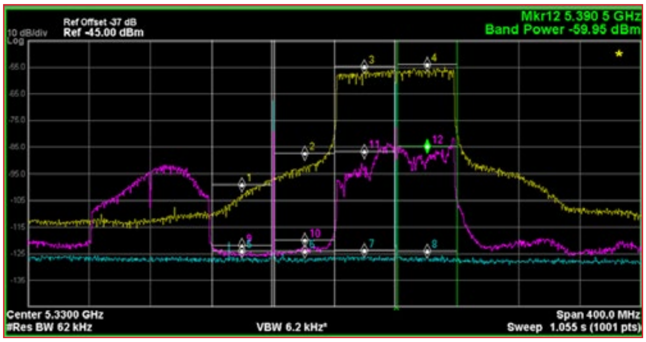

Fig. 9 Two 5 GHz radios with 0 MHz gap.

When the guard band is smaller, 80 MHz for example, it is usually not feasible to use fixed filters, as the Tx /Rx guard band is not large enough. With the canceller, the transmit noise in the receive channel is reduced close to the noise floor (see Figure 8). With a gap of 80 MHz, the transmit noise of approximately −76 dBm in the receive channel is suppressed to −98 dBm, 22 dB cancellation—only limited by the noise floor. Tx blocker suppression is similar to the first case.

The ultimate challenge is to maximize spectral use by eliminating the guard band and operating co-located radios on immediately adjacent frequencies, i.e., with zero guard band between them. Fixed filters obviously cannot be used in this configuration. However, self-interference cancellation can (see Figure 9). In this case, about 40 dB cancellation in the immediately adjacent channel is achieved. Adding to the challenge, the interfering transmitter is now operating at a higher frequency than the receiver. Switching the radios is possible with the software configuration of the canceller, yet impossible using fixed filters. It is immensely valuable to have this flexibility, especially when the two radios have different MIMO orders. The spectrum analyzer response shows a "hump" in the cancellation signal to the left of the receive channel; this reflects insufficient I/Q imbalance compensation in the test board.

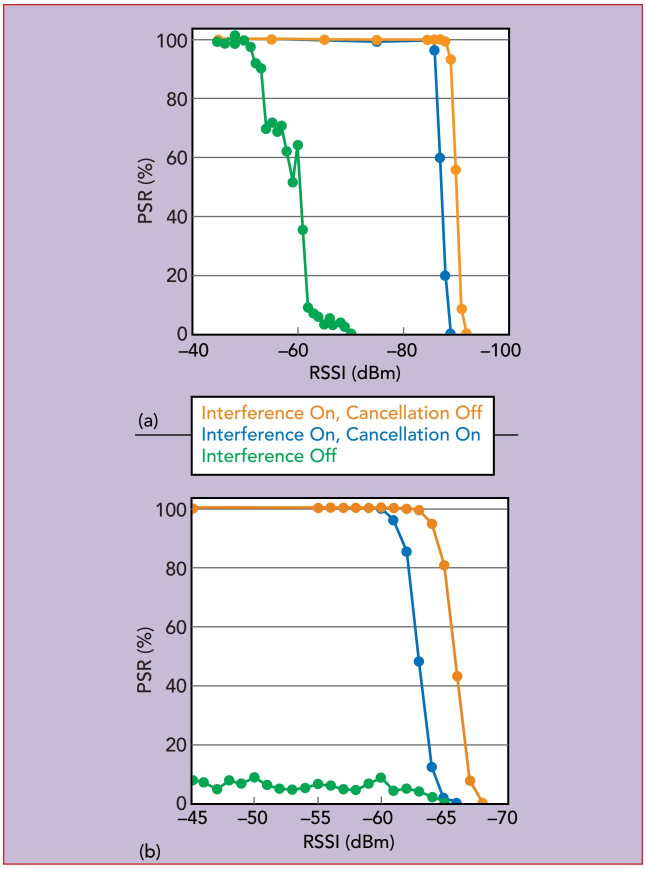

Fig. 10 Zero guard band PSR vs. RSSI for MCS-0 (a) and MCS-9 (b).

In addition to cancellation and noise figure, the packet success rate (PSR) in the presence of local interference was measured (see ***Figure 10***), evaluating radio performance at different received signal strengths (RSSI) and modulation and coding schemes (MCS), selected to show performance at two extremes: MCS-0 is the lowest data rate coding, BPSK rate ½ and MCS-9 is 256-QAM, rate ⅚. Without cancellation, using the high data rate MCS-9 is impossible, and packets at MCS-0 barely squeak by. The performance with cancellation very closely mirrors the performance of the system without interference. The delta relative to the optimal performance with no interference is often smaller than the insertion loss of filters.

SUMMARY

For applications where two physically co-located radios must operate on close frequency channels, self-interference cancellation provides a solution that is often better than using traditional fixed filters. Fixed filters introduce insertion loss into the receive chain; the cancellation circuit is only attached to the receiver via a coupler, minimizing the impact to noise figure. Cancellation is software programmable and can adjust to changing transmit and receive frequencies, crucial for frequency-hopping systems such as IoT and military radios. Cancellation can also operate with absolutely no guard band, i.e., when the interfering radio is on the channel immediately adjacent to the receiver.

These scenarios when two co-located radios need to co-exist without interference are common, found on nearly every military platform and consumer electronics in the unlicensed bands. Soon the challenge will be with 5G systems using the TDD bands, where radios from different operators will interfere with each other unless they are synchronized.■

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