

Applications of Self-Interference Cancellation in 5G and Beyond

Steven Hong, Joel Brand, Jung Il Choi, Mayank Jain, Jeff Mehlman, Kumu Networks
Sachin Katti, and Philip Levis, Kumu Networks and Stanford University

ABSTRACT

Self-interference cancellation invalidates a long-held fundamental assumption in wireless network design that radios can only operate in half duplex mode on the same channel. Beyond enabling true in-band full duplex, which effectively doubles spectral efficiency, self-interference cancellation tremendously simplifies spectrum management. Not only does it render entire ecosystems like TD-LTE obsolete, it enables future networks to leverage fragmented spectrum, a pressing global issue that will continue to worsen in 5G networks. Self-interference cancellation offers the potential to complement and sustain the evolution of 5G technologies toward denser heterogeneous networks and can be utilized in wireless communication systems in multiple ways, including increased link capacity, spectrum virtualization, any-division duplexing (ADD), novel relay solutions, and enhanced interference coordination. By virtue of its fundamental nature, self-interference cancellation will have a tremendous impact on 5G networks and beyond.

INTRODUCTION

“It is generally not possible for radios to receive and transmit on the same frequency band because of the interference that results.”

(Andrea Goldsmith,
Wireless Communications [1])

The above quote captures a long-held assumption in wireless system design that radios have to operate in half duplex mode (i.e., either transmit or receive, but not both simultaneously) on the same channel. Recent work has attempted to invalidate this assumption. Researchers at Stanford [2–5] and Rice [6], and several other groups in industry [7] and academia [8, 9] have proposed various designs to build in-band full-duplex radios. Full duplex, if possible, has tremendous implications for network design; for example, enabling cellular networks to double their spectral efficiency. LTE frequency-division duplex (FDD) today uses two separate channels, one for uplink and one for downlink, to enable

radios to achieve full duplex. With an in-band full duplex system, a single channel can be utilized to achieve the same performance, immediately doubling the value of spectrum assets worth billions of dollars.

Why is full duplex hard to realize? When a radio transmits a signal, some of that energy is heard by its own receiver. Because it is generated locally, this unwanted self-interference energy is billions of times (100 dB+) stronger than the desired receive signal. Trying to transmit and receive at the same time in the same channel is the equivalent of trying to hear a whisper while shouting at the top of your lungs. This is a known and unsolved problem; every radio ever designed avoids self-interference by either transmitting or receiving on a given frequency, never doing both simultaneously.

Given that half duplex operation is necessitated by self-interference, how would future 5G wireless networks change if *radios could completely cancel self-interference*? Tremendous progress, in both industry and academia, has been made in self-interference cancellation (SIC), with several groups demonstrating live cancellation results in real world environments. Coupled with the ever expanding body of knowledge on the topic, many believe that it is a matter of when, rather than if, SIC performance will enable true full duplex. While we briefly review the state of the art in SIC architectures and performance, the goal of this article is not to delve into the sophisticated modeling of self-interference, nor is it to evaluate the efficacy of different cancellation techniques, as there are numerous well written articles on both. Rather, our intention is to explore the long-term and short-term implications of SIC as an enabler to support the future demand for data consumption, seamless global roaming, high-throughput services, and low-latency applications cost effectively within the limited available spectrum for fifth generation (5G) wireless communications and beyond.

SIC offers the potential to complement and sustain the evolution of 5G technologies toward denser heterogeneous networks and can be utilized in wireless communication systems in multiple ways, including:

- Increased link capacity: Theoretically, true full duplex doubles the link capacity with respect to traditional half duplex, because the available spectral resources can be fully utilized in time and frequency.
- Spectrum virtualization: Full duplex is the extreme case where two channels are completely overlapped, but SIC can isolate any pairs of transmit and receive frequencies. In essence, it can act as a software controlled duplexer to simplify and reduce the cost of supporting multiple fragmented frequencies, effectively enabling radios to exploit fragmented spectrum.
- Any-division duplexing (ADD): SIC eliminates the distinction between TDD and FDD. TDD is rendered obsolete, replaced by in-band full duplex, while legacy FDD greatly benefits from the configurability of SIC, becoming adaptive and capable of flexible carrier aggregation.
- Novel relay solutions: Simultaneous reuse of spectrum resources in both the backhaul and access is possible with self-interference cancellation, enabling almost instantaneous retransmission and high-throughput mesh operation for heterogeneous networks.
- Enhanced interference coordination: Simultaneous reception of feedback information (e.g., control channel signaling) while transmitting data enables reduced air interface delay and tighter time/phase synchronization for interference cooperation techniques such as coordinated multipoint (CoMP) transmission.

In practice, even when SIC performance sufficiently enables full duplex wireless, the potential adoption of SIC into future 5G networks and other applications will be dictated by regulatory acceptance. Regulatory acceptance includes standards adoption (e.g., 5G) as well as spectrum policy shifts by regulatory bodies, both of which act together to align disparate actors (i.e., handset and infrastructure original equipment manufacturers, OEMs), allowing all parties to take advantage of network effects and increasing returns.

Not all applications require standards modifications; in fact, many require none at all. Self-interference is a phenomenon that limits the performance of all half duplex systems today, and SIC can be employed immediately to solve many of these problems. Figure 1 shows how different applications are impacted to various degrees with respect to the need for standardization, and you can see that several applications can benefit tremendously even without standards modifications. In this article, we evaluate the potential impact of SIC to different applications as a function of this vector, beginning with applications that require no standards modifications before discussing those that will require 5G standardization. We finish on a more general note, discussing applications of SIC beyond 5G cellular networks.

We frame the conversation by first discussing the general architecture of an SIC solution, highlighting the drivers of performance and integration. We then begin with applications that can leverage SIC with absolutely no change or modifications of existing standards or infra-

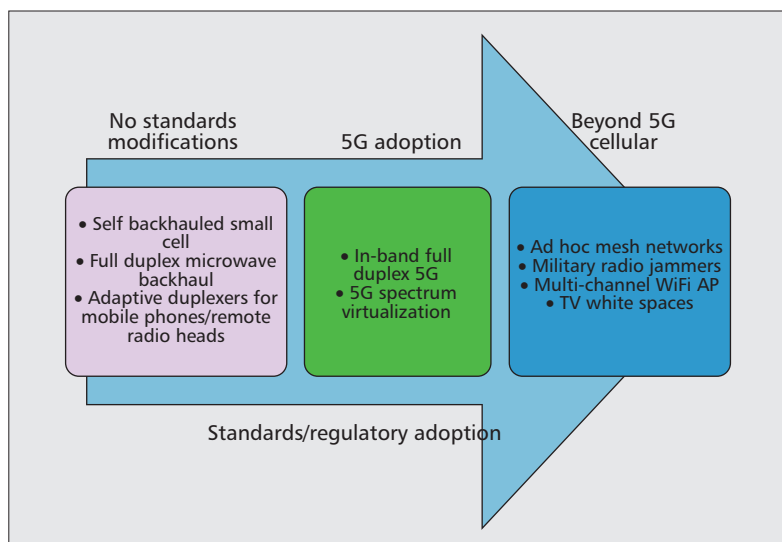


Figure 1. SIC impacts a variety of horizontal applications. Some applications can be implemented without any standards modifications (shown in purple), while others require standardization to be realized (shown in green). Beyond 5G, SIC is applicable to any and all radio designs with varying degrees of standards required (shown in blue).

structure. Among these applications, we order them beginning with those employed on the infrastructure side before moving on to those that can also be employed on the handset side. Lastly, we conclude by discussing the long-term implications of SIC in 5G, the impact of different degrees of regulatory acceptance, and what we believe will be the inflection points driving standards and spectrum policy adoption.

SIC ARCHITECTURES: COST AND INTEGRATION DRIVERS

Why is self-interference hard to subtract? After all, the sender knows the signal being transmitted, so subtracting it should be relatively simple to implement. In practice, this abstraction is incorrect: while the radio knows the clean transmitted digital baseband signal, once the signal is converted to analog and up-converted to the right carrier frequency, the transmitted signal looks quite different from its baseband incarnation. The numerous analog components in the radio TX chain distort the signal in both linear and nonlinear ways (e.g., analog circuits will create cubic and higher-order components of the signal), add their own noise (e.g., power amplifiers add transmitter noise), are slightly inaccurate (e.g., an oscillator is tuned slightly off 2.45 GHz), or delay it by different amounts at different frequencies, and so on. In effect the transmitted signal is a complicated nonlinear function of the ideal transmitted signal along with unknown noise. Unsurprisingly, naively subtracting a “known” baseband version of the transmit signal without accounting for all these analog distortions does not work [2].

The goal of any SIC architecture is to model and predict these distortions such that it can compensate for them at the receiver [2]. There are two effects that must be dealt with: receiver

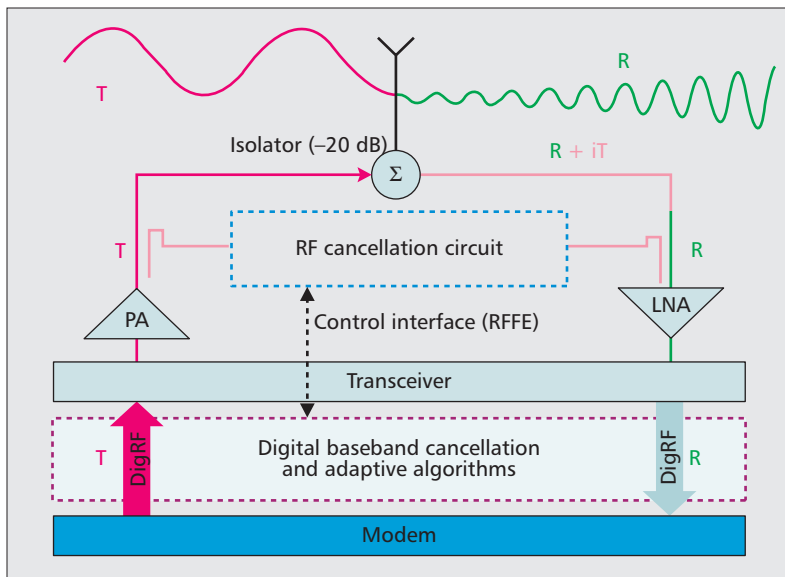


Figure 2. Analog cancellation (shown in blue) is necessary to prevent receiver saturation (~50–80 dB). Once within the dynamic range of the receiver, digital cancellation (shown in purple) can handle the remaining distortions (~60 dB).

saturation and nonlinear self-interference. Receiver chains in radios get saturated if the input signal is beyond a particular level that is determined by their analog-to-digital conversion (ADC) resolution. Even if the receiver had infinite dynamic range and did not saturate, the leaked interference self-interference looks nothing like the transmitted baseband signal, consisting of several nonlinear harmonic components that are significantly higher than the noise floor. Any cancellation done in digital must model these distortions and adjust to variations over time.

Thus, any cancellation architecture must follow a mixed signal design; to prevent receiver saturation, the interfering signal must be sufficiently cancelled in analog at RF before it hits the low-noise amplifier (LNA) (shown in blue in Fig. 2), and to fully cancel the remaining interference in digital, cancellation algorithms operating on the digital baseband IQ samples between the transceiver and the baseband modem must model all of the nonlinear distortions (shown in purple in Fig. 2). The cost and ease of integration of an SIC solution are dictated primarily by the size and complexity of the RF cancellation circuit, which could vary in implementation from a discrete board-level solution to a multi-chip module (MCM) to a single die radio frequency integrated circuit (RFIC). On the other hand, state-of-the-art digital cancellation algorithms are much easier to integrate as they are similar to digital predistortion (DPD), an increasingly common feature in most wireless systems, in terms of resource requirements and integration.

APPLICATIONS WITHOUT STANDARDS MODIFICATION

Much of the cellular telephony industry's success can be attributed to the development and adoption of standards, which are a core alignment mechanism

heavily influencing the rate and direction of technical change, while at the same time themselves being the result of new breakthrough technological change. Take Qualcomm's code-division multiple access (CDMA): the technology was pioneered at a time when GSM had already reached a critical momentum, and was never a factor in 2G standards. Despite that, the technology was commercialized in limited 2G CDMA networks, an important victory which proved that power control, the single biggest engineering challenge for a functioning CDMA system, could be mastered. When technologies for 3G standardization were being considered, CDMA technology emerged as the standard-bearer, having already proven its technological merit.

The latest generations of mobile telecommunication networks are anchored by the long standing assumption that radios must be half duplex within a single channel. Thus, every existing standard today operates in either TDD or FDD fashion. In-band full duplex operation may have obvious and indisputable merits, but similar to the circumstances into which CDMA was born, standards are unlikely to adopt full duplex wireless until SIC technology proves its merit in a successfully deployed real-life system.

Self-interference is a phenomenon that appears in a number of contexts, even in half duplex systems. Take an FDD system, for example: even when a radio transmits and receives on different channels, transmit interference still overwhelms the receiver unless it is filtered out in analog at the front-end of the transceiver. However, filters can only operate in narrowly predefined fixed band pair configuration, and are often too large and heavy in high-power applications. However, they continue to play a critical role in radio access systems because self-interference must be dealt with. Self-interference cancellation solves the same problem, but is frequency agnostic — you can tune it to different frequencies, as shown in Fig. 3. Furthermore, cancellation enables you to transmit and receive on multiple bands [4]. Not only does this enable adaptive FDD filters, it dramatically simplifies the RF front-end for applications like carrier aggregation and enables radios to be built with smaller, lighter, and more efficient filters.

The above example is just one instance of how SIC, *by itself*, can be leveraged to deliver tremendous network benefits without any standards modifications. In this section, we touch on several applications where SIC technology can be leveraged immediately to solve existing problems without any need for standardization. These applications vary in their sensitivity to cost and integration, so for organizational purposes we first cover those that are able to absorb a discrete cancellation solution before discussing those that may require an integrated design. All of the applications discussed in this section do not require modification of any existing standards.

REUSE ACCESS SPECTRUM FOR BACKHAUL, ELIMINATING THE CHALLENGES ASSOCIATED WITH SMALL-CELL BACKHAUL

Small cells and heterogeneous networks represent a promising system concept to enable 5G networks to support the desired 1000× higher

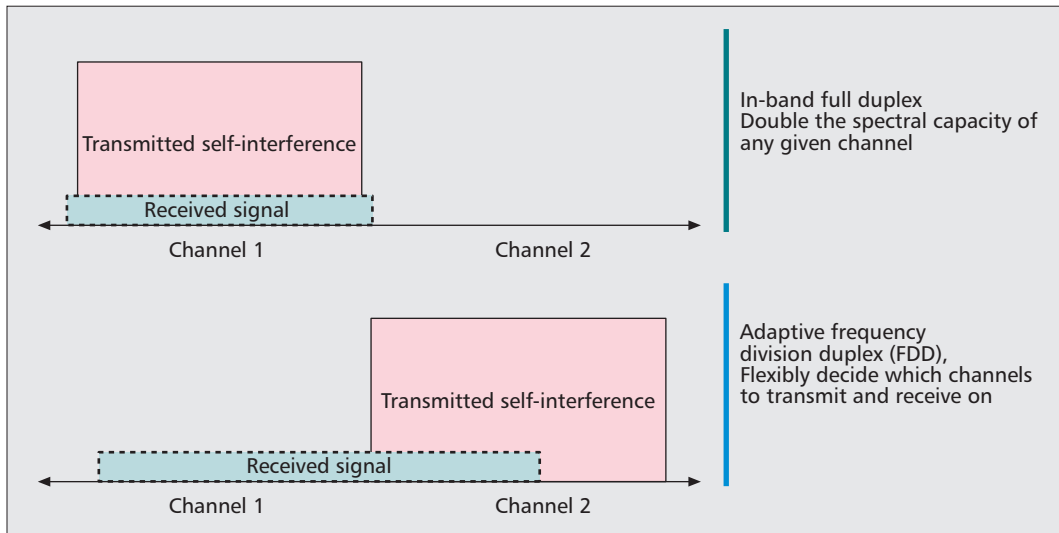


Figure 3. SIC enables more than in-band full duplex; it effectively acts as a software configurable adaptive duplexer, allowing for the transmission and reception of signals on arbitrary disjoint channels.

mobile data volume per area, enabling spectral resources to be reused in space by virtue of their smaller footprints. Small cells typically rely on out-of-band resources for backhaul (fiber, microwave, etc.), but this has become a serious challenge since wired connectivity is cost-prohibitive, microwave backhaul requires line of sight, and low frequencies that allow good propagation in non-line-of-sight (NLOS) urban environments are simply not available.

One potential solution to solve this dilemma is to leverage the same RAN spectrum, simultaneously, for both access and backhaul using the LTE protocol as shown in Fig. 4. In the downlink channel, the small cell would receive from the macro while *simultaneously* transmitting to the users' equipment (UE). In the uplink channel, the small cell would receive from the UE while simultaneously transmitting data to the macro. In this fashion, the small cell would effectively *backhaul itself*, completely eliminating the need for a separate backhaul solution and a separate frequency band (whether licensed or unlicensed), significantly reducing the cost and complexity of rolling out a small cell network. With SIC, both the access and backhaul links would operate as standard FDD, meaning that no changes or additional infrastructure would have to be implemented at either the macro or the UE. Furthermore, radio access network (RAN) spectrum is ideal; LTE coverage is fairly ubiquitous, and its low frequency makes it perfect for NLOS operation.

However, the main criterion when it comes to evaluating a backhaul option boils down to the amount of capacity it can deliver. Here, somewhat surprisingly, the self-backhauled small cell solution performs nearly as well as a small cell backhauled with fiber. Figure 5 highlights the intuition: today's Release-8/9 macro networks are designed to deliver spectral efficiencies of approximately 5 b/s/Hz, about 100 Mb/s in a 20 MHz. However, the empirical data from several operators worldwide [10, 11] shows that a typical busy time network is actually severely under-

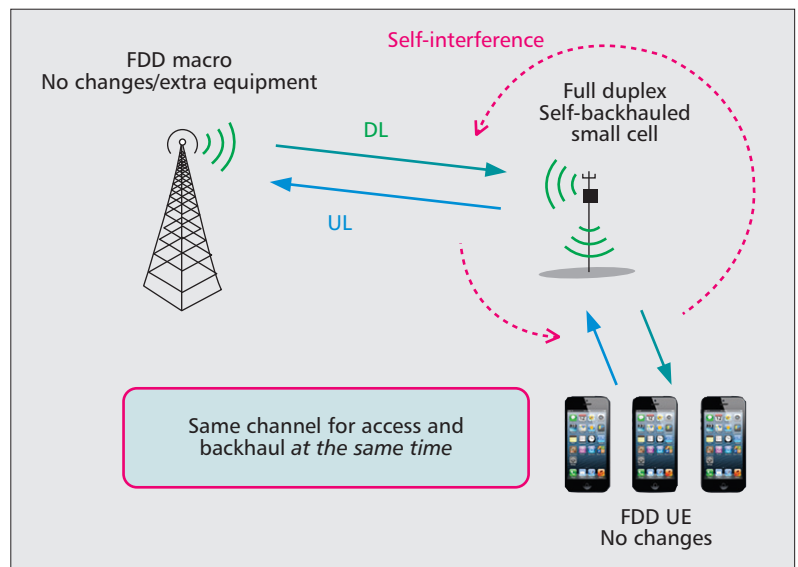


Figure 4. SIC enables a small cell to reuse its LTE access spectrum for backhaul as well without any throughput degradation, effectively backhauling itself. It operates in an FDD context, requiring no changes at the macro eNB or at the handset.

leveraged: networks typically deliver somewhere on the order of 1.25 b/s/Hz, a number which amounts to approximately 25 Mb/s or 25 percent RAN utilization. Self-backhauled small cells leverage this underutilized asset to backhaul the data. By virtue of their larger form factor and static/fixed deployment locations, self-backhauled small cells are able to achieve significantly higher spectral efficiencies than equivalent UE handsets.

Future 5G standards are trending toward increased levels of spatial multiplexing through higher orders of multiple-input multiple-output (MIMO), with 4×4 and 8×8 MIMO (with a corresponding spectral efficiency of 30 b/s/Hz) already specified in LTE Release-10 [10]. Most UE, though, will be unlikely to support these

The proprietary nature of point-to-point backhaul modems would enable self-interference cancellation to be adopted without any standards modifications, effectively doubling the capacity within existing spectrum allocations.

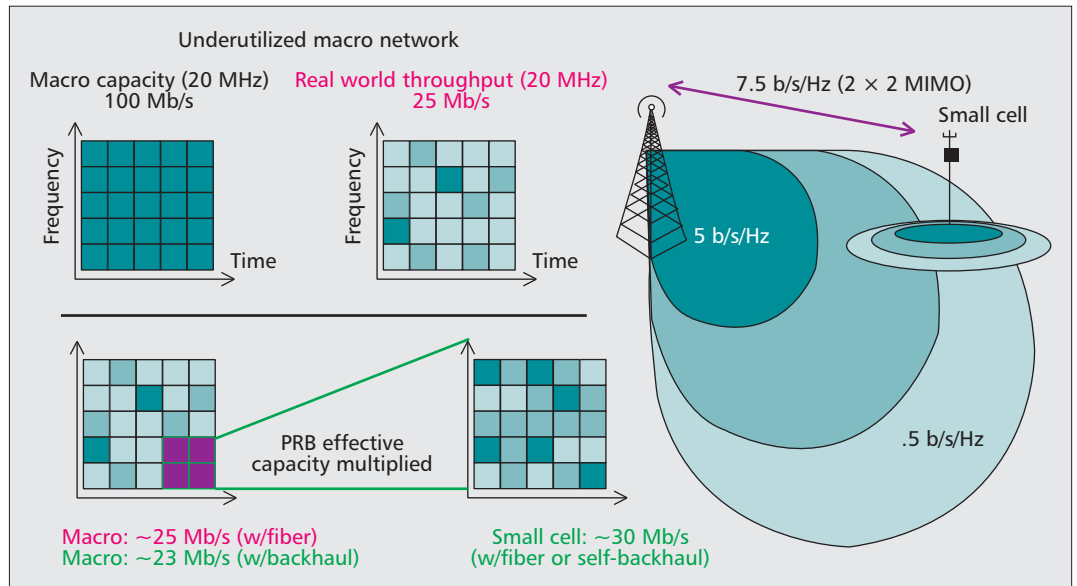


Figure 5. By leveraging the underutilized LTE macro network to backhaul access traffic from the small cell, NLOS and ubiquitous backhaul for heterogeneous networks is essentially provided for free.

higher-order MIMO modes due to their limited size and power. A larger form-factor small cell, though, will have no problem supporting a higher number of antennas — directly translating into much more efficient use of the same spectral resources than UE could achieve. Furthermore, the larger form factor allows much larger directional backhaul antennas, which provide increased gain. UE devices typically have antenna gains of less than 2 dBi, and in normal modes of operation are obstructed by human appendages. Small cells utilizing antennas with gains of up to 17 dBi are not out of the question, again enabling the macro to small cell link to operate at a much higher modulation and coding scheme (MCS) than an equivalent macro to UE link.

What the self-backhauled small cell effectively enables a network operator to do is to make more efficient use of the expensive macro network that has already been deployed. From an access perspective, the small cells provide identical performance whether they are backhauled out of band or in band. The difference between the performance of the two is in how efficient the backhaul link is, as this dictates how many macro resources must be consumed to backhaul the data. But as we have shown, LTE trends are favorable to the ongoing improvement of the backhaul link, which will narrow this gap further.

DOUBLE CAPACITY AND REDUCE SPECTRUM REQUIREMENTS FOR BACKHAUL POINT-TO-POINT SOLUTIONS

Microwave (wireless systems with carrier frequencies between 6 and 60 GHz) is widely used in macrocell backhaul, comprising more than half of global backhaul connections in 2013. For many service providers, spectrum licenses already represent one of the largest recurring costs in their backhaul network, accounting for

as much as 40 percent of a backhaul operator's 10-year total cost of ownership. Looking at future 5G capacity requirements, where hundreds of megabits or more will be needed, increased spectral efficiency will be essential in order to ensure the ongoing economic viability of these backhaul networks.

Future advances in modulation depth are possible, but this is a case of diminishing returns. For example, going from 256-quadrature amplitude modulation (QAM) to 512-QAM adds significant cost and complexity, but provides only a 12 percent increase in throughput. In addition, higher modulations entail greater export controls, which will complicate the procurement of these systems. Consequently, higher modulations alone will not deliver the capacity and spectral efficiency needed to support advanced 5G services.

One approach that could effectively double capacity within existing spectrum allocations is to leverage full duplex spectrum communications on the same RF channel. The proprietary nature of point-to-point backhaul modems would enable self-interference cancellation to be adopted without any standards modifications, effectively doubling the capacity within existing spectrum allocations. Compared to the long-term operations savings generated, additional costs incurred by discrete SIC hardware would be minimal. In Europe, where spectrum lease costs are calculated on a per link basis, there is a direct correlation between the amount of spectrum used and the cost, so it becomes very important to minimize the spectrum requirements in order to minimize the licensing costs. In regions such as South Asia and Latin America, where wireless operators obtain area licenses for a given band of spectrum, full duplex operation is particularly attractive, since minimizing the number of channels used can significantly reduce the spectrum costs. In both of these cases, increasing spectral efficiency in smaller and cheaper channels is of critical importance.

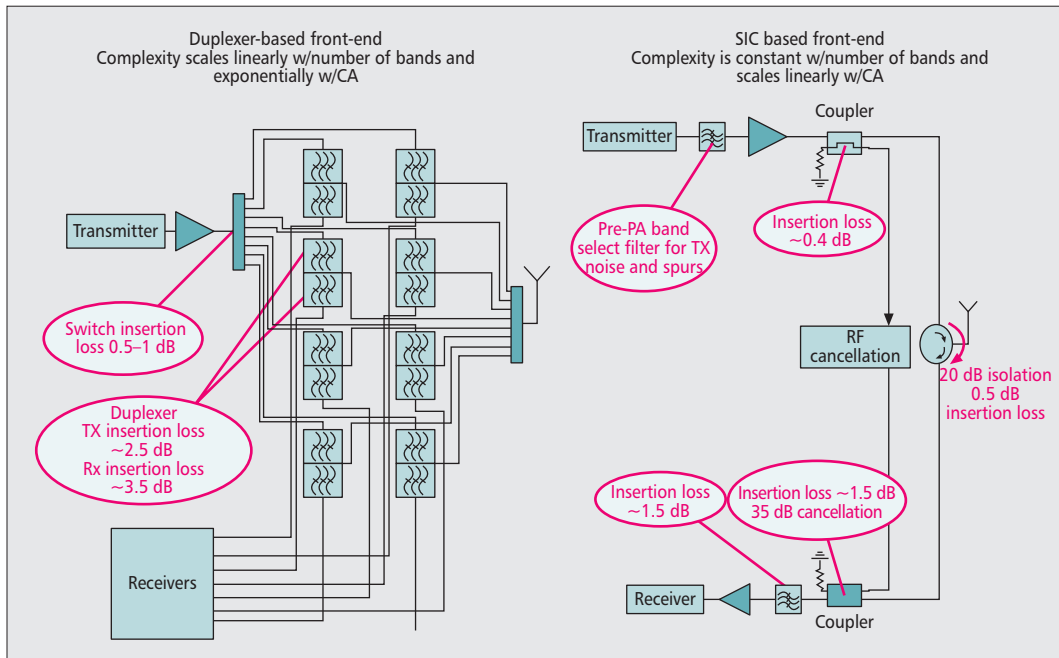


Figure 6. Since cancellation is frequency agnostic while filtering is not, SIC dramatically simplifies the RF front-end architectures needed to support multiple bands and carrier aggregation. TX/RX insertion losses are comparable if not improved in an SIC-based front-end.

MULTI-BAND ADAPTIVE DUPLEXER IN CELLULAR INFRASTRUCTURE AND MOBILE PHONES

Cellular spectrum fragmentation has become a major issue globally in LTE because of short-sighted regulatory planning [12]. Most LTE deployments today are FDD, requiring a static duplexer predefined specifically for one uplink/downlink pair to cope with self-interference. Today, there are more than 40 different LTE band pairings worldwide, an impossible number to support on any mobile handset, restricting global LTE roaming. This problem will only exacerbate moving forward as carrier aggregation (CA) will exponentially increase the number of band combinations required, as shown on the left side of Fig. 6.

Similarly, CA and multi-band support cause problems for base station radio infrastructure, which typically utilizes large and heavy cavity filters to provide the increased isolation necessitated by high-power amplifiers. Base station radio infrastructure is typically mounted on top of expensive leased tower space; hence, there is a premium on minimizing size and weight. Supporting CA with multiple cavity filters is at best an expensive and unattractive proposition, and at worst an impossible task given the lack of tower space in dense metropolitan areas.

Self-interference cancellation dramatically simplifies the RF front-end for applications like carrier aggregation, and enables radios to be built with smaller, lighter, and more efficient filters. Because cancellation is frequency agnostic, a single cancellation circuit can programmatically tune to isolate different sets of frequency, effectively acting as a software-configured duplexer, the “Holy Grail” of software-defined radio. Not only would such a solution enable

handset manufacturers to save costs by replacing disparate chipsets with a single integrated solution, as shown in Figure 6, but it would also facilitate global roaming and liberate consumers to more easily switch network operators, potentially driving improved quality of service due to increased competition between service providers.

5G STANDARDIZATION

FULL DUPLEX 5G COMMUNICATIONS

Spectrum fragmentation will be compounded in 5G due to the scarcity of spectrum. The problem is exacerbated by the duplexing requirements of paired spectrum, making it exceedingly difficult to allocate FDD spectrum. This problem has given rise to the relatively inefficient TDD standards in 4G, designed to allow operators to use a single unpaired frequency. While TDD sacrifices performance in some aspects with respect to FDD, the increased flexibility and cheaper cost of utilizing unpaired frequency has led several operators worldwide to accept the performance trade-offs.

As SIC technology reaches the cost maturity point, enabling it to be integrated into the handsets as well as base station infrastructure, it obviates the need for the trade-offs inherent in TDD spectrum. With in-band full duplex, networks operating on unpaired spectrum can transmit and receive simultaneously in a single channel. In other words, it allows for FDD operation over cheaper unpaired spectrum, traditionally allocated for TDD operation, simplifying spectrum management without any of the performance trade-offs.

With respect to spectrum policy, the requirements for in-band full duplex would be identical to TD-LTE in terms of spectrum allocation, RF conformance, and emissions standards. As evidenced

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For future 5G networks, the implication is that global harmonization of spectrum would be achievable for the first time, facilitating international roaming and reducing the cost of mobile devices due to increased economies of scale.

by the popularity of TD-LTE, allocating unpaired spectrum dramatically simplifies spectrum management and vastly increases the pool of available spectrum for 5G networks, since unpaired frequency is much more readily available and suitable for refarming than paired spectrum.

SPECTRUM VIRTUALIZATION

Attempts to harmonize the spectrum plan globally have failed time and time again because what works well for one country or region does not always work well in another region. While the ability to leverage half the amount of unpaired spectrum to obtain the same performance as FDD simplifies spectrum management, it is just one specific instance of how SIC can be leveraged.

The more general point is that SIC technology essentially acts as an adaptive duplexer, allowing any combination of bands, whether paired or unpaired, to be utilized in the exact same fashion. As a software defined filter, it effectively allows any-division duplexing (ADD), eliminating the distinction between FDD, TDD, and even in-band full duplex, since any of these can be supported by the RF front-end utilizing SIC. TDD would be rendered obsolete, replaced by in-band full duplex, while legacy FDD systems could still exist, but would benefit by leveraging SIC to aggregate and adapt to multiple disjoint frequencies.

Self-interference cancellation, in essence, virtualizes the use of spectrum by acting as a software-configurable filter enabling any random collection of channels to be aggregated. For future 5G networks, the implication is that global harmonization of spectrum would be achievable for the first time, facilitating international roaming and reducing the cost of mobile devices due to increased economies of scale. The positive economic impact of globally harmonized spectrum plans would be enormous — estimated by some groups such as the GSM Association (GSMA) as hundreds of billions of dollars [8].

Operators could further leverage cheaper fragments of spectrum that are non-uniform across different regions, something which is economically infeasible to utilize today, to obtain significant increases in bandwidth. For example, this would enable 5G networks to take advantage of the white space spectrum freed up by the switchover from analog to digital broadcasting [12]. The problem with white spaces today is that spectrum is only available in narrow disparate channels that vary across time and space. As a result, the only application currently discussed in the context of this spectrum is machine-to-machine communication, which requires very low throughput that can be handled by a single channel. Radios equipped with SIC-enabled software-configurable filters would be able to aggregate any random collection of white space channels to support high bandwidth throughputs, essentially taking what is today unattractive spectrum property and turning it into prime beachfront real estate. GSMA estimates that access to spectrum of this quality would be worth trillions of dollars in additional gross domestic product (GDP) [12].

CONCLUSION

Self-interference cancellation invalidates a long-held fundamental assumption in wireless network design that radios can only operate in half duplex mode on the same channel. Beyond enabling true in-band full duplex, which effectively doubles spectral efficiency, SIC tremendously simplifies spectrum management. Not only does it render entire ecosystems like TD-LTE obsolete, it also enables future networks to leverage fragmented spectrum, a pressing global issue that will continue to worsen in 5G networks.

In the short term, the technology offers the potential to facilitate the evolution of future networks toward heterogeneous small cell networks. Self-interference cancellation effectively eliminates the backhaul problem by enabling the small cell to reuse LTE radio resources simultaneously for access and backhaul. The solution provides aggregate throughput improvements comparable to out-of-band backhaul solutions by achieving high spectral efficiencies in the backhaul link with MIMO and directional antennas, enabling it to leverage underutilized macro resources to backhaul traffic. By virtue of this built-in backhaul link, small cells utilizing this technology dramatically simplify and reduce the cost of rolling out heterogeneous networks.

By virtue of its fundamental nature, SIC is likely to have an impact far beyond 5G. Every future radio, from WiFi [4] to military grade jammers [9], can benefit from this technology. In WiFi, for example, it allows an access point (AP) to eliminate co-channel broadband noise, enabling it to simultaneously utilize multiple independent channels, multiplying the effective capacity of an AP even without modification of the clients. In military applications, jammers flood the airwaves with strong transmission to prevent other devices from communicating (e.g., cell phones to activate improvised explosive devices). But as it does so, it also prevents its own radios from transmitting, making communication impossible. With SIC technology, the military could continue to disrupt enemy communications and at the same time listen to its own troop communications, thus saving lives in the field.

Several companies are utilizing ad hoc mesh networks of satellites [13] or wirelessly connected balloons [14] to provide cost-effective connectivity across massive scales to the remaining billions on the planet without Internet access. As with any traditional mesh network, they suffer from degradation of throughput with an increase in the number of hops if the same frequencies are utilized. Identical to the self-backhauled small cell concept, SIC technology applied in this context would help maintain throughput end to end, regardless of the number of hops. This would increase the expansion and effectiveness of these networks, helping to bring connectivity to billions around the world.

Half duplex radio limitations have shaped the wireless industry in terms of standards, applications, and architectures for the past century.

Self-interference cancellation technology removes this barrier, fundamentally changing not only how radios are built, but how standards and regulators will approach spectrum management. With SIC, future 5G generations of wireless applications will be implemented at significantly reduced cost to everyone involved: regulators, operators, equipment manufacturers, and consumers.

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BIOGRAPHIES

STEVEN HONG (steven@kumunetworks.com) is a co-founder and director of product at Kumu Networks. He received his B.S. in electrical engineering from the University of Michigan, Ann Arbor in 2009, his M.S. degree in electrical engineering from Stanford University in 2011, and his Ph.D. in electrical engineering from Stanford University in 2012.

JOEL BRAND is vice president of product management at Kumu Networks. He previously held executive positions in other wireless and networking companies. He received his B.Sc. in electrical engineering and M.Sc. in reliability engineering from the Technion, Israel Institute of Technology in 1989 and 1992, respectively, and his M.B.A from National University in 2000.

JUNG IL CHOI is a co-founder and chief systems architect at Kumu Networks. He received his B.S. in electrical engineering from Seoul National University in 2005, his M.S. degree in electrical engineering from Stanford University in 2007, and his Ph.D. in electrical engineering from Stanford University in 2011.

MAYANK JAIN is a co-founder and chief technology officer at Kumu Networks. He received his B.E. in Electronics and Telecommunications from Netaji Subhas Institute of Technology in 2002, his M.S. degree in electrical engineering from Stanford University in 2007, and his Ph.D. in electrical engineering from Stanford University in 2011.

JEFF MEHLMAN is a co-founder and director of engineering at Kumu Networks. He received his B.S. in electrical engineering from the University of Massachusetts, Amherst in 2007, his M.S. degree in electrical engineering from Stanford University in 2011, and is currently on leave from the Ph.D. program at Stanford University.

SACHIN KATTI is a co-founder and chief executive officer at Kumu Networks and an assistant professor in electrical engineering and computer science at Stanford University. He received his B.S. in electrical engineering from the Indian Institute of Technology, Bombay in 2003 and his Ph.D. in computer science from the Massachusetts Institute of Technology in 2008.

PHILIP LEVIS is a co-founder and former president at Kumu Networks and an associate professor in electrical engineering and computer science at Stanford University. He received his B.S. in computer science from Brown University in 1999 and his Ph.D. in computer science from the University of California, Berkeley in 2005.

With self-interference cancellation, future 5G generations of wireless applications will be implemented at significantly reduced cost to everyone involved: regulators, operators, equipment manufacturers, and consumers.