



RF Innovation and the Transition to 5G Wireless Technology

WHITEPAPER

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Executive Summary

The next generation of wireless technology, 5G, is still in the early stages of definition, but is receiving increased visibility, as the number of wireless-enable devices expands from mobile phones to mission-critical devices and the emerging Internet of Things (IoT). Carriers and manufacturers envision 5G as a standard that continues to advance data speeds for mobile video and fixed-wireless devices, while also providing connectivity for the massive number of IoT devices – two very different network demands. No matter how 5G will ultimately be implemented, higher data-rates, more capacity and many more connected “things” will be parts of the wireless future. The emerging definition of 5G envisions dramatic performance improvements in network capacity, mobile connections, latency, cost, data rates and coverage.

The transition from 4G to 5G will be very different from prior transitions. 4G represents the first global wireless standard and wireless carriers have only recently invested considerable capital to acquire spectrum and build out and support their 4G networks. On the other hand, the continuing evolution of the wireless environment will force carriers and device manufacturers to “push the envelope” and deploy 5G technologies as quickly as they become viable. For the foreseeable future however, 4G will serve as the dominant network technology, with 5G serving as supplementary service.

The 5G Radio Access Network will be a combination of technologies, nodes and frequencies. Densification of the network will require new models that make deployment economically viable; dynamic and adaptable allocation of resources to maximize performance, increasing automated software control; multiple and dynamic use of different modulation schemes; and device-to-device communication facilitating network capacity off-load.

5G devices will exist in an environment that includes more complexity, more components (particularly filters), more performance demands, smaller size and lower cost components, and dual connectivity between cellular and WiFi networks. More bandwidth will be needed (>6GHz), which will require higher frequency components, more carrier aggregation (CA), more complex multiple-input-multiple-output (MIMO) antennas, new and adaptable waveforms, and improved interference mitigation.

5G RF front-end designs for all wireless-enabled products will be driven by cost, power efficiency and available space within the unit. They will need to be small, highly efficient, and able to be manufactured in large quantities to meet fast-growing global demand. The requirements for 5G filters will include complex multiplexing, increasing integration, more filters, and the capability to handle much higher frequencies than are currently in use.

Resonant has developed a comprehensive Electronic Design Automation (EDA) RF design platform, Infinite Synthesized Networks (ISN), initially focused on acoustic wave filter design, which is a key absent design block for the RF front-end. ISN is specifically intended to solve many of the 5G challenges that will face design engineers: speed, flexibility and tools that drive down system cost. ISN brings together modern filter theory, finite element modeling (both electro-magnetic and acoustic), and novel optimization algorithms, enabling engineers to design and test filters before a design is committed to mass production. Testing has proven that ISN's models are extremely accurate and reflect physical details of the filter structures, matching the measured performance of manufactured filters, not only in loss and isolation but also in power handling and linearity. Thus, ISN is an ideal platform for quickly, efficiently and cost-effectively scaling filter design to meet emerging 5G demand.

The emerging definition of 5G envisions dramatic performance improvements in network capacity, mobile connections, latency, cost, data rates and coverage.

What is the Vision for 5G?

Despite the best efforts of the standards bodies, the definition of each mobile telecom generation is generally determined by the marketing needs of major global carriers and network suppliers. For instance, much-hyped improvements such as LTE and LTE-Advanced are commonly classified as 4G, even though they do not meet the basic throughput requirements originally defined by the International Telecommunications Union (ITU). Thus, each new mobile

network advancement refers largely to significant improvements to the user experience, rather than adhering rigidly to specified performance standards. For example, the transition from 1G to 2G defined the transition from analog to digital; the transition from voice to data dominance is called 3G; and 4G refers to much higher data throughput rates than prior generations.



FIGURE 1

Progression in wireless technologies from 1G to 5G¹

¹ "Understanding 5G", White Paper, Anritsu

The emerging definition of 5G envisions dramatic performance improvements in network capacity, mobile connections, latency, cost, data rates and coverage. As with every new generation of mobile technology, the performance targets are ambitious – some would say impossible – since they are driven as much by user demands as by the pace of technological change. Carriers and device manufacturers want to offer service and equipment as soon as possible that satisfies user demands for higher data rates for HD video, extremely low power consumption for long battery life, and extreme reliability for industrial applications.

The conflicting demands driving the development of a standard that will be known as 5G include:

- Greater network capacity: The demand for wireless capacity and connectivity for mobile devices and the emerging Internet of Things (IoT) is growing at an astronomical rate. By 2021, analysts forecast that there will be 26 billion devices transmitting data over wireless networks, or 1.5 devices for every person on earth³, and that by 2020, mobile data traffic will reach 30 exabytes—or 30 million gigabytes—per month, an eight-fold increase from 2015 levels.⁴

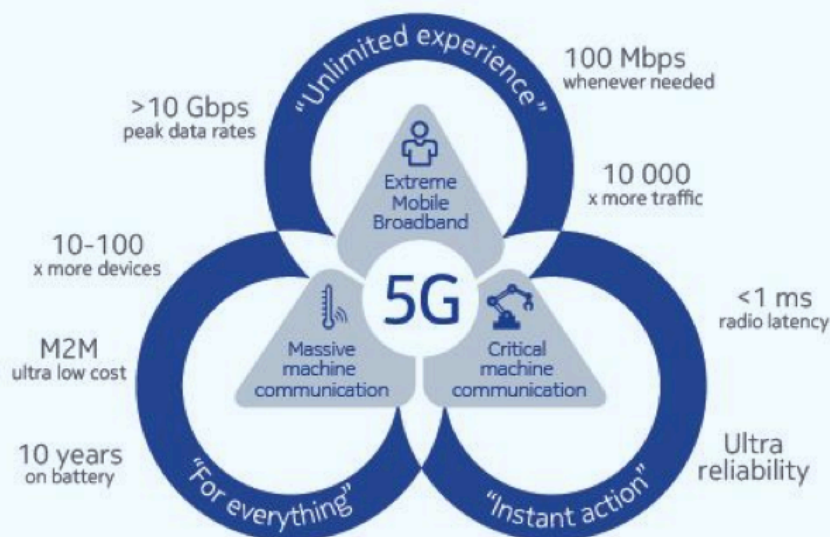


FIGURE 2

5G: Service, use case and requirements².

In many ways, the drivers for 5G are conflicting: increased data rates and capacity for a richer visual experience (for use cases including HD video, augmented reality (AR) and virtual reality (VR)), but also ultra-high reliability, low device cost and a massive increase in the number of connected devices (including the ubiquitous Internet of Things, as well as smart cars, smart cities and smart homes).

In addition, maximum data rates per device are expected to increase from ~100MB/s today to 10GB/s by 2020.

- Better coverage: As new devices come into service, users expect them to work anytime and anywhere, especially for bandwidth-intensive purposes such as gaming and streaming videos. As higher data rates take hold, carriers will be forced to add network capacity

² "5G for Mission Critical Communications", White Paper, Nokia, 2016

³ Ericsson Mobility Report, June 2016

⁴ Cisco VNI Global Mobile Data Traffic Forecast, 2015-2020

simply to ensure that users can actually experience the improved service.

- Improved latency: Users are already frustrated by latency issues that slow their experience. As wireless devices become more and more central to a wide range of daily activities, users are becoming less willing to accept such delays.
- Improved battery life: Application-intensive use-cases drain the battery quickly, creating demand for long-life, fast-charging power sources; some machine-to-machine applications draw minimal power at any one time, and thus require very long life batteries that will provide uninterrupted power for 10 years or longer.

Capacity

Wireless spectrum bandwidth is a finite resource. So in order to meet burgeoning user demands, networks require more spectrum bandwidth, local to the user, and the networks need to be flexible enough to efficiently deploy the extra bandwidth.

The general consensus is that 5G capacity will be defined as:

- 10Gb/s data rate for static users
- 1Gb/s data rate for low mobility users
- 100Mb/s, minimum, in urban areas

If these goals are indeed met, 5G networks will have 10,000 times the capacity of current networks.

Coverage

As with previous generational technology upgrades, along with increased capacity requirements comes increasingly ubiquitous

coverage. There is no point in having local areas with very high data rates if the wireless link is continually dropped due to poor coverage. Wireless technologies are limited in their reach from an antenna, based upon propagation over the air, and through obstacles and walls. Because most of the low-frequency spectrum (which has better propagation characteristics, and can penetrate further) is already allocated, the additional capacity for 5G will have to come from the higher frequency spectrum above 6GHz and potentially up to 300GHz. However, these high frequencies present a significant coverage challenge as signal strength drops off rapidly with distance from the radiating node.

To work, the 5G network will need many more radiation points, where resources can be allocated dynamically based upon user needs. This will create a heterogeneous network, combining low frequency, tall antenna macro cell sites for large area coverage with high frequency, and local points of presence (small cells).

Latency

Coverage and capacity continue to drive the traditional wireless user experience. However, for 5G, new user types are defining new requirements, which include real-time interactive applications and machine-to-machine interactions. Real-time interactive applications, such as augmented reality and multi-user games, require extremely low latency.

The 5G target for latency is less than 1msec, which is an exceptionally aggressive target for a cloud service with communication between the access network, core network, servers and the wireless device. To put that in context, consider that current average LTE latencies in the U.S. are 70-85msec.

Battery Life

Improving battery life for consumer mobile devices is very high on the list of priorities for device manufacturers, but they have not yet commercialized batteries that can keep up with the needs of power-intensive applications such as video recording and streaming. On the other hand, some machine-to-machine use cases generally involve low-power applications and minimal bandwidth, but require long battery life (in some cases, greater than 10 years). This will necessitate extended “sleep” periods for the radios, as well as minimizing any processing, plus ensuring extreme reliability. In both cases, reducing the power demands of components such as RF antennas and filters will help improve battery life for these disparate use cases.

Range of Devices That Will Connect to the 5G Network

As the network has grown in complexity, so too have the types of devices that are now being connected. Long gone are the days when the majority of devices were simply handheld phones. Current networks are already straining under the demands generated by these new devices, which include:

- 1 Mission-critical devices: Reliability of the link is paramount for mission-critical devices, such as those monitoring power plants and other essential infrastructure. Therefore, always-on connectivity to multiple technologies and access points will be needed to provide link redundancy for dependable service. In some cases, low latency will be required, which may then use direct device-to-device links in order to circumvent the time delay associated with transport through the network.
- 2 IoT devices: Cost and power efficiency are critical for IoT services. Many low-cost IoT devices are expected to have battery lives of 10 years or more, and the initial applications will involve fixed devices only. Mobility for IoT devices will require increased signaling, low cost and shorter battery life. Hence, mobility may be a future service.
- 3 Next-generation mobile devices: Smart phones will continue to grow in complexity, and will be increasingly controlled by the network, allowing for re-configuring of the device and optimizing of the user experience. A 5G mobile broadband device will be expected to leverage the advances in 4G, support multiple bands and modes, aggregate multiple frequency bands, and longer term, aggregate the higher frequency bands available in 5G.

When Will 5G Transition from Vision to Reality?

The schedule for any new generation goes through three phases:

- 1 Definition of requirements and identification of key technologies;
- 2 Standardization;
- 3 Demonstrations and trials.

This is followed by commercial deployments (see figure 3).

to “push the envelope” and deploy 5G technologies as quickly as they become viable. For instance, Verizon has already announced 5G trials for fixed wireless connections using 28GHz spectrum, with the goal of having a 5G pilot running in 2017. Verizon CFO Fran Shammo has said that Verizon’s initial vision for 5G is as a fixed service – used as a broadband replacement technology – and not a mobile service. He has also said that LTE/4G



FIGURE 3

5G schedule⁵.

TECHNOLOGY	STANDARDIZATION	NEW SPECTRUM ALLOCATIONS
5G PPP METIS 5GIC Industry R&D	NGMN (requirements) ITU 3GPP (beyond Rel 12/13) IETF IEEE	WRC-15 • more mobile broadband frequencies • Harmonize 700 MHz bands WRC-18 • more bands needed for 5G

4G to 5G Transition: Overlay or Overhaul?

The transition from 4G to 5G will be very different from prior transitions. 4G represents the first global wireless standard and wireless carriers have only recently invested considerable capital to acquire spectrum and build out and support their 4G networks. On the other hand, the evolution of the wireless environment described above will force carriers and device manufacturers

will still be Verizon’s dominant network technology for the foreseeable future, with 5G serving as a supplementary service.⁶

This is the likely scenario that will play out for most wireless operators. A few, particularly those looking for marketing exposure, will push ahead with demonstrations to show more advanced capabilities, such as during the upcoming Olympics in Japan and S. Korea.

⁵ “Understanding 5G”, White Paper, Anritsu

⁶ Verizon Q1 2016 Earning call

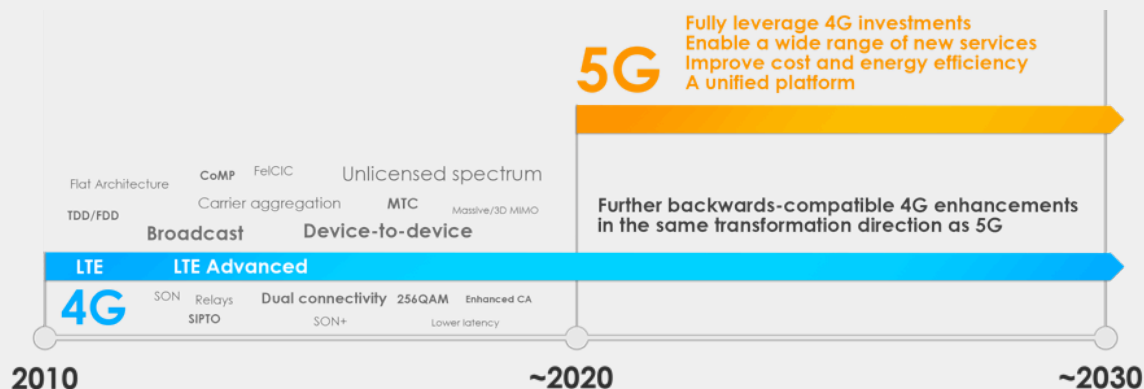


FIGURE 4

Parallel development of 4G and 5G to maximize their potential⁷.

Thus, the most likely strategy for most global networks will be to deploy 5G initially in high frequency spectrum for “last mile” high-speed access to homes and business as an alternative to fiber. Then, 5G will be added as a supplement to 4G for high-speed, local connections for applications requiring high-speed wireless broadband access, such as HD video, and also for

low-power IoT applications (most likely non-mobile). 4G macro sites will remain the workhorse for coverage, but will (with much higher data capacity) also provide anchor points for small cell, machine-to-machine and distributed antenna systems – the systems that make up a heterogeneous network (HetNet).

⁷ “Providing the Connectivity Fabric for Everything” presentation, Qualcomm, May 2015

5G Access Network and User Equipment

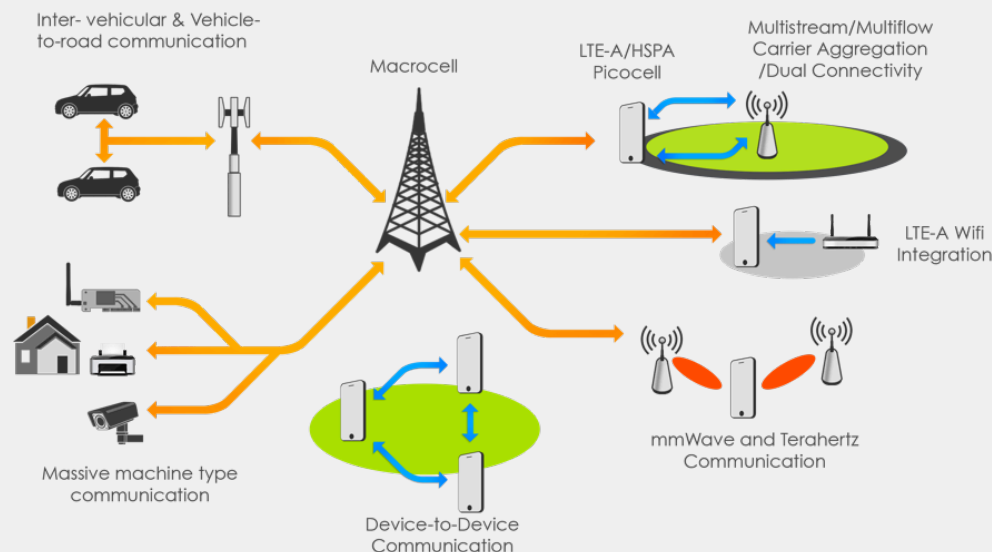


FIGURE 5

5G mobile wireless network architecture.

Radio Access Network (RAN)

The RAN for 5G will be a combination of technologies, nodes and frequencies, and this mix will result in one of the biggest challenges for 5G deployment. Densification of the network will require:

- New models that make deployment economically viable: Planning for 5G deployment will be extremely difficult, and the large number of nodes will make non-optimum sites the norm. Increasingly, deployments will include shared equipment between carriers.
- Dynamic and adaptable allocation of resources to maximize performance, increasing automated software control: This will include interference coordination and capacity allocation, even in unplanned and chaotic environments. Coordinated multipoint (CoMP) will be required for efficient spectrum usage. Accurate channel state information will be critical to the correct allocation of resources.
- Multiple and dynamic use of different modulation schemes: The diversity of use cases in 5G well beyond those requiring high-speed data (4G) will be the driver of a wide range of modulation schemes.
- Device-to-device communication facilitating network capacity off-load: Network architecture will have to be optimized to incorporate security, off-load potential, privacy, use of the network for acquisition and connection maintenance, and additional UE capability.

One of the key differentiators for 5G is the many different use cases, which suggests a set of network settings/functions, including Radio Access Technologies (RAT) settings for any particular use case – this is referred to as a “5G slice.” The idea behind the 5G slice is that the overall environment is maintained with only the necessary functionality for each use case so as to efficiently allocate available resources.

Given the technical challenges outlined above, we can draw some conclusions about end-user wireless devices, particularly mobile broadband phones. These devices will exist in an environment that includes the following:

- More complexity
- More components, particularly MIMO and CA filters
- More demands on performance – high isolation between bands, low insertion loss (especially at band edges)
- Smaller size and lower cost – overall phone size will not change significantly nor will overall mobile device margin

requirements. Thus, even though there will be more components built into the unit, they will have to be smaller and cheaper

- Dual connectivity between cellular and WiFi networks
- Higher frequency components (>6GHz) will be introduced as these components drop in size and cost

A critical consequence of the increasing complexity and additional components is that the RF link itself will degrade, despite improvements in the overall performance of individual elements.

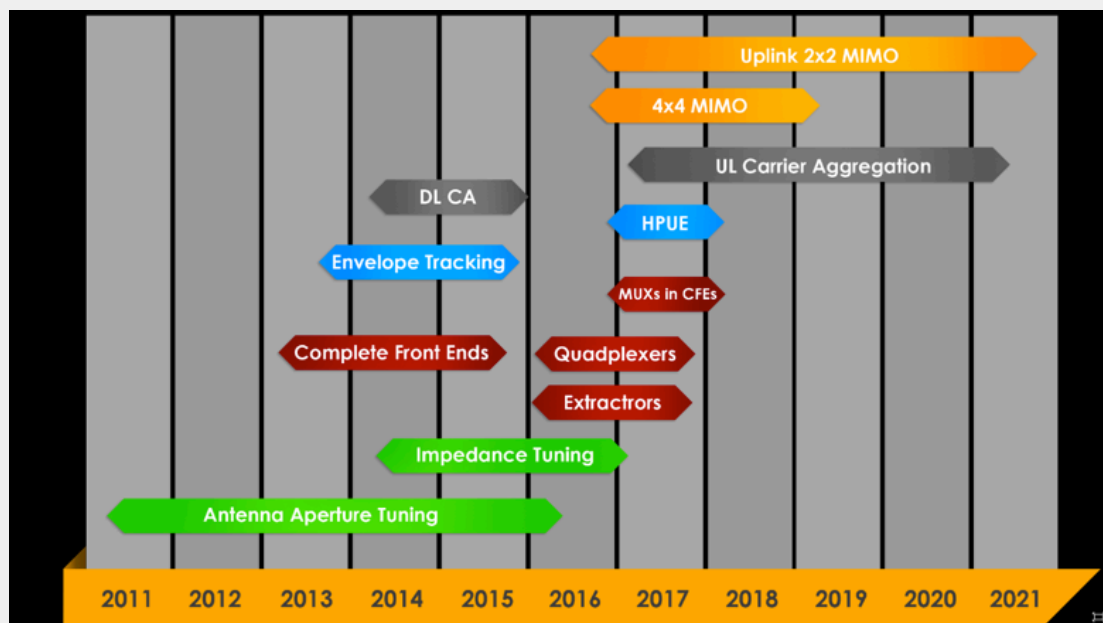


FIGURE 6

Key technology development schedule⁸.

⁸ "RF Front Ends for Mobile Devices" Report, Mobile Experts, May 2016

Key Technologies Needed to Make 5G a Reality

In order to meet, or at least approach, the challenging targets for 5G data rates, coverage and connections, new technologies will be required. Identified technologies include:

- 1 New frequencies, especially higher than 6GHz
- 2 Massive MIMO (Multiple Input/Multiple Output), resulting in high RF complexity at low cost
- 3 Network densification & Interference mitigation
- 4 New and adaptable waveforms

High Frequency Spectrum (>6GHz):

With almost all of the available spectrum below 6GHz now allocated, carriers will be forced to move to higher frequency spectrum to secure bandwidth. However, as the frequency increases, RF propagation is reduced, and penetration into buildings suffers. Thus, the bandwidths available above 6GHz lend themselves to short range, point-to-point, line-of-site connections (likely in-building). Traditional network planning becomes difficult, but a much higher frequency, millimeter wave (mmWave, or near mmWave, e.g. 28GHz) mesh network could work in dense urban environments. While components are generally smaller as frequency increases, reduced semiconductor performance at these higher frequencies will impact cost and power consumption.

Massive MIMO: MIMO is already used in LTE and LTE-Advanced networks, where multiple antennas are deployed either at the base station or mobile device (or both) to improve the link. However, massive MIMO is used in this context to leverage a large number of antennas in order to allow spatial beamforming, so that the energy can be focused directly at the user's device. Large increases in capacity are possible by generating multiple beam

paths. Although this technology has been experimentally verified, significant advances in processing and interoperability will be required for wide-scale deployments.

Interference Mitigation: 5G demands use of large spectrum bandwidths and massive overlapping of cells, which will result in both in-band and out-of-band interference. In general, 3G and early deployments of 4G were limited in their performance due to incomplete coverage. Performance within a cell was largely determined by signal-to-noise ratio (SNR). The extreme densification of the network envisioned for 5G will change the limitations from coverage to interference, and performance will be determined by the signal-to-interference + noise ratio (SINR). RF filters will play a critical role in improving SINR. In 4G, cell edge performance in urban environments is dominated by co-channel interference from overlapping cells. Electrical antenna tilt can help, but inter-cell interference coordination (ICIC) has been introduced to reduce the impact on cell edge users. ICIC uses different resource blocks for different users at the cell edge, which increases the effective re-use rate from 1 to 3. eICIC (Enhanced ICIC) will be required for 5G, where resource block allocation will be dynamic in the time domain. This will be essential for heterogeneous networks, where small cells are within the macro footprint.

New and Adaptable Waveforms: OFDMA is the waveform used in 4G networks because, by using sub-bands, the bandwidth is easily scalable, enabling higher data rates. However, OFDMA is susceptible to interference and procedures to allocate resources are inefficient for small (data or packet) payloads. Extensive investigation of more efficient orthogonal as well as non-orthogonal waveforms is underway to identify candidates for 5G. RF filters will play a critical role in OFDMA performance.

Implications for the 5G RF Front-End

In this section we focus on the implications of 5G on the development of the RF front-end for mobile broadband devices. The current state-of-the-art for a mobile smartphone RF front-end separates the frequency spectrum into low-band (698MHz-960MHz), mid-band (1710MHz-2200MHz) and high band (2400MHz-3800MHz) frequencies, which isolates the RF components, minimizes cross-talk, and optimizes the entire power amplifier-filter-switch path. Although integration of components is logical, the increasing complexity of 5G limits the number of manufacturers that have the expertise to execute on such a complex RF sub-system.

5G RF front-ends for all wireless-enabled products will be driven by cost, power efficiency and available space within the unit. They will need to be small, highly efficient, and able to be manufactured in large quantities to meet fast-growing global demand. To commercialize affordable custom parts for IoT devices in particular, RF front-ends will need to be designed with a minimum number of components, and manufacturing volumes will have to increase dramatically from current levels to reduce per-unit cost. In the current environment, most IoT devices are being built with low-cost parts originally developed for high-volume mobile phone production.

As we move toward 5G, the complexity of the RF front-end continues to increase. For instance, in addition to the main antenna path modules, diversity antennas provide both link robustness and increased down-link data rates. Designers are increasingly using receive diversity modules to process the diversity path, comprised of receive (Rx) filters and switches (and increasingly incorporating low-noise amplifiers - LNAs). Wireless carriers demanding higher 5G data rates will drive more carrier aggregation, creating more potential interference. Consequently, the onus on RFFE designers moving forward will be to reduce complexity, reduce cost, while at the same time improving performance. These represent a significant set of challenges for RFFE design and manufacturing.

Please see **FIGURE 7** on next page.

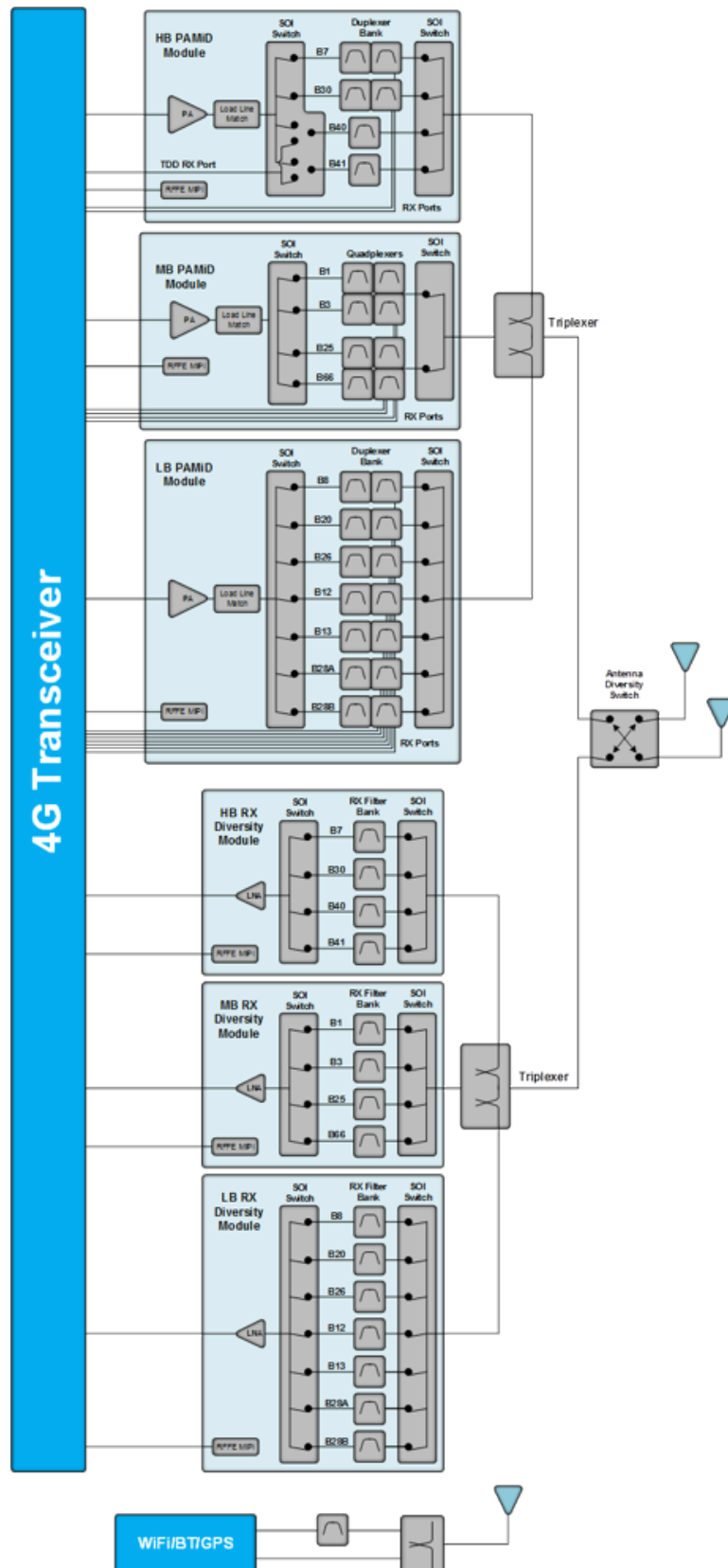


FIGURE 7

Current state-of-the-art RF front-end architecture.

5G Filter Requirements

The growth in the sheer number of filters, and the ever more demanding filtering requirements, make RF filtering the critical pain point of the RF front-end. Unlike the power amplifier, where a single device can be used for multiple frequency bands and technologies, at the present time a single filter is required for each individual frequency band.

Although specific 5G requirements for filters will be developed in the future, the basic outline for those requirements has already become clear. It includes:

1 Complex multiplexing: Carrier aggregation will drive more complex multiplexing, which in turn drives more complex designs.

2 Increasing integration: Overall RFFE performance is crucial. Maximizing PA efficiency on the uplink, and receiver sensitivity on the downlink, will require optimization of the entire RF chain. As complexity increases, it will be crucial to understand the RF chain and any interactions between elements. For example, consider the co-existence of band 5 and band 12, and the intermodulation distortion (IMD) that can interfere with other frequency bands (see table). Including IMD generation up to the seventh order, IMD products will land in five FDD receive bands, four TDD bands, 2.4GHz Wi-Fi and 5GHz Wi-Fi. For filters, optimizing the interface to PA and LNA will also be required in the filter design process.

Intermodulation CA 5-12					Intermodulation CA 5-17				
	F1_Low/F2_Low	F1_Low/F2_High	F1_High/F2_Low	F1_High/F2_High		F1_Low/F2_Low	F1_Low/F2_High	F1_High/F2_Low	F1_High/F2_High
2nd IMD(a-b)	126	108	151	133	2nd IMD(a-b)	120	108	145	133
2nd IMD(b-a)	-126	-108	-151	-133	2nd IMD(b-a)	-120	-108	-145	-133
2nd IMD(a+b)	1522	1611	1547	1565	2nd IMD(a+b)	1528	1540	1553	1565
3rd IMD (2-1)	950	932	1000	982	3rd IMD (2-1)	944	932	994	982
3rd IMD (1-2)	572	608	547	583	3rd IMD (1-2)	584	608	559	583
3rd IMD (1+2)	2220	2256	2245	2281	3rd IMD (1+2)	2232	2256	2257	2281
3rd IMD (2+1)	2346	2364	2396	2414	3rd IMD (2+1)	2352	2364	2402	2414
4th IMD (3-1)	1774	1756	1849	1831	4th IMD (3-1)	1768	1756	1843	1831
4th IMD (1-3)	-1270	-1324	-1245	-1299	4th IMD (1-3)	-1288	-1324	-1263	-1299
4th IMD (1+3)	2918	2972	2943	2997	4th IMD (1+3)	2936	2972	2961	2997
4th IMD (3+1)	3170	3188	3245	3263	4th IMD (3+1)	3176	3188	3251	3263
4th IMD (2-2)	252	216	302	266	4th IMD (2-2)	-584	-608	-559	-583
4th IMD (2+2)	3044	3080	3094	3130	4th IMD (2+2)	3056	3080	3106	3130
5th IMD (4-1)	2598	2580	2698	2680	5th IMD (4-1)	2592	2580	2692	2680
5th IMD (1-4)	-1968	-2040	-1943	-2015	5th IMD (1-4)	-1992	-2040	-1967	-2015
5th IMD (1+4)	3616	3688	3641	3713	5th IMD (1+4)	3640	3688	3665	3713
5th IMD (4+1)	3994	4012	4094	4112	5th IMD (4+1)	4000	4012	4100	4112
5th IMD (3-2)	1076	1040	1151	1115	5th IMD (3-2)	1064	1040	1139	1115
5th IMD (2-3)	-446	-500	-396	-450	5th IMD (2-3)	-464	-500	-414	-450
5th IMD (2+3)	3742	3796	3792	3846	5th IMD (2+3)	3760	3796	3810	3846
5th IMD (3+2)	3868	3904	3943	3979	5th IMD (3+2)	3880	3904	3955	3979
7th IMD (6-1)	4246	4264	4396	4378	7th IMD (6-1)	4240	4228	4390	4378
7th IMD (1-6)	-3364	-3472	-3339	-3447	7th IMD (1-6)	-3400	-3472	-3375	-3447
7th IMD (1+6)	5012	5120	5037	5145	7th IMD (1+6)	5048	5120	5073	5145
7th IMD (6+1)	5642	5660	5792	5810	7th IMD (6+1)	5648	5660	5798	5810
7th IMD (5-2)	2724	2688	2849	2813	7th IMD (5-2)	2712	2688	2837	2813
7th IMD (2-5)	-1842	-1932	-1792	-1882	7th IMD (2-5)	-1872	-1932	-1822	-1882
7th IMD (5+2)	5516	5552	5641	5677	7th IMD (5+2)	5528	5552	5653	5677
7th IMD (2+5)	5138	5228	5188	5278	7th IMD (2+5)	10556	5228	5218	5278
7th IMD (4-3)	1202	1148	1302	1248	7th IMD (4-3)	1184	1148	1284	1248
7th IMD (3-4)	-320	-392	-245	-317	7th IMD (3-4)	-344	-392	-269	-317
7th IMD (4+3)	5390	5444	5490	5544	7th IMD (4+3)	5408	5444	5508	5544
7th IMD (3+4)	5264	5336	5339	5411	7th IMD (3+4)	5288	5336	5363	5411

TABLE 1

Intermodulation products from band 5/ band 12 and band 5/ band 17. Green for FDD RX. Red for 2.4GHz Wi-Fi/BT. Blue for TDD. Yellow for GPS. Orange for 5GHz Wi-Fi.

3 Increasing number of filters: MIMO and spectrum proliferation will continue to grow and require more filters. Thus, the size and cost of filters must continue to decrease.

And as such, the requirements for isolation and minimizing leakage into the Rx path, and vice versa, grew. This will only be further exacerbated by high-power user equipment (HPUE),

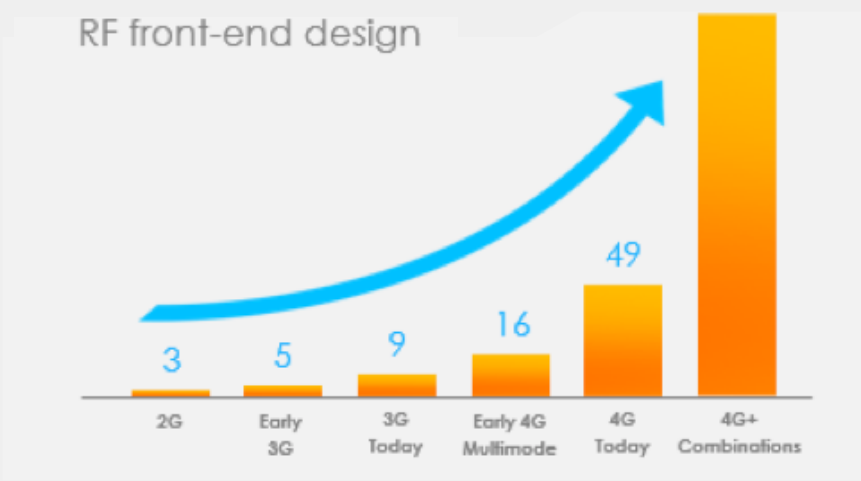


FIGURE 8

Increase in the number of filters required for mobile Smartphones.

4 More demanding specifications:

Isolation, loss and power handling requirements continue to create new challenges. Filters in the RF chain are a major contributor to loss, which is critical for total Tx efficiency (and ultimately for the current draw for the PA and battery life), and the total noise figure in the Rx path (and ultimately for the SNR and the data rate) LTE, which is optimized for high-speed data, demanded significantly higher power than 3G protocols such as CDMA.

which uses more Tx power for improved cell edge coverage. In addition, power durability of progressively smaller filters becomes a major concern.

5 Frequencies greater than 6GHz, and frequencies of operation greater than 20GHz, will require different filter technology than the current acoustic wave filters used in mobile devices. Significant advances will be needed to reduce size and cost.

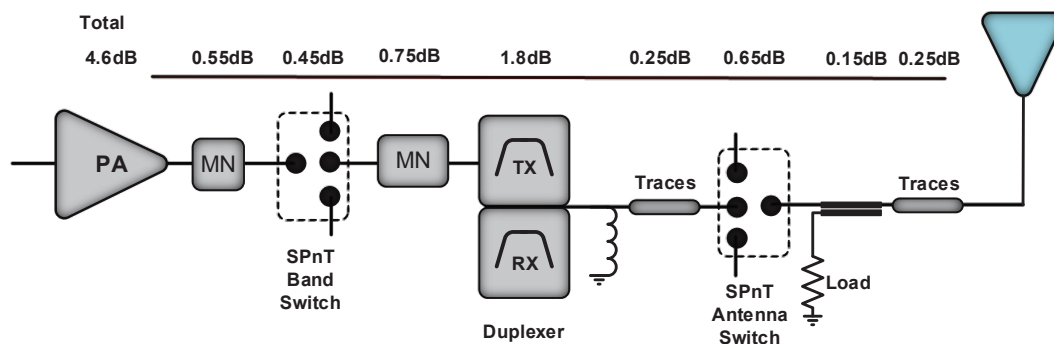


FIGURE 9

Tx path component line-up with estimated losses.

In combination, all of the above clearly shows that a 5G RFFE for mobile broadband will be extremely complex and that the goal for filter design will be to both simplify the design process and the RFFE itself. Innovation that minimizes and reduces the complexity of components will be of paramount importance, and tools enabling this innovation will be critical to simplifying the RFFE. Innovations that enable 5G RFFEs will need to include a low-loss triplexer

(to minimize the number of antennas), multi-mode, multi-band PAs, and reconfigurable and multi-band filters (to reduce the number of filters and switches), all of which will need to be optimized as a complete system to reduce matching components.

In the Figure below, we envision a 5G RFFE that minimizes size and cost while improving performance and reducing complexity.

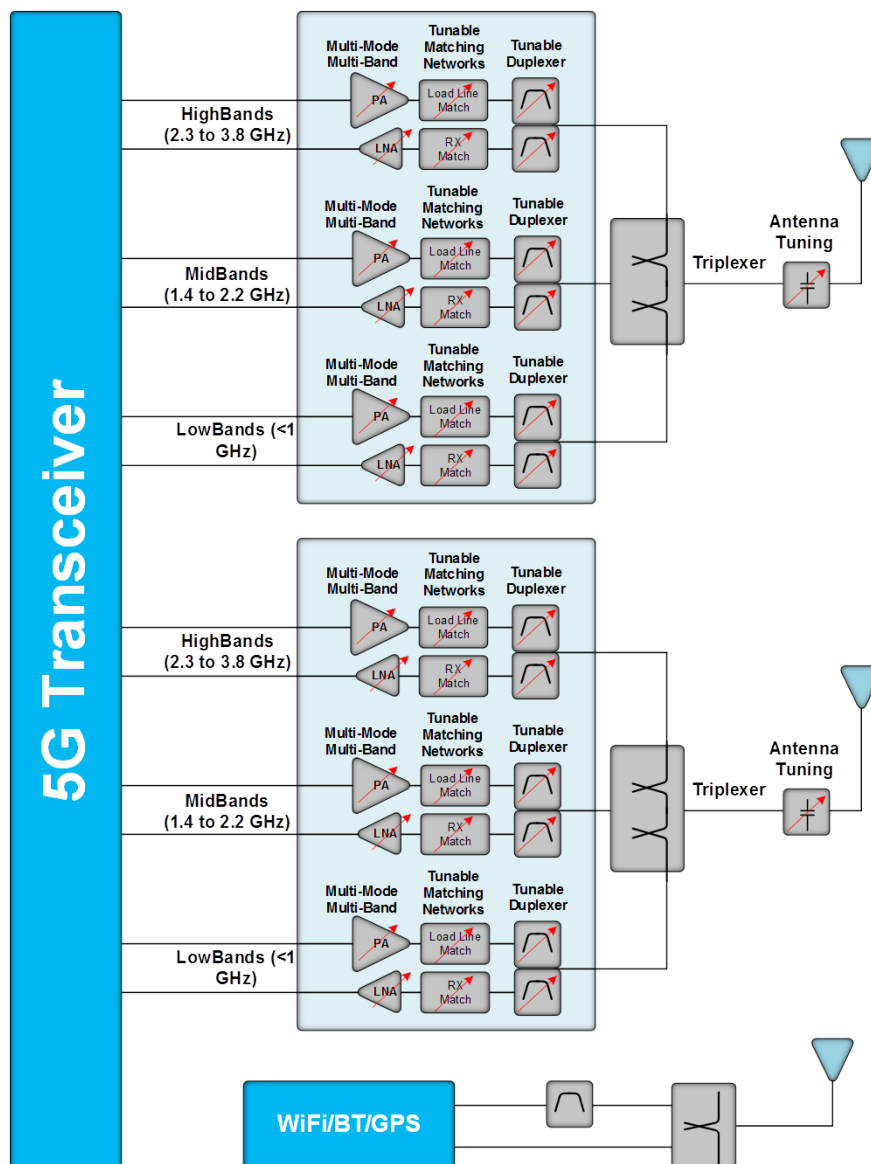


FIGURE 10

Proposed future RF front-end architecture for minimized size and cost.

Resonant ISN: Addressing 5G Design Needs

Resonant has developed a comprehensive filter Electronic Design Automation (EDA) platform: Infinite Synthesized Networks (ISN). Resonant's ISN platform is analogous to solutions used in integrated circuit design, and brings together the following elements:

- Modern filter theory
- Finite element modeling (both electro-magnetic and acoustic)
- Novel optimization algorithms

simultaneously and screened to maximize the ultimate performance of the device. Leveraging the expertise of filter design engineers for an increasing number of more complex designs can be achieved using ISN. This will be critical as the RFFE migrates to 5G in an environment where resources are constrained by a tight labor market of experienced design professionals.

Resonant's ISN models are extremely accurate and reflect physical details of

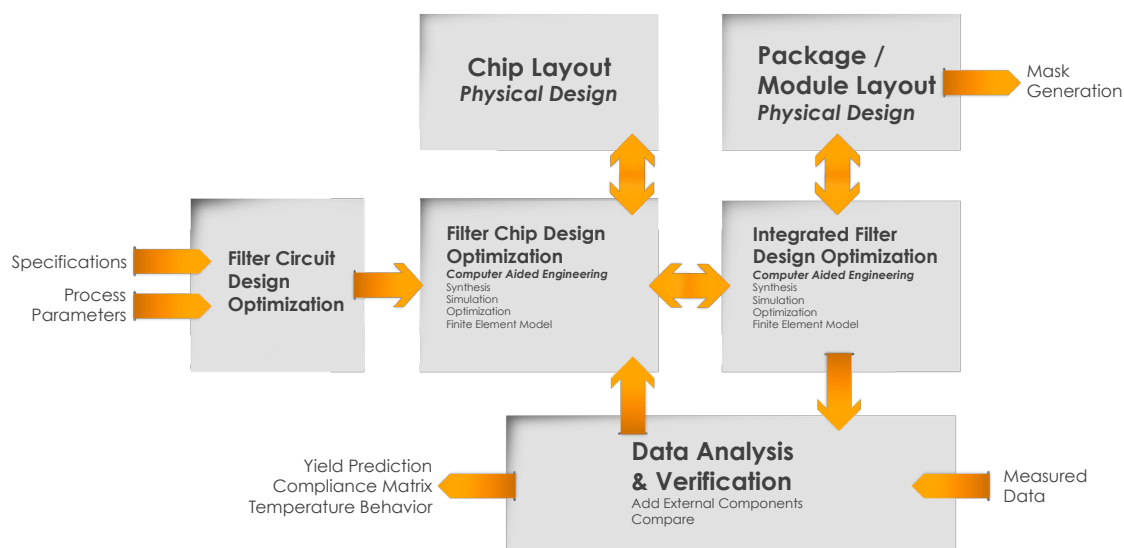


FIGURE 11

ISN schematic, showing process flow from Initial design to completed mask.

This platform enables filter design teams to create novel filter structures that outperform traditional filter designs, in a smaller footprint and using lower-cost technologies. In addition, ISN's grounding in fundamental materials physics, while optimizing for high-volume design screening, enables designs that are unconstrained by traditional acoustic wave filter design techniques. Consequently, a designer using ISN can create multiplexers, wide passbands and high-power performance, and predict manufacturing yields as well, before a design is committed to mass production. Thousands of designs can be developed

the filter structures, matching the measured filter performance not only in loss and isolation but also in power handling and linearity. Figure 12 shows how closely ISN-modeled performance tracks the actual data measured on a Band 3 duplexer. The accurate modeling of acoustic filters using ISN enables the following:

- Reduced development time and cost: Optimization is performed by the computer and the designer, rather than with expensive iterations in fab.

- Solutions to challenging design problems: Empirical design techniques will ultimately be limited in headroom as more design parameters constrain the problem. This is particularly true for multiplexing and tunable filters. The flexibility and accuracy of the ISN tool suite is ideally suited for creating novel solutions to these increasingly complex requirements.
- Design for multiple temperatures: The ISN framework allows optimization over multiple temperatures, optimizing performance at the higher temperatures that we can expect in a 5G RF module.
- Designs optimized for high-power performance: LTE operates at higher power than CDMA, requiring designs that can withstand high power, at elevated temperatures, for extended periods of time. High bandwidth applications for 5G will continue this trend of higher power in order to achieve the highest data rates possible.
- Improved yield and lower cost of production: Resonant models help production engineers to create relevant fabrication parameters for reducing variability in the manufacturing process.

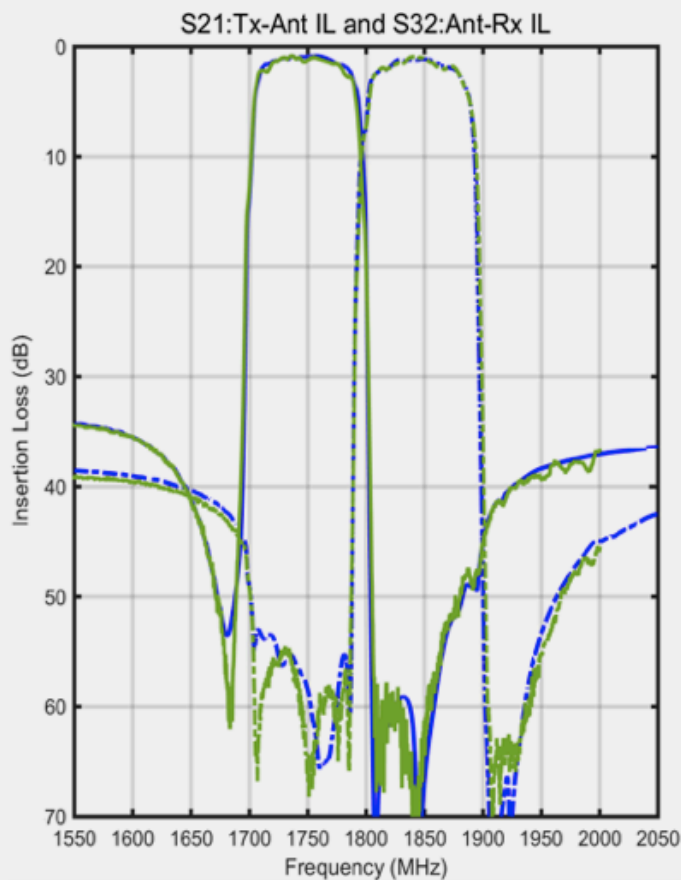


FIGURE 12

Measured (blue trace) and modeled (green trace) duplexer performance.

Appendix A:

Mobile Device RF Front-End Performance

A mobile device RFFE can vary in complexity from the simplest (Figure 13) used in original cellphones, comprising one antenna with duplexer, power amplifier (PA) and low-noise amplifier (LNA), to the much more complex, found in modern smartphones (Figure 7). Each frequency band incorporated into the mobile device requires separate filtering and amplification, leading to multiple RF paths and an exponential increase in RF content. With increasing complexity comes increasing total BOM cost, board size and reduced performance (Figure 14).

The effect of these substantial losses on the Rx and Tx paths have quite different consequences, but ultimately the effect is that they degrade the SINR and increase required power amplifier output power that reduces battery life, thus reducing the efficiency of data transfer from the mobile device to the RF node, and vice versa. It is immediately apparent from Figure 14 that the component contributing the most to loss is the duplexer. However, the duplexer is essential to minimizing added noise and interference from signals in other frequency bands.

In the case of the mobile device transmitter, the goal is to provide, as efficiently as possible, the maximum signal strength from the antenna without degrading neighboring frequencies. Because the maximum power from the mobile device is limited, this uplink is usually the limiting link for coverage. Typically, for every additional 0.1dB loss, an additional 10mA is required for the power amplifier, affecting battery life and talk time.

For the best possible data throughput to the mobile receiver, the goal is to maximize SINR from as many data streams as possible. Any loss before the LNA reduces the maximum possible data rate.

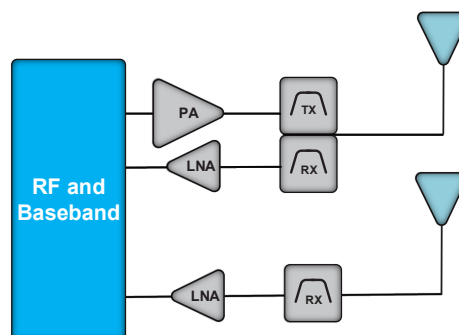


FIGURE 13

Simple cell phone architecture found in the early phones.

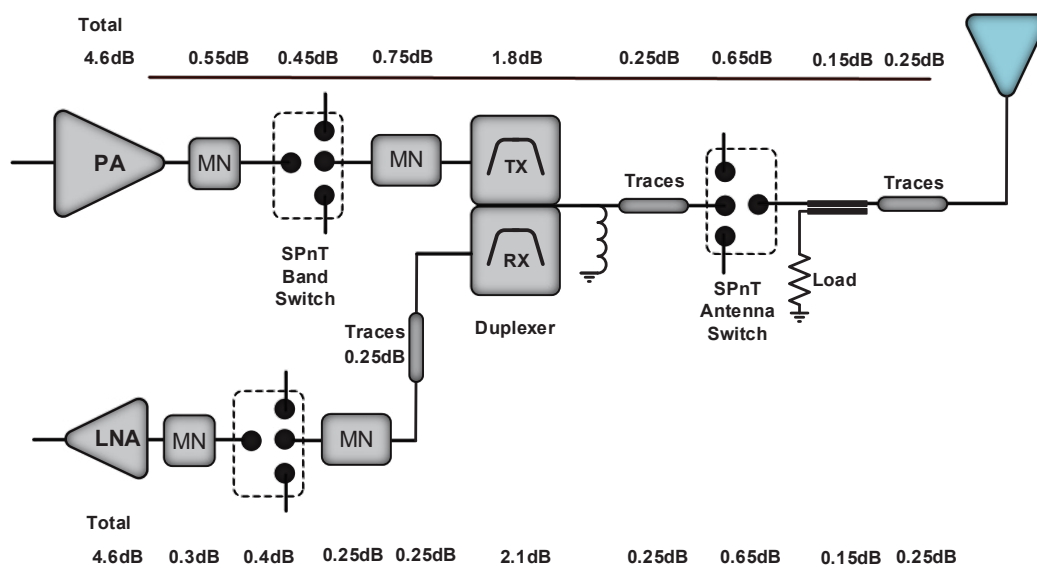


FIGURE 14

RFFE schematic, showing the losses from the individual components on receive (Rx) and transmit (Tx) paths. Note that in the case of the Rx path, this will be duplicated for each frequency band supported in the mobile.

Abbreviations

3GPP	3G Partnership Project	mmW	Millimeter wave
AR	Augmented Reality	MTM	Machine to Machine
BOM	Bill of Materials	OFDMA	Orthogonal Frequency-Division Multiple Access
BT	Bluetooth	PA	Power Amplifier
CA	Carrier Aggregation	PAMiD	Power Amplifier Module including Duplexers
CDMA	Code Division Multiple Access	RAN	Radio Access Network
CoMP	Coordinated Multipoint	RAT	Radio Access Technology
DL	Downlink	RF	Radio Frequency
EDA	Electronic Design Automation	RFFE	Radio Frequency Front-End
eICIC	enhanced Inter-Cell Interference Coordination	SINR	Signal to Interference plus Noise Ratio
ET	Envelope Tracking	SNR	Signal to Noise Ratio
FDD	Frequency Division Duplex	SOI	Silicon on Insulator
GPS	Global Positioning System	TDD	Time Division Duplex
HB	High-Band	UE	User Equipment
HD	High Definition	UL	Uplink
HPUE	High Power User Equipment	VR	Virtual Reality
ICIC	Inter-Cell Interference Coordination	WRC	World Radiocommunication Conference
IMD	Inter-Modulation Distortion		
IoT	Internet of Things		
ISN	Infinite Synthesized Networks		
ITU	International Telecommunication Union		
LB	Low-Band		
LNA	Low Noise Amplifier		
LTE	Long Term Evolution		
MB	Mid-Band		
MIMO	Multiple Input Multiple Output		



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