

Analog advancements make waves in 5G wireless communications

Connecting people and devices around the world
through technology innovation



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Imagine sitting on a bench in a city park, talking on your smart phone to a friend while busy traffic streams by. Autonomous, invisibly controlled vehicles are evenly spaced and moving at a uniform speed, interweaving as they cross each other in the intersections with no need to stop.

As you finish talking, your friend recommends you see a certain movie. You immediately watch the trailer on your smartphone in high resolution, with no streaming delays. Next, you get updates on a football game covered by multiple ultra-HD cameras showing a variety of perspectives. Expect to see these capabilities integrated into smartphones and through multimedia – including 4K cinema resolution.

Later, you turn to the news. You see a lead story about remote-controlled robots performing surgeries that are directed by doctors across the globe from their patients. Another story is about automated factories that react immediately to sensed feedback in complex processes. As you watch, you realize improvements enabled by technology are not limited to your smartphone and entertainment. The lives of hundreds of millions of people in the world are being significantly improved by efficient agriculture, smart factories, safer automobiles and transportation, secure travel and other applications. But what does it take to ensure we are equipped to make these high-tech innovations possible?

A number of important technologies are involved in these advances. Important among them is fifth-generation (5G) wireless communications, which will begin deployment early in the next decade. 5G will extend the advances of today's fourth-generation (4G) wireless communications by providing much higher data throughput and by vastly reducing the response time of the network. Other goals include increased quality of service and much greater energy

efficiency per bit delivered. 5G will also be flexible and extensible to keep pace with changes in the network and applications.

With 5G deployment, high-speed applications such as video and gaming will download and interact with the user in real time. Equipment that requires low-latency, immediate response, such as vehicles in traffic and robots involved in time- and life-critical tasks, will be able to operate with virtually no wait, meaning less than a millisecond for a network connection versus several tens of milliseconds it takes today. And increasingly, many more people around the world in highly populated and remote locations will be connected simultaneously.

Like earlier generations of wireless communications, 5G depends on a number of factors, including leading-edge software development, a favorable regulatory and social environment, as well as new applications and features that can profit from improved communications. Important also is innovation in the underlying hardware, enabled by advanced integrated circuit (IC) technology. Texas Instruments (TI) plays a leading role in developing the

IC solutions required for communications infrastructure and wireless communications advances. The company is committed to developing the advanced transceiver, signal chain, signal processing, power management and other semiconductor technologies required for the transition and deployment of 5G communications in the upcoming years.

5G goals and challenges

One central need for 5G is to carry more bits per second to more users more efficiently. Today, total mobile traffic worldwide is measured in exabytes per month — that is, bytes expressed in units with 18 trailing zeros. Much of this demand is fueled by video downloads, with their already high bit volumes enlarged by ever-increasing resolution and features such as 3D or virtual reality. Traffic will continue to grow exponentially, as even more users and devices connect. The most recent Mobility Report, a penetrating assessment of the industry by Ericsson, predicts that “By 2021 there will be: 9 billion mobile subscriptions, 7.7 billion mobile broadband subscriptions and 6.3 billion smartphone subscriptions.” In addition, network service providers

predict that in the same time period the Internet of Things — objects, without counting human users — will grow to tens of billions of connected devices that will be potentially uploading to the cloud for analysis and sharing.

Once installed, new 5G networks will address the need for greater capacity and new services by providing high-speed data transmission, support for a large number of connected devices, low latency, low power consumption and extremely high reliability. Since 5G is envisioned as an evolving complex of converging technologies, the central challenge for IC suppliers and equipment manufacturers will be to bring all the different pieces into an integrated platform. Different parts of the network will have to be harmonized for interoperability by equipping the entire system with enough intelligence to optimize its responses automatically.

A crucial piece of the evolution to 5G lies in solving difficult base station hardware challenges. Existing towers will provide higher performance in order to carry many more channels at higher data rates. In addition, much smaller base stations, which are

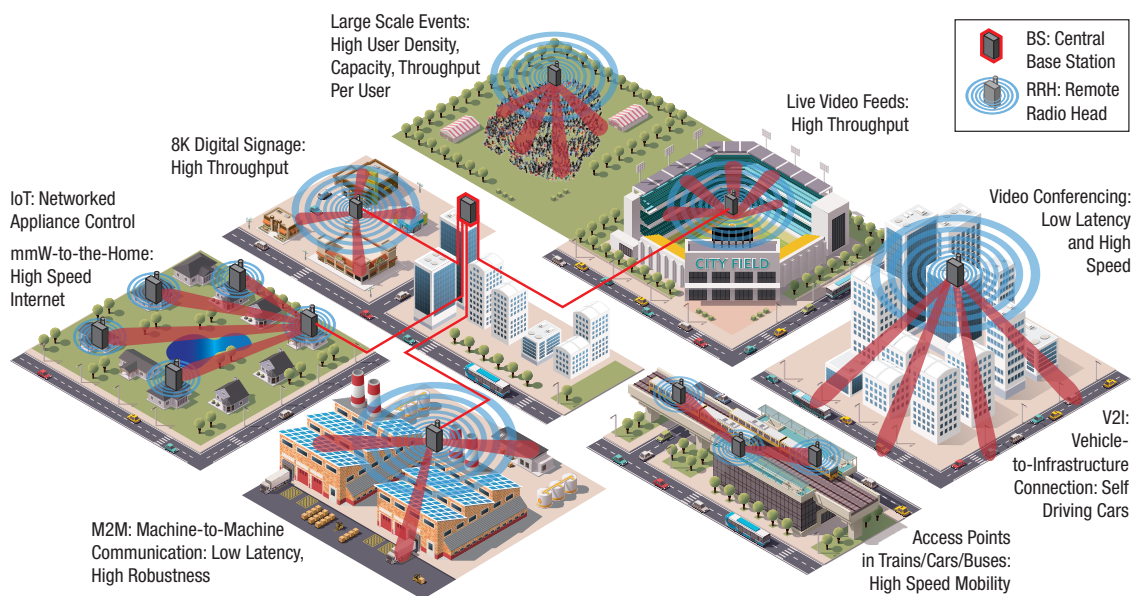


Figure 1. 5G will bring higher performance and more channels in smaller base stations with signals closer to users, especially in highly populated areas.

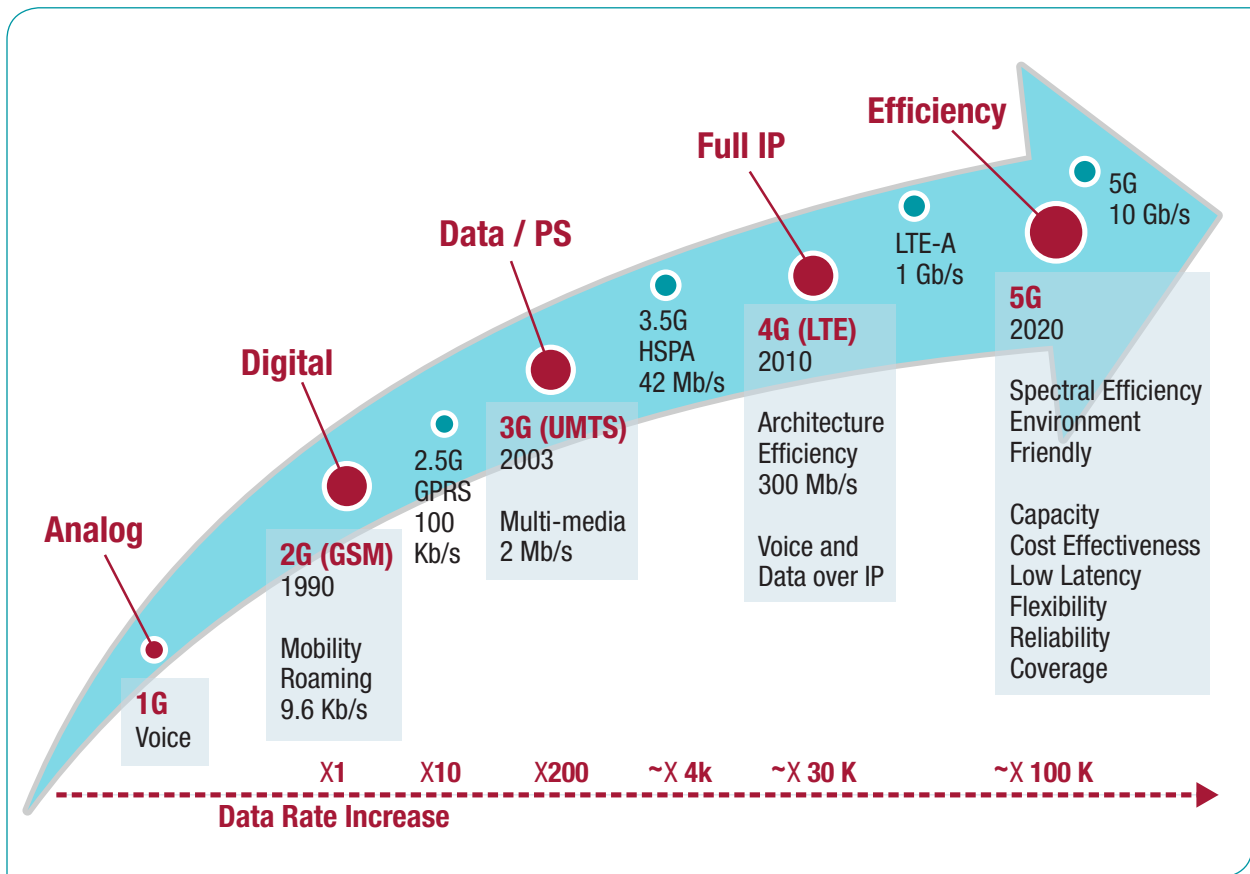


Figure 2. Evolution of wireless generations, and frequencies.

easily deployed, will bring the signal closer to the user. Already there is a trend to deploy small base stations, which have been labeled micro-, pico- and even femtostations, depending on their range. 5G will push this trend much farther, with many more base stations operating in downtown streets, shopping centers, stadiums, office buildings and other highly populated areas (Figure 1). These small-cell base stations will bring transmission closer to the user, use lower power and provide more bits per second, especially in the downlink (base station to user or fiber to the home), where video delivery needs the majority of the bandwidth.

Meeting these expectations effectively requires a large-scale integration of components, along with higher performance and greater power savings. Advances will be introduced in transceivers, clocking, data

conversion, microprocessors and microcontrollers, and power management devices — virtually all the functional areas of base station hardware.

More channels in existing infrastructure

Each wireless generation has experienced an increase in frequency band allocation (Figure 2). Fourth generation, or 4G, which was introduced earlier in this decade, now operates at frequencies up to 6 Gigahertz (GHz). How to increase data throughput within this spectrum is the immediate challenge, and part of the ongoing half-generation step forward, that will lead to full 5G. The key to this increase lies in the introduction of multiple-input, multiple-output (MIMO) antenna technology on a massive scale.

Traditionally, tower antennas possessed two polarized receivers and transmitters, making it possible to simultaneously carry two multiplexed channels (each with a large number of user connections). Towers currently being installed or retrofitted feature four-channel antenna arrays with four receivers and transmitters each. The increase in antennas and channels is only beginning. The current release of the 3GPP™ standards incorporates antenna arrays with up to 16 MIMO channels, and forecast arrays with 64, 128 and even 256 channels. Theoretically, the total number of bits-per-second capacity in the cell area increases proportionately with the number of channels. Even if the theoretical multiples prove impossible to achieve in practice, the actual increase will still bring a significantly greater number of user connections, or the same number of connections using much greater bandwidth – or some combination of each. Larger numbers of MIMO channels also help equalize the wireless signal strengths at the receiver devices and therefore enable greater robustness of

the communication and lower connection latency – aligning with the goals of the 5G standard. As shown in **Figure 3**, each MIMO channel has its own signal path from the receiving and transmitting antennas to the microprocessor. At the very least, the receiver path involves down-conversion from the high radio frequency (RF) received by the antenna to a low-baseband frequency where input sampling can take place, plus signal conversion from analog to digital. The transmission path has a similar set of functions operating in reverse. Modern “RF-sampling” radio architectures eliminate this initial conversion step by directly sampling the RF signal with high-speed, giga-sample-per-second analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). Depending on how massive the MIMO is in a base station, signal paths may be placed in parallel from four up to 256 times. Conditions make it essential to minimize size, heat and complexity in massive MIMO systems, while also reducing the bill of materials and overall cost of operation.

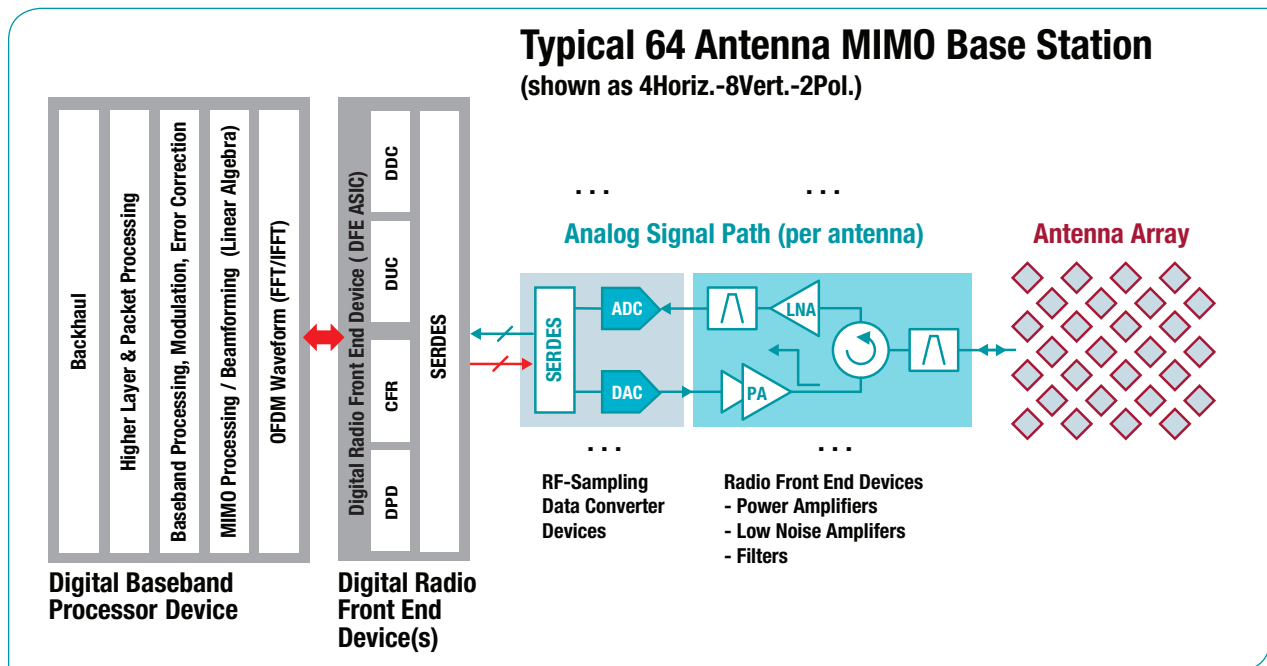


Figure 3. Diagram of generic base station with massive MIMO channels.

IC integration is the means to achieving these goals, and TI works closely with its base station equipment customers to produce highly integrated RF sampling data converters, radio transceivers and optimized signal chains for the evolving roll-out of massive MIMO. TI's AFE7500 transceiver, for instance, supports two signal paths per device and is utilized in 4- or 8-channel antenna arrays that are currently being installed. Solutions to support arrays with even more channels per device are under development. TI's LMK0482x jitter cleaner family and clock buffer families help to generate and distribute clocks with the lowest phase noise and low channel-to-channel variation to any transceiver or other signal chain element in massive MIMO systems. This allows engineers to clock a high amount of channels in a simple and efficient way.

Another key to reducing signal chain size and complexity is to sample and convert data directly from the RF to the digital baseband without the intermediate step of analog signals at baseband frequencies. Direct RF sampling ADCs are available now (ADC32RF45, ADC32RF80) with direct RF sampling DACs becoming available in the near future, further stimulating the advance to massive MIMO and the increase in capacity that it brings. Direct broadband RF sampling further reduces radio hardware complexity by combining multiple RF bands into one analog signal path. This provides even smaller implementation footprints, more flexible hardware, and greater MIMO massiveness across multiple RF bands simultaneously.

Dealing with a higher-frequency frontier

While massive MIMO has immediate advantages, one key challenge is to determine how far the massiveness will go. When an array of 256 antennas operating at 2.7GHz frequencies is built, it will be

approximately one square meter. The antennas, with supporting circuitry and enclosures with cooling fins, will be heavy to mount on a tower, and an array the size of a card table will pull like a sail in the wind. Additionally, the complexity of using the airwaves grows as more channels are put in use.

The sub-6GHz spectrum is highly fragmented, with some frequency bands reserved in some countries, but not others. Worldwide, the spectrum is apportioned in 46 frequency bands, causing great difficulties for equipment vendors, service providers and, sometimes, end users. Considerable overhead is involved in providing massive MIMO base stations into the worldwide fragmented spectrum in use today.

So how do we overcome these types of limitations? One goal of 5G is to open spectrum to more and faster transmissions. Massive MIMO in the sub-6GHz space will help, but it is also crucial to employ higher frequencies with much higher bandwidths that have not yet been allocated for other uses or are used sparsely today. Currently, large areas of the spectrum above 24GHz are available worldwide, offering a sizeable range of frequencies that can be grouped into un-fragmented frequency bands that can enable the wide range of 5G services. The wireless industry and regulatory agencies are collaborating closely to negotiate for use of this spectrum. 5G networks will get an early start in the sub-6GHz bands, but will become enabled to full 5G expectations in much higher frequency bands.

Above 24GHz, communications are often referred to as millimeter wave (mm-wave) transmissions, as opposed to the tens of millimeters that measure wavelengths below 6GHz. The 10x difference in wavelengths between, for example, a traditional 3GHz and future 30GHz signal means that receiving antennas can be one-tenth the size (one-hundredth the area), so that an array of antennas receiving 256 channels in mm-wave transmissions can be

approximately 10x10 centimeters squared (about 4x4 inches squared). Simply by moving to much higher-frequency transmissions with the larger bandwidth available there, wireless service providers will be able to pack 10x the wireless throughput capacity into each base station. Meanwhile, the size of the antenna array shrinks considerably, allowing for more inconspicuous and lower-cost base station equipment deployments (Figure 4).

Since the smaller antenna elements do not create and capture as much energy in signaling, multiple antennas are used in an array for a single channel, employing a technique known as “beam forming.” Beam forming focuses on both transmission and reception in a specific direction. Instead of a single transmission that is omnidirectional, now multiple transmissions can be sent to and received from different directions. Effectively, due to the special separation between different beams, this results in another 10x increase in channel capacity.

Smaller wavelengths of mm-wave transmissions mean that their range may be less. In addition, the wavelengths can be easily absorbed by solid

obstacles such as walls, buildings or moving objects such as cars and trucks, low-energy coated windows in homes and cars. Also, the transmissions do not bend around the corners of buildings and hallways. In 5G mm-wave, transmission space will be compartmentalized using very small base stations, such as one along a block or two of a north-south street and another along the same length of an east-west street.

Many more of these base stations can be deployed in a more closely packed network topology, bringing mm-wave transmission links close to end users, thus enabling many more user connections and higher data rates. This increase in proximity causes a third increase of 10x in capacity, bringing the total capacity increase of 5G mm-wave networks to 1000x beyond what is available today (10x from the greater spectrum, 10x from directional transceivers, 10x from the increased number of base stations). When these capacity increases above 24GHz are added to those that come with massive MIMO in the sub-6GHz space, it is clear that 5G capacity will be vastly greater than what is available today.

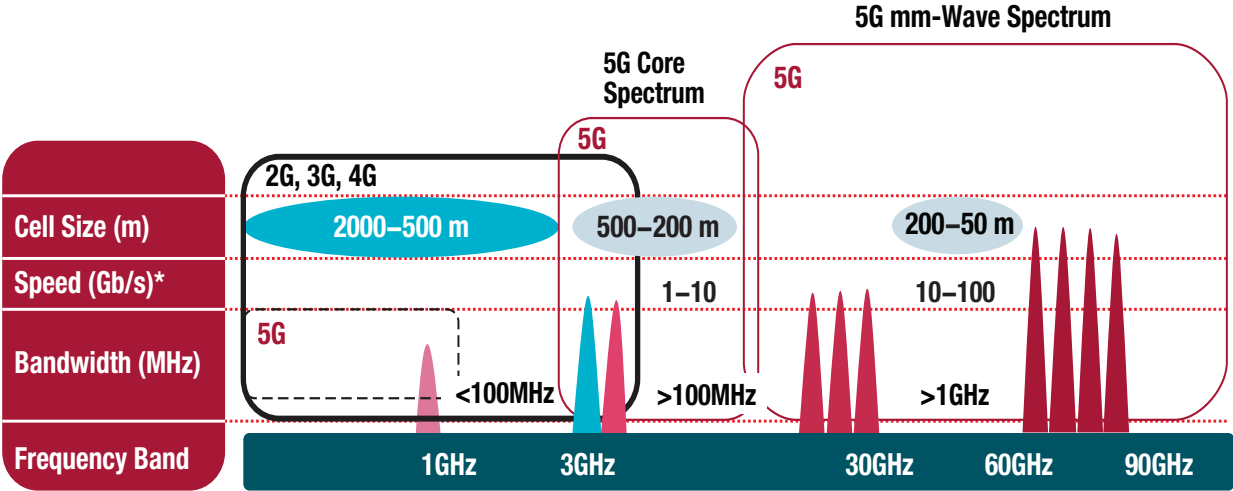


Figure 4. Diagram showing cell size, throughput, frequency of mmWave.

IC requirements

Base station deployment using mm-wave GHz frequencies is still a few years away, but field trials are scheduled much sooner. By early in the next decade, the first commercial mm-wave 5G installations are expected to be operating. Even before then, last-mile broadband services in homes will be enabled by mm-wave connectivity due to cost and deployment advantages over traditional copper or fiber-optic connections.

Scaling. The smallest base stations will feature an antenna array the size of a credit card, creating big challenges in integration, low power consumption and connectivity. Solutions for larger sub-6GHz base stations are equally faced with these issues, since size and weight present a different kind of challenges for massive MIMO arrays on towers.

Integrated sub-6GHz transceivers that already exist are being further incorporated into multi-channel devices such as the AFE7500, with more highly concentrated units to follow. Direct RF sampling, such as the ADC32RF80/45 RF-to-bits ADC and TI's accompanying bits-to-RF DAC, will help make signal chain devices more agile and compact.

Solutions for mm-wave transmission have not yet been introduced but will follow suit. Since this is a new frontier for the wireless industry, base station manufacturers rely heavily on IC suppliers to help them open the territory. The goal for these new mm-wave transmission solutions is to achieve 10-Gbps throughput with range up to one kilometer and one milli-second latency in the transmission link.

Power density. Every bit requires energy at every stage of transmission, reception, signal conversion and processing. Up to three orders of magnitude more bits per second will be transmitted and received from every 5G massive MIMO array base station,

so the energy spent for every bit must be reduced faster than the data rates are expected to rise. If bit conversion energies stay at today's efficiency, just the size reduction expected from mm-wave arrays will significantly increase the power density consumed. The enormous challenge that technologists face is that every block in the signal chain, whether it is the RF power amplifier, low-noise receiver amplifier, ADC or DAC, needs to follow a very aggressive efficiency improvement. Otherwise, the temperature of these credit card-sized arrays cannot be managed in the harsh environments where they are placed. TI invests heavily in state-of-art technology, including best figure-of-merit GHz ADCs and DACs, as well as RF signal paths, to enable such aggressive integration and the RF frequency shift to mm-wave.

Smart power management. Another area of importance is the power consumption of signal path electronics, since the circuitry will require that its power be converted and delivered into smaller physical space with overall high efficiency. In addition to supplying power more efficiently to other devices, the power management functions themselves will be more efficient to fit into the smaller space and volume of such base stations. For very small mm-wave base stations, total power savings aid in size reduction, while in the case of sub-6GHz massive MIMO arrays, less heat can also reduce weight, since the cooling fins needed to manage the temperature of attached circuitry may weigh as much as the rest of the assembly combined.

In addition, intelligent power management for next-generation radios provides remote supervision and communication for distributed power management. Power Management bus (PMBus) and other protocols like SMBus and I²C are among the many digital communication interfaces which have been deployed to engage power conversion modules with the base

station's overall smart system control. A power system manager is often used to coordinate system power distribution and monitoring, which communicates with various converters in the system.

Switched-mode power supplies inherently include a closed control loop that defines the transient and steady state performance of the system. On the other hand, analog control loops have been commonly used for high-efficiency conversion. "Digital power" improves the footprint of so-called brick power supplies. It also offers advanced adaptive control algorithms for smart switching mode converters. Digital Point of Load (POL) controllers provide the POL designer with a very high degree of configurability. With this extreme flexibility at their fingertips, system designers can quickly configure the POL's outputs and phases to meet the specific needs of their designs. The digital power management capabilities allow for integration of more sophisticated sequencing processes in complex high-current multiphase applications with many power rails. Designers can carefully prescribe and easily deploy the most effective sequence for powering up and powering down the various rails in the system.

Also, real-time tuning of power converter parameters to optimize the performance in various load conditions is highly desirable. It can improve the efficiency of both light and full loads in wireless base stations and improve ease of use.

Many key innovations have contributed to the rise of smart power management. New architectures, such as high frequency soft switching and multiphase converters, loop control with signal processing algorithms, and power devices with a high figure of merit (including new materials like GaN), are critical for competitive smart power management of next-generation wireless infrastructure.

Timing. At higher frequencies, precise timing becomes more important than ever, so devices using

the mm-wave spectrum will use ultra-low-jitter clocks with 10x improvement over those in use today to keep circuit timing as accurate as possible. TI's jitter cleaners provide the industry's best in-band phase noise performance and enhanced synchronization features like the JESD204B SYSREF generation. Moving forward, even higher performing and more integrated devices will meet the upcoming needs of 5G and mm-wave radios. Finally, microprocessors and system software will continue to improve signal-processing efficiency. The overall goal is to operate as many channels through as few chips while creating as little heat as possible. In this way, system size and complexity continue to decrease, as do the bill of materials and operating costs per channel.

Through advanced process technologies and its design expertise, TI is well poised to meet these demands through a range of innovative solutions for its customers, including:

- High-speed direct RF sampling data converters
- Multi-channel, highly integrated RF transceivers
- Ultra-low-jitter and phase noise clocking devices
- Highest-efficiency and highest-density power management solutions
- A range of high-linearity and dynamic range signal conversion paths
- A variety of other state-of-the-art analog-based products

TI also has long history of developing leading-edge technology for communications infrastructure and wireless communications designers, and it participates in a variety of wireless industry associations and standards bodies. In addition, TI provides the systems expertise for a wide variety of other applications, enabling technology employed in one area to be more easily adapted for use in others. All of these factors position TI well to help customers deploy the next generation of connectivity and capabilities.

Forging ahead to the next wireless generation

5G wireless communication promises faster speeds, minimal latency, more connections and lower power in the decade of the 2020s and beyond. However, we are still blazing trails on the technological path leading to these benefits. Existing and new base stations on towers will be upgraded with massive MIMO antenna arrays to support many more channels beyond what is possible with today's installations. Smaller base stations with mm-wave transmissions will also be spread around heavily populated areas to enable ultra-high speed coverage. In addition to these major deployments, 5G, like the wireless generations before it, will include enhancements that range from basic carrier specifications to security, which will serve to make the user experience more satisfying.

At the most fundamental level, the changeover to 5G depends on innovative IC solutions and a continued focus on semiconductor technology advancement.

TI's portfolio of innovative chips spans almost all functions in base stations, and the company is committed to developing the innovations needed for its customers to deliver 5G communications. As the world readies itself for, then adapts to the next generation of wireless services, it will benefit from advanced technology developed by TI.

For more information:

- Read our [“5G: The next wave in connecting more people and things”](#) blog
- Explore [TI solutions for Communications Equipment](#)
- Check out TI's [ADC32RF80](#) and [ADC32RF45](#) RF-to-bits ADCs, as well as the [LMK0482x](#) clock jitter cleaner family

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