WHITE PAPER

Ralf Bendlin,
System Engineer
Tony Ekpenyong,
System Engineer
Debbie Greenstreet,
Strategic Marketing
Texas Instruments

Texas Instruments

Paving the path for wireless capacity expansion

Abstract

There is no argument that the advent of smart phones and other handheld devices, and the plethora of data-consuming applications used on them, not only brought the wireless customers in, but has left them wanting more. The various predictions of data demand on wireless networks over the next three to ten years show significant growth, outpacing the predicted network capacity. Furthermore, studies show that as the wireless data usage increases, the service providers' average revenue per user (ARPU) is declining. What are these service providers to do as the data demand continues? They can act defensively and start installing data usage monitoring and throttling mechanisms, limiting the data traffic to users; or they can go on the offensive and establish network topologies and advanced techniques to maximize network capacity (hence more data throughput) and improve the efficiency at which they do so.

Wireless base station manufacturers play an important role in this capacity strategy, and can face numerous challenges in doing so. This white paper explores some of the techniques that operators can use to increase capacity and their relative costs. This paper also discusses how Texas Instruments' new wireless System-on-a-Chip (SoC) plays a key role in enabling manufacturers to meet this capacity challenge.

Introduction

One of the most significant technology challenges operators face today is coping with the data deluge. According to the Global Mobile Data Traffic Forecast Update by Cisco Systems in 2011, global mobile data traffic is expected to increase 26-fold between 2010 and 2015, reaching 6.2 exabytes per month of data in 2015. The use of smart phones and other data-consuming handheld devices has been met with even more popularity than the operators probably anticipated. With the never ending launch of new data-hungry applications for these devices, subscribers continue to drive the demand for more capacity. Service providers not only need to close the gap between capacity and demand to satisfy subscribers but they must also find a path that provides profitable average revenue per user (ARPU).

However, this isn't the only issue with which the service providers are coping. Many operators see 4G technologies such as LTE as a way to address the onslaught of user data, but they cannot simply throw a switch and upgrade from 2G to 3G or 3G to 4G overnight. Subscribers do not upgrade their devices all at once, or even over several years, so operators will always have a mix of subscriber technologies to support, and as such, operators need to support multiple technologies in their networks over any given period of time.

These network requirements in turn create capital expense (CAPEX) and operational expense (OPEX) challenges; CAPEX because equipment upgrades are costly and OPEX because of the cost of installing and maintaining parallel networks. A good portion of the operator's OPEX cost is electrical power consumption. The cost of the actual operating power, plus the pressure to reduce their overall carbon footprint causes operators to place significant emphasis on "green" power strategies.

Fortunately, there are multiple techniques that operators can leverage today. These are solutions that enable them to expand their network capacity, close the gap and meet the growing demand. Additional spectrum, improvements in spectral efficiency, advanced antenna techniques and the use of smaller cells as part of heterogeneous networks, are all possible tools in the tool box. However, each operator will likely prioritize the techniques to achieve that capacity differently. This in turn creates a challenge for the base station manufacturers supplying to wireless operators worldwide. How then can base station manufacturers maintain a successful business at supplying cost/performance/power-optimized solutions to each and every operator while maintaining a viable R&D environment and time to market delivery?

Capacity constraints

No discussion on wireless network capacity would be complete without at least a brief mention of the theoretical physical limits of information transmission in data communications as described by Bell Labs scientist, Claude Shannon.

Claude Shannon showed that the capacity of any channel, denoted as C can be defined as the maximum rate at which information can be transmitted over the channel with arbitrarily small error probability. Using a simple illustration of how many small spheres can be packed into a large sphere, whose radius is equal to the magnitude of the received signal, the capacity of an Additive White Gaussian Noise (AWGN) channel can be expressed as

$$C = W \log_2\left(1 + \frac{P}{N_0 W}\right) \quad \text{bits per sec}$$

where P is the transmit power, N_0 and W are the one-sided noise power spectral density and the one-sided bandwidth in Hz, respectively. It is more illustrative to express the capacity in terms of the rate at which we can transmit given a finite amount of spectrum. This is particularly important for wireless communications where RF spectrum is a limited and expensive resource. Hence the capacity can be defined in terms of the achievable spectral efficiency as

$$\begin{aligned} C' = \frac{C}{W} &= \log_2\left(1 + \frac{P}{N_0 W}\right) \\ &= \log_2\left(1 + \mathrm{SNR}\right) \text{bits/s/Hz} \end{aligned}$$

It can be observed that the capacity is a logarithmic function of the signal-to-noise ratio (SNR). Therefore, increasing the SNR increases the capacity. However, this suffers from the law of diminishing marginal returns. The main objective in many communication applications is to minimize the energy required to transmit an information bit. This goal is even more important given the demand for more energy efficient, “green”, communication techniques. By applying a small value approximation to the equation above it can be shown that the minimum SNR per bit is given by

$$\left(\frac{E_b}{N_0}\right)_{\min} = \frac{1}{\log_2 e} = -1.59dB$$

This limit is called the Shannon limit and is used to measure how close a code comes to achieving Shannon capacity.

Practical communications

For the AWGN channel, Shannon used a random coding argument of information theory to show that capacity achieving codes do exist. Since his seminal paper in 1948 much of communication and coding research has focused on designing (near) capacity-achieving codes. This led to the discovery and usage of increasingly more efficient codes such as the so-called turbo codes and low density parity-check (LDPC) codes.

As mentioned, these values are theoretical, and not practical in today's environment. The capacity definition makes no assumption on the modulation whereas for practical systems a discrete modulation (e.g., QAM) is used. For example, LTE employs up to 64 QAM which provides 6 bits per transmitted symbol. So we have a capacity limit that applies to wireless communications, and defines our theoretical maximum. The good news is that as an industry we have yet to achieve this theoretical maximum, and, furthermore, there are a variety of methods for which operators can continue to increase such capacity.

Bandwidth

The first element to increase channel capacity is bandwidth. Obviously more bandwidth relates to more capacity and, as wireless technologies have evolved, wider channel bandwidths are supported by the standards. For example LTE, a 4G technology supports up to 20-MHz bandwidth today, representing a 4× increase over the 5-MHz bandwidths of WCDMA. The LTE-A specification continues the increase in bandwidth with support for up to 100-MHz bandwidth.

Spectrum

These wider bandwidths, however, are not always available to each and every operator. In the cellular wireless market, the ability to obtain licensed spectrum (the "permission" and right to transmit in a given frequency) is a significant and costly challenge in doing business for operators worldwide, and can be a barrier to entry. The science and politics behind assigning functional applications to spectrum, and licensing that spectrum to rights holders, is complex and varies worldwide. Figure 1 shows a snapshot in time of a

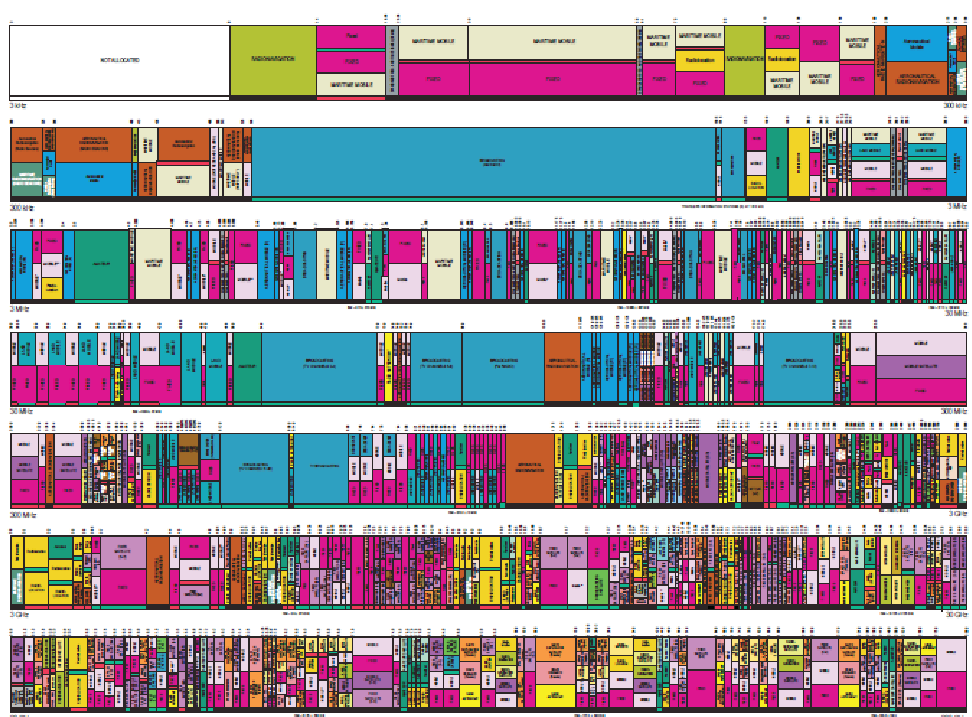

Figure 1. A snapshot in time of a portion of the U.S. spectrum allocation.

portion of the U.S. spectrum allocation. One doesn't need to see the details to understand the very segmented and complex nature of all the assignments. Only a small portion of this radio spectrum is allocated for cellular communications. The allocation of certain frequency bands is a lengthy and complicated process. Once a particular band is assigned to a cellular technology, operators compete to pay hefty prices for the exclusive rights to such frequencies. This costly but necessary asset for operators has been exemplified in the news lately, with spectrum acquisitions and transfers between major U.S. operators. So in summary, while acquisition of spectrum is an option for operators to increase their bandwidth in support of capacity, it is an expensive approach (at least for now) while spectrum is so scarce.

Carrier aggregation

A further nuance in the spectrum maze is that an operator may be licensed for bandwidth that is actually a sum of frequency bands that are disparate, non-adjacent in the spectrum. This means that in theory they could use these to increase the channel bandwidth but it is in no way as simple as implementing a single, wider band or carrier. However, this may be the only choice an operator has to obtain a wider bandwidth, and hence they may choose to employ a scheme of carrier aggregation to do so. Carrier aggregation will be even more prevalent in LTE-A solutions where operators can aggregate five 20-MHz bands to meet the 100-MHz LTE-A bandwidth.

The LTE Release 10 standard specifies protocols and procedures for implementing carrier aggregation. While this provides a standard approach for implementation, this aggregation does not arrive without a cost. Certainly the radio front end of the base station has more components and complexity, and an additional protocol burden (as well as overall bandwidth processing capability) is levied onto the baseband processing.

Spectral efficiency

We now take a more detailed look at how actual wireless technology implementations can be optimized to get closer to that theoretical maximum channel capacity detailed by Shannon, that is, techniques to improve spectral efficiency. Certainly cellular network deployments are nowhere near such capacity today.

Optimized wireless technologies

One of the most likely ways to strive towards the Shannon limit of capacity is to establish a communications exchange between sender and receiver that is so efficient that its theoretical implementation comes closer to the ideal efficiency. The worldwide 3GPP organization, comprised of scientists from operators, equipment manufacturers, silicon and software vendors from around the world, is spending a significant amount of effort and money to collectively establish the most efficient yet realistic protocol feasible, within the constraints of physics. Their latest standard releases, LTE (Release 8/9) and soon to follow LTE-Advanced (Release 10 and beyond), are indeed the most spectrally efficient to date and one reason why many operators around the world have either started LTE trials and deployments or made announcements to do so.

The values in Table 1 on the following page correspond to the peak LTE spectral efficiencies. Peak means that a scheduled user receives two code-words, and two spatial streams per code-word, and each spatial stream is transmitted with 64 QAM. This corresponds to the peak downlink throughput equaling 300 Mbps (within 20 MHz) or a peak spectral efficiency of 15 bits/s/Hz. The expected throughput differs across different users depending on many factors. Yet assuming that all the users are equally served, the average throughput per user has an upper limit of 300/K Mbps. Obviously, this number is achieved under idealized channel conditions.

Table 1. Peak LTE spectral efficiencies

Bandwidth	LTE Rel 8, 9 20 MHz	LTE Rel 10 20×5 = 100 MHz	WCDMA Rel 8 5 MHz	WCDMA Rel 10 20 MHz
DL peak data rate	300 Mbps, 64 QAM	300×2×5 = 3 Gbps 64 QAM	42 Mbps 64 QAM	168 Mbps 64 QAM
DL peak spectral efficiency	300/20 = 15 bits/s/Hz	3000/100 = 30 bits/s/Hz	42/5 = 8.4 bits/s/Hz	168/20 = 8.4 bits/s/Hz
UL peak data rate	75 Mbps 64 QAM	300 Mbps×5 = 1.5 Gbps 64 QAM	11 Mbps 16 QAM	44 Mbps 16 QAM
UL peak spectral efficiency	75/20 = 3.75 bits/s/Hz	1500/100 = 15 bits/s/Hz	11/5 = 2.2 bits/s/Hz	44/20 = 2.2 bits/s/Hz

While LTE is the most spectral efficient wireless technology to date, achieving idealized channel conditions in LTE is a challenge in practice and we would not expect LTE deployments, especially early ones, to achieve the theoretical spectral efficiency of LTE. Hence the goal is to implement features that do indeed increase the efficiency.

Interference cancellation

Another means of improving spectral efficiency is by reducing the noise of the channel, thus increasing the signal-to-noise ratio. This can be done by mitigating or cancelling interference; where interference is defined by noise introduced by adjacent communications occurring simultaneously. Cellular interference can be lumped into two categories, interference introduced within the cell or sector, and interference due to adjacent wireless cells.

Uplink intracell interference is noise that is introduced by other User Equipment (UE) or handsets within the same cell. Within WCDMA networks, common advanced receiver techniques in the base station such as Parallel Interference Cancellation (PIC) and Successive Interference Cancellation (SIC) can be employed to reduce interference. Within an LTE system, an Inference Rejection Combining Receiver (IRC) for the uplink shared data channel can be employed at the base station.

Intercell interference may be encountered near cell edges especially as heterogeneous networks become more prevalent and small cells are near and within macro cells. Interference avoidance schemes can be used, and may be implemented via advanced user scheduling that helps to avoid such interference. Also, enhanced Inter-cell Interference Coordination (ICIC) techniques have been defined in later versions of the LTE specification, enabling UEs to share more information and proactively avoid interference.

The implementation of the schemes mentioned doesn't come for free. Interference cancellation requires additional bit processing, as well as the implementation of a more advanced base station receiver algorithm. These algorithms require a significant amount of signal processing, including complex matrix operations.

Similarly, the inter-cell interference coordination schemes require additional real time signal processing to maintain the optimum user experience.

Optimized LTE user scheduling

Another key aspect to improving spectral efficiency and achieving higher capacity in an LTE system is to maximize the number of users scheduled for transmission in a given time slot. LTE leverages a dynamic frequency aware radio resource allocation and the LTE scheduler decisions take in to account instantaneous channel conditions, traffic situations and user Quality of Service (QoS) requirements. As such, advanced LTE user scheduling algorithms have the potential to improve the spectral efficiency of the LTE channel over solutions using a much simpler scheduling scheme.

LTE user scheduling algorithms can be a tool for performance differentiation by both service providers and base station manufacturers. More advanced schemes require significantly more processing horsepower, while simultaneously requiring execution within a limited amount of time. These algorithms typically execute multiple search and sort loops and complex matrix operations, while maintaining low-latency communications with the physical channel.

Multiple antenna strategies

The previous sections described the capacity of a channel as a single link between a transmitter and a receiver and what can be done to optimize that particular channel. The time and frequency dimensions [e.g., an orthogonal frequency division multiplexing (OFDM) system] can be exploited to optimize the achievable communication rate over a wireless channel. However, the spatial dimension can also be exploited to increase the capacity of a wireless channel. If we consider an antenna as a pipe (in space) then all things being equal, by increasing the number of pipes, we can effectively transmit more streams (data) in space, relative to a single pipe. The Shannon capacity sets a limit for the best possible data rate you can transmit over all the pipes.

Figure 2 shows a downlink channel between a base station and mobile UE. There are N_t transmit antennas and N_r receive antennas at the base station and UE, respectively, and this is called a multiple input multiple output (MIMO) system. From matrix theory the MIMO channel provides min (N_t, N_r) degrees of freedom, or equivalently, min (N_t, N_r) parallel spatial streams over which communications can take place. Therefore, by adding multiple antennas at the transmitter and receiver the capacity increases linearly with the number of parallel spatial streams that can be obtained as:

$$C = \min(N_t, N_r)\log_2(1+\mathrm{SNR})\ \text{bits/s/Hz}$$

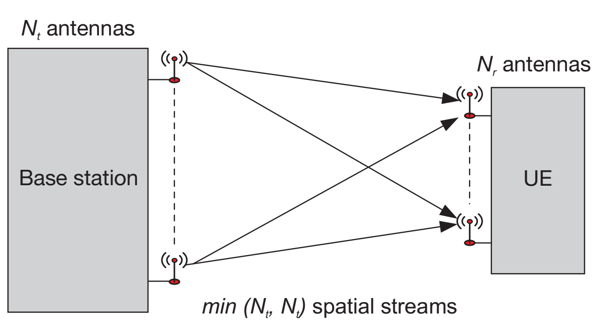

Figure 2. Illustration of a MIMO system between a base station and UE.

To illustrate the benefits of MIMO, a 200 percent gain in spectral efficiency is obtained for a 4×4 MIMO system over the same spectrum allocation owned by a cellular operator!

MIMO in cellular systems

MIMO is currently employed in HSPA and LTE systems. It is particularly challenging for CDMA-based systems because the (W)CDMA multipath channel causes inter-symbol interference (ISI) which destroys orthogonality of the spreading codes. This in turn causes inter-chip interference between such spreading codes. It also calls for complex receivers for interference cancellation.

LTE is an OFDM based (multi-carrier) system, where the channel is approximately constant in one subcarrier. MIMO processing can be performed per subcarrier because there is no ISI to pre-cancel and requires a simpler receiver design than needed for other wireless technologies such as CDMA. Efficient and optimal receiver techniques of maximum likelihood decoding can be employed.

However, that does not mean that a MIMO implementation comes without cost. A MIMO implementation increases the number of antennas that both the handset and the base station need to support, and as such increases the complexity (and cost) of the radio front end. It also requires more signal processing than in single-antenna configuration. This mainly comes in the form of complex matrix operations which must be executed real time.

Small cells, more cells

Probably the most commonly used capacity-enhancing approach over the history of wireless communications has been the use of smaller cell sizes. This trend appears to continue as we see LTE and heterogeneous networks' popularity rise as small cell base stations are being deployed.

In a traditional cellular network, good network planning is constituted by deploying macro base stations in such a way that ubiquitous coverage is guaranteed for all users while at the same time minimizing the overlap of coverage provided by different macro base stations. Ideally, and at least from an efficiency viewpoint, a user can seamlessly move through the network without ever losing connection (e.g., a dropped call) and continuous coverage is guaranteed with the minimal number of macro base stations.

Heterogeneous networks fundamentally change this notion by overlaying existing homogeneous networks—homogeneous because they mainly provide coverage—with smaller cells. Since coverage is already provided by the macro base stations, small cells are deployed to boost the capacity of the network in highly populated areas such as business districts, universities, malls and during sporting events, commonly termed "hotzones." In general, macro base stations create coverage cells whereas small cells are booster cells. There are also some cases where small cells can be deployed to fill in coverage holes, either outdoor or indoor.

An additional benefit of small cell deployments is that the base stations of the smaller cells have the potential to reduce expenses for the operator due to their somewhat lower complexity, smaller form factors, and lower transmit power requirements.

How do small cells improve capacity?

As noted earlier, channel capacity is measured in bits per second. For an OFDM-based system like LTE, where resources are partitioned into a time-frequency grid, a channel use comprises a set of OFDM sub-carriers (frequency) as well as a set of OFDM symbols (time). A natural metric for the channel capacity of a cellular network is the achievable spectral efficiency which was defined in bits per second per Hertz or simply bits/s/Hz. In a co-channel deployment, small cells use the same time-frequency resources as the macro cells. However, instead of placing the cells "next to each other" as in the case of coverage-oriented homogeneous networks, the additional small cells are placed "on top of" the macro cells, hence the term overlay. As a result, the re-use of the time-frequency resources is significantly increased amounting to a significantly higher capacity in the Shannon sense. An appropriate measure of the Shannon capacity of a heterogeneous network is the area spectral efficiency in bits/s/Hz/m^2 in reference to the re-use of resources in time, frequency and space[1]. Because the coverage areas of multiple cells overlap in heterogeneous deployments with overlay, the coverage area of a macro base station encompasses multiple small cells. The capacity improvement that small cells provide is termed a cell splitting gain and originates both in the physical layer and in higher layers.

Since small cells increase the cell deployment density of the network, they result in shorter average distances between a user and the nearest base station. For instance, a user which would have connected to a macro base station in a homogeneous network may now be in the vicinity of a small cell. Due to the fundamental trade-off between link rate and range, decreasing the distance between the transmitter and the receiver reduces the path loss that the transmitted signal experiences. This is the single most powerful means to improve the link quality and results in a larger capacity for the link. Historically, as cellular networks progressed from 2G to 3G and now to 4G, smaller and smaller cell sizes—together with ever-growing bandwidths—have been the main driver to increase the capacity of cellular networks. Small cells take this principle one step further by not only decreasing the cell size but by aggressively re-using the available resources in space as described above. In addition, the small cell sizes help to isolate the cells, by using lower transmit power in the small cell base station significantly reducing intercell interference in the network.

On top of the cell-splitting gains in the physical layer, there are additional benefits and associated gains in higher layers of the network architecture. For example, users that are connected to small cells free up resources at the macro base stations which would have otherwise been used to serve those users. This is referred to as offloading gain. Users are "offloaded" from the macro network to the small cells to balance traffic and to increase the overall network throughput and efficiency. An example of how spectral efficiency can be improved by employing small cells is shown in Figure 3 on the following page. Here it can be seen that the spectral efficiency improves as small cells (reduced output power) are added to a homogeneous macro sector.

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[1] Space here refers to the geographical deployment of macro cells and small cells and should not be confused with the spatial dimensions provided by multiple antennas at a transmitter and receiver.

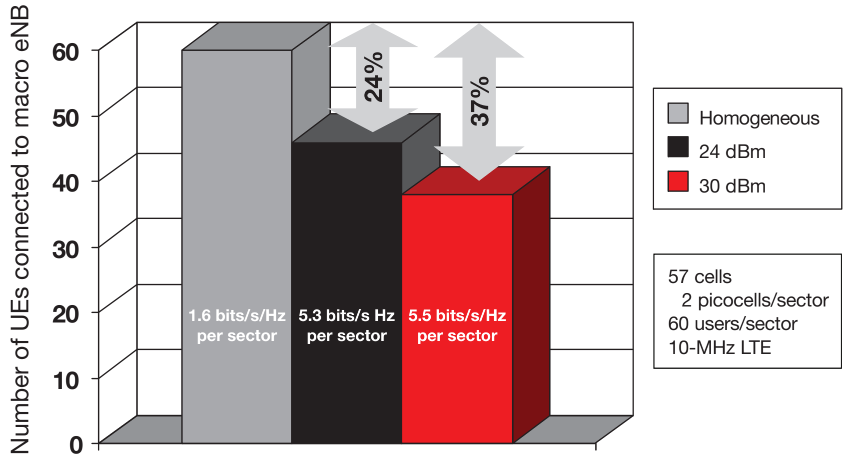

Figure 3. Spectral efficiency improvements with small cells.

What is the ideal solution?

While it is challenging for operators to achieve higher network capacity in the wake of increasing user data demands, they do have some tools available to them today (and in the future) to leverage. Additional spectrum, improved spectral efficiency, multiple antennas and small cell topologies are all viable options. Can operators simply employ them all at once? That scenario is unlikely, due to the unique situations and assets of each operator and to the fact that each tool carries implementation costs. So then, is there some level of ideal combination of these techniques that makes sense? Well certainly not one that satisfies each and every operator requirement and situation.

Where then does this leave base station manufacturers whose success is based on delivering high performance, with optimal cost and power consumption? These vendors, who must utilize their precious R&D resources wisely while achieving a competitive time to market, have a real challenge in deciding which tools to focus on and which knobs to turn to achieve increased capacity when operators all have different strategies. Ideally they need a single platform which provides common hardware architecture and a software programming paradigm, affording development efficiencies while allowing for unique operator configurations and differentiated features.

Introducing the TCI6636 SoC

TI's TCI6636 SoC has been designed to enable operators and network equipment OEMs to harness the merits of small cells with ease and efficiency while also enabling an optimal platform for differentiation through the other aspects of capacity improvement. As a single SoC for a small cell application, the TCI6636 SoC supports a full sector of high-performance WCDMA and LTE capacity, with LTE-Advanced support through optimized configurable accelerators and DSP and RISC processors. It affords additional signal, packet and control processing capability to provide data capacity improving functions.

While the TCI6636 SoC is an ideal high-performance, small-cell solution, it also serves as a perfect WCDMA/LTE macro controller device. A controller, in the sense that it provides high-performance Layer 2, Layer 3 packet/transport processing capacity sufficient enough to support a multi-sector macro base station, and works in conjunction with additional SoCs, providing the same performance/differentiating capability for a macro as the single SoC serves for the small cell.

The TCI6636 SoC is the first wireless infrastructure SoC based on TI's new KeyStone II architecture. The TCI6636 SoC is ideally suited to the data-centric performance that wireless network operators are demanding today for 4G small-cell base stations and provides the power to help the operator migrate to future standards. The eight TMS320C66x DSP cores provide programmable performance while expanded AccelerationPacs focus on packet, symbol and bit-rate processing to allow base station manufacturers to support a mix of WCDMA and LTE users, easing the transition from 3G to 4G. The TCI6636 SoC is the first SoC to integrate four ARM® Cortex™-A15 RISC cores, bringing high-performance RISC processing at the ultra-low power consumption levels.

By integrating the ideal combination of LTE acceleration and DSP horsepower, the TCI6636 SoC has been designed to support bandwidths of up to 40 MHz, positioning it as an early platform for LTE-A market entrance. This allows operators to employ carrier-aggregation techniques, expanding data throughput. The C66x DSP in the TCI6636 SoC supports fixed- and floating-point operations and is ideal for complex matrix algorithms, providing an optimal compute platform for several capacity-improving functions. Advanced LTE user scheduling algorithms require such complex matrix operations to perform user condition analysis in real time. These algorithms leverage search and sort algorithms for which the DSP executes efficiently. The C66x compiler includes recent enhancements optimizing these search and sort type instructions. The complex matrix operations pair up with the bit-rate processing AccelerationPacs in the device to provide a high-performance, low-overhead approach to interference cancellation algorithms. The bit-rate accelerator performs process-intensive, low-latency signal-chain execution while the DSP executes a variety of interference-cancelling operations. This allows base station manufacturers to differentiate with interference cancellation techniques.

MIMO processing is executed in a similar manner. Because the bit-rate processing acceleration, including turbo decoding, is extremely powerful, it is able to process multiple transmit and receive channels simultaneously as required for MIMO solutions. In parallel, once again the C66x DSP is leveraged to execute complex matrix operations necessary for MIMO algorithms, and provides each manufacturer the ability to differentiate such algorithms in software. These capacity-enhancing capabilities apply to both high-end small cell and macro base stations. This not only provides the manufacturers with a platform for supporting a variety of operator capacity-enhancing options but affords them a common hardware and software platform to maximize their R&D development efforts and achieve optimal time to market.

In summary, the TCI6636 SoC provides a common KeyStone architecture for base station manufacturers to efficiently provide a variety of small-cell and macro-cell base stations to operators worldwide. For more information on TI's KeyStone architecture and SoCs, visit **www.ti.com/multicore**.

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