Keywords: RF DAC, RF digital-to-analog converter, LTE-Advanced, direct RF conversion, carrier aggregation, MIMO, active antenna system, eNodeB, radio access technology

APPLICATION NOTE 6062

LTE-ADVANCED RELEASE-12 SHAPES NEW ENODEB TRANSMITTER ARCHITECTURE: PART 1, TECHNOLOGY EVOLUTION

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Abstract: Analog integration plays an important role in addressing new challenges faced by LTE-Advanced radio engineers. The 3rd Generation Partnership Project (3GPP) is working on Release 12 (Rel-12) of the LTE-Advanced standard. 3GPP Rel-12 includes many enhancements to 4G radio access technology including wideband carrier aggregation, multi-layer spatial multiplexing and advanced antenna configurations. The Rel-12 enhancements will challenge radio designers to integrate more RF transmitter channels that will enable smaller, lower power and higher performance eNodeB base stations. Advancements in RF analog integration and disruptive radio architectures can help engineers successfully overcome the integration challenge.

Introduction

This two-part application note series reviews new developments in the Fourth Generation Long Term Evolution (4G-LTE) cellular standard. The application note series explores LTE-Advanced (LTE-A) Release-12 (Rel-12) features and the impact on eNodeB radio frequency (RF) transmitters. The application notes reveal how analog integration can overcome design challenges arising from the latest 4G developments. A **Glossary of Technical Terms** is appended to the end of each application note.

Part 1, this application note, examines market forces driving global adoption of the LTE standard and trends in 4G radio access technology. Readers will learn about work items outlined in the 3rd Generation Partnership Project (3GPP) Rel-12 specification. Topics include carrier aggregation (CA), spatial multiplexing, and active antenna systems (AAS).

Part 2 of this series will explore the analog integration challenges in 4G base stations. Rel-12 features such as wideband downlink carrier aggregation, downlink multiple-input multiple-out (MIMO) spatial multiplexing, and AAS with embedded RF, present new design challenges in next-generation eNodeB radios. A disruptive bits-to-RF solution is introduced that can help engineers shape alternative radio transmitter architectures. The discussion focuses on novel RF digital-to-analog converter (RF-DAC) technology that yields a single-chip, wideband RF transmitter solution. Readers will learn about system-level applications of the RF-DAC and the integration benefits that it delivers to eNodeB radio design.

Overview

Long-Term Evolution (LTE) is recognized as the fastest growing mobile broadband technology, and becoming the most widely adopted cellular standard worldwide. LTE's global rate of adoption by wireless service providers has exceeded prior second-generation (2G) and third-generation (3G) deployments. The popularity of LTE is mainly due to its high spectral efficiency and high peak data rates, low-latency IP-based network, and evolutionary roadmap. For consumers, this translates to reliable high-speed mobile access and anywhere-anytime connectivity. For wireless service providers, LTE offers efficient spectrum utilization, network capacity gains and significant improvements in total cost of ownership (TCO). But LTE is not "true 4G" service and is technically still considered 3.9G.

The true fourth-generation (4G) radio communication standard, known as International Mobile Telecommunications-Advanced (IMT-Advanced), must meet the requirements set forth by the International Telecommunication Union Radio Sector (ITU-R).

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The true fourth-generation (4G) radio communication standard, known as International Mobile Telecommunications-Advanced (IMT-Advanced), must meet the requirements set forth by the International Telecommunication Union Radio Sector (ITU-R). IMT-Advanced defines 4G as a service that delivers 100Mbps peak data rates to high-mobility users, and 1Gbps peak data rates for low-mobility clients. To comply with the IMT-Advanced vision, the 3GPP has developed many enhancements since the initial LTE Rel-8 standard published in 2008.

In Rel-10 the 3GPP introduced LTE-Advanced as "true 4G" service to meet or exceed the IMT-Advanced requirements. LTE-A Rel-10 was the next step in the mobile broadband evolution and further expanded on LTE's basic feature set. Presently, Rel-12 is close to introduction with a functional freeze date planned for March 2015. Rel-12 will include evolutionary enhancements across radio access technology. **Figure 1** illustrates LTE development timelines where it can be seen that theoretical peak downlink (DL) and uplink (UL) data rates have increased about 10x and 20x, respectively, from DL = 300Mbps/UL = 75Mbps in Rel-8 to DL = 3Gbps/UL = 1.5Gbps in Rel-10. The extraordinary increase in peak data rates is due in part to wideband CA, complimented by multilayer spatial multiplexing introduced in Rel-10 and now an important part of Rel-12 enhancements.

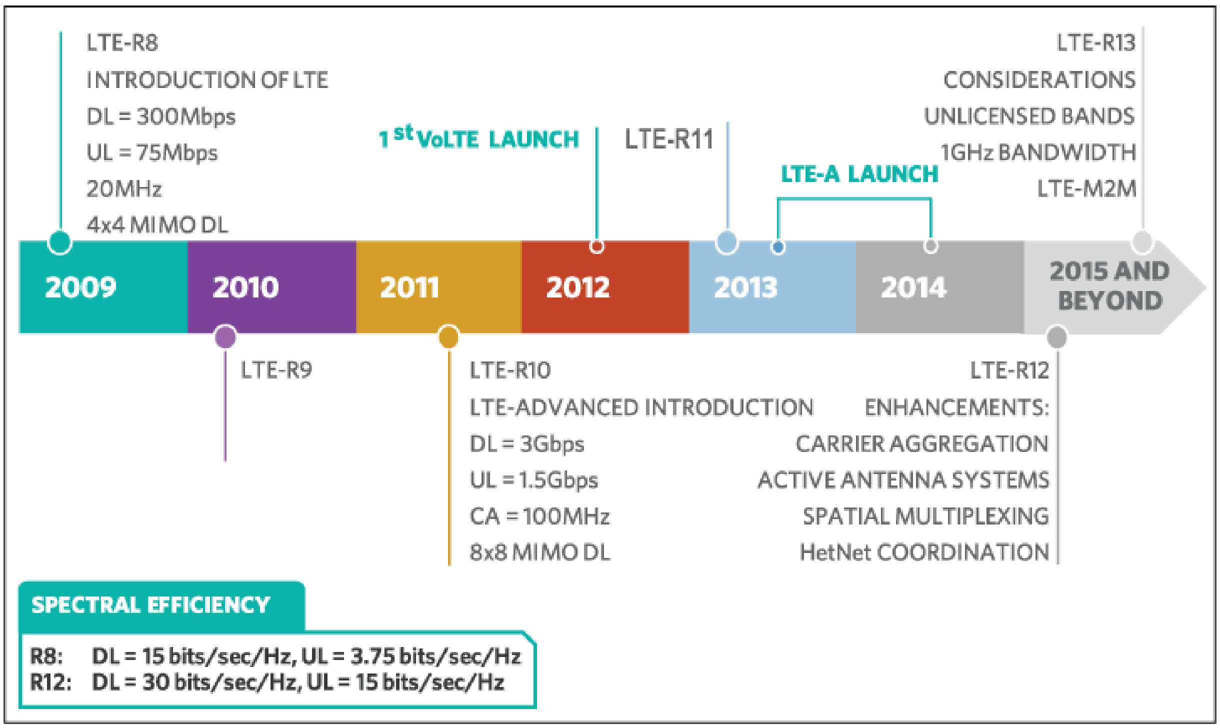


Figure 1. LTE release timeline showing evolutionary advancements in radio access techology.

LTE-A Rel-12 and the Impact on eNodeB Radios

Rel-12 enhancements will significantly impact how evolved NodeB (eNodeB) radios are designed. Some of the important Rel-12 items include new combinations of carrier aggregation, spatial multiplexing enhancements with downlink MIMO, and RF requirements needed in AAS. **Figure 2** summarizes some of the Rel-12 items with respective features and benefits.

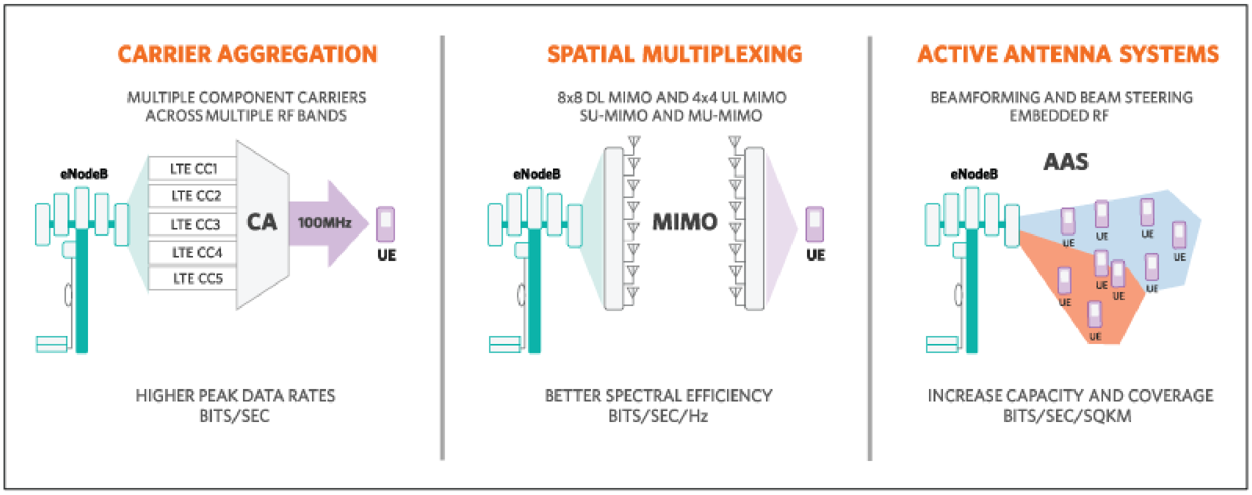


Figure 2. The features and benefits of Release 12 work items.

A closer look at the Rel-12 features reveals how the LTE mobile broadband network is evolving to realize improvements in capacity, spectrum utilization, peak data rates, and coverage. Carrier aggregation allows operators to deliver higher peak data rates (bits/sec) and better manage fragmented radio spectrum spanning 700MHz to 3.5GHz. Adopting spatial multiplexing with 8x8 MIMO increases spectral efficiency (bits/sec/Hz) to serve users with higher peak data rates while maximizing limited and valuable spectrum resources. Migration to AAS enables macro-cell base stations to implement beamforming techniques that will improve cell-edge and sector capacity while reducing power consumption. The Rel-12 feature enhancements bring many benefits to the LTE ecosystem, along with new radio design and radio architecture challenges.

Downlink carrier aggregation (DL-CA) means that base-station radio transmitters must support ultra-wide bandwidths with carrier frequency agility, and 8x8 MIMO requires more RF transmitter channels. AAS with embedded RF dedicates a radio transceiver for each antenna element with up to 16 antenna elements. This significantly increases radio channel density. In macro cell base-station applications the DL-CA, MIMO, and AAS features drive a need for compact, low-power, high-dynamic-performance radio solutions. Bound by a triad constraint of form-factor size, power consumption, and system cost, the effect of Rel-12 enhancements is profound. RF engineer's face new eNodeB design challenges: integrate more radio channels in a smaller footprint and operate at lower power with better dynamic performance, all without increasing system cost. To help engineers overcome these challenges, RF analog integration and disruptive radio architectures offer a solution that can reshape eNodeB transmitter design.

Before addressing the details of Rel-12 features, it is important to understand the market drivers and why LTE-A Rel-12 is being drafted. Simply put, is there market demand for more capacity, better coverage, and higher quality of experience? And is there a business case to justify capital expenditure (CAPEX) investment in deploying LTE-Advanced?

Market Forces Driving LTE-A

Mobile traffic is transitioning from voice to "data centric" as mobile users embrace video streaming, web browsing, and social networking on their smartphones, tablets, and mobile PCs. Over the next five years the mobile industry forecasts exponential growth in mobile data traffic and mobile broadband subscribers on the order of 60% data traffic growth and 27% subscriber growth. The anticipated result will be 16 exabytes per month traffic and six billion worldwide subscribers in 2018.[1] [2] Industry experts acknowledge that to sustain the surge in mobile broadband demand and ensure high quality-of-experience services with ubiquitous connectivity, the wireless service providers must improve network coverage, increase capacity, and maximize spectrum utilization. Meeting these objectives requires that the service provider invest in network modernization with upgrades to infrastructure that transition from 3G to 4G radio access technology and core network equipment.

Upgrading from 3G to 4G requires new network equipment. Therefore, LTE networks are more costly to deploy and require higher initial CAPEX investment. This makes CAPEX investment an important market driver. Consequently, justifying the CAPEX investment on 4G wireless infrastructure equipment demands a compelling business case that demonstrates profitability and adequate return on investment (ROI). The 4G-LTE networks are about 4x faster than 3G on average,[3] allowing service providers to capitalize on the growing mobile data demand. Also, the flat all-IP LTE network is less expensive to operate than 3G, making 4G ideal for lowering the cost-per-bit service and improving profitability.

LTE-A plays a critical role in bringing differentiated service to mobile networks and acts as a conduit for monetizing mobile data growth. Early LTE adopters who invested in LTE infrastructure like South Korea, Japan, and the United States, the world's most advanced mobile markets, have seen successful revenue growth and increasing data average-revenue-per-user (ARPU). Furthermore, because LTE provides lower cost-per-bit service, the early adopters achieved better control over operational expenses which, in turn, helped improve TCO. The early adopters quickly realized the importance of "first to market" and "best to market," or phrased another way, "build it and they will come."

Verizon Wireless,[4] SK Telecom,[5] and NTT DoCoMo are good examples where the major wireless service providers invested early in migrating to LTE. Each has reported data ARPU growth with stable profitability. Conversely in Europe, where wireless providers delayed LTE and tried to recoup expensive 3G investments, those providers are experiencing sharp declines in ARPU. **Figure 3**[6] illustrates the contrast between the average revenue per connection (ARPC) and ARPU in the U.S. versus Europe, where consumers in both markets are seeing the benefit of lower cost per connection. However, because U.S. consumers connect with more data-intensive devices, the revenue per subscription is increasing. The ARPU-ARPC gap coincides with LTE network deployments and mobile ecosystem expansion in the U.S. In fact, in 2013 the two largest U.S. operators spent $21B in CAPEX, more than all 20 operators serving the five largest EU countries. Consequently, to achieve revenue growth and profitability like that seen in the early LTE adopter markets, today the global investment in 4G infrastructure is a major reason why service provider CAPEX will reach $250B in 2017.

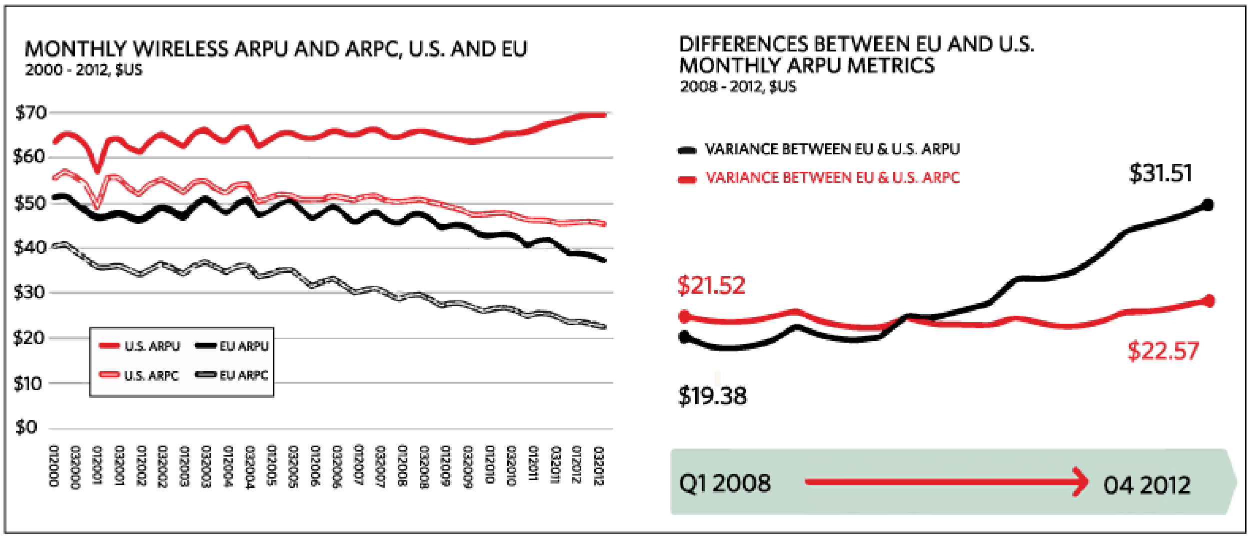


Figure 3. When mobile users connect with more data-intensive devices, as in the U.S. LTE market, the decline in revenue-per-connection is muted and operators generate higher ARPU. Source of image is GSMA Wireless Intelligence.www.gsma.com/.

Improving profitability and generating higher data ARPU are today's catalysts for the new cycle of worldwide investment in mobile infrastructure. As shown in **Figure 4**,[7] CAPEX is forecast to grow at 4.7% compounded annual growth rate (CAGR) from 2013 to 2020. Generally, the equipment-to-CAPEX ratio is about 33%. Approximately 35% of the 2017 infrastructure equipment investment is targeted at LTE which is forecast to grow at 16% CAGR from 2012-2017.[8]

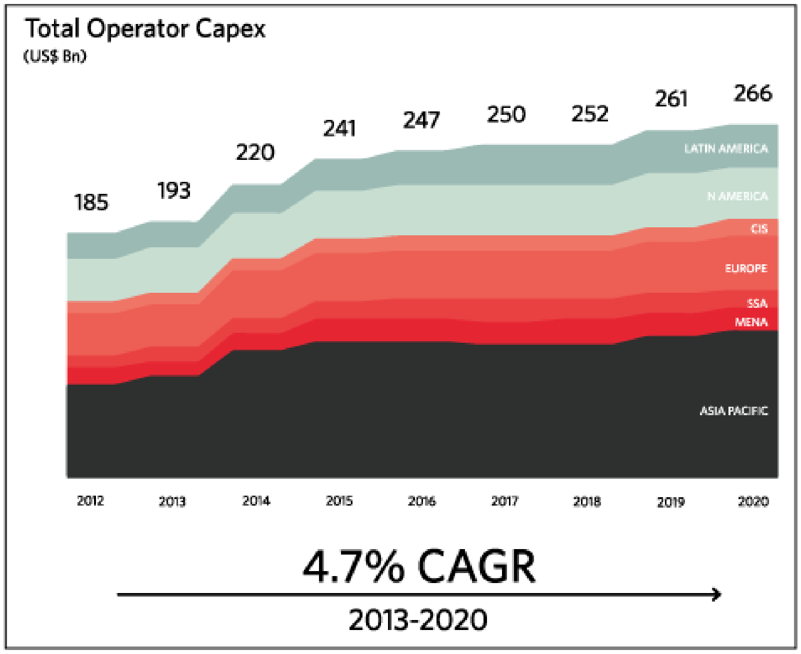


Figure 4. To sustain data growth, the operator CAPEX investment in mobile networks is forecast to exceed $1.7 trillion (USD) from 2012 to 2020. Source of image is GSMA Wireless Intelligence.

Figure 5 summarizes the primary market forces driving the evolution of 4G LTE-A and the deployment of new eNodeB equipment. Mobile data traffic and the number of mobile broadband subscribers are growing exponentially. Mobile network performance must evolve to sustain the increasing demand for bandwidth-hungry applications and this, in turn, requires service-provider CAPEX investment in network modernization. The confluence of these forces drives the evolution and adoption of LTE-A.

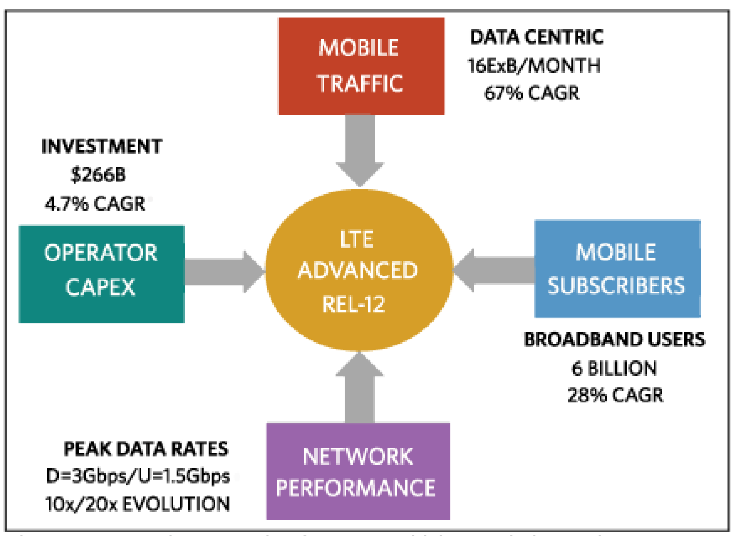


Figure 5. Four primary market forces are driving evolutionary improvements in radio access technology.

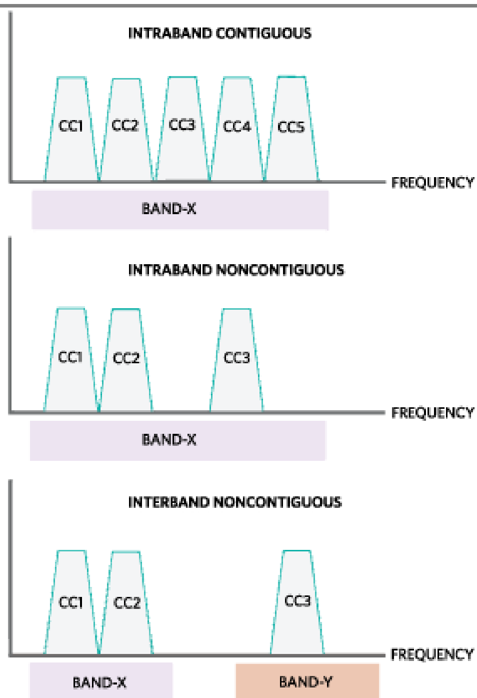
Rel-12 Trends in Macro Cell Base Station Transmitters

Market drivers, including service provider's CAPEX, are good indicators that the investment in LTE wireless infrastructure will continue out to 2020 and beyond. Much of this investment will focus on building new LTE macro cell networks and transitioning 3G macro cells to 4G access. Macro-cell base stations provide excellent wide-area coverage, often over 10s of kilometers (dozens of miles), and serve multiple RF bands spanning 700MHz to 2.6GHz. When needed, they provide backhaul for other base stations. As such, macro cells play a critical role in the cellular network and will continue their vital role well into the future. Rel-12 enhancements address ways to help service providers add more macro cell capacity and improve cell-edge performance while lowering TCO. Carrier aggregation (DL and UL), AAS, and spatial multiplexing are three Rel-12 features that augment macro cell base-station performance.

Downlink Carrier Aggregation

DL-CA groups individual component carriers (CC) together to effectively increase the transmission bandwidth available for mobile users. Component carriers can be located across the spectrum of LTE bands. DL-CA allows service providers to better utilize fragmented spectrum from 700MHz to 2.6GHz while delivering higher user peak data rates and increasing overall network capacity. Rel-10 specified 100MHz of maximum aggregated bandwidth per user, comprising up to five 20MHz component carriers. Initial LTE deployments are limited to aggregated bandwidths up to 40MHz to better serve network operator spectrum assets and allocation scenarios. Typical applications aggregate 5MHz, 10MHz, or 20MHz component carriers in different frequency bands.

There are three types of DL-CA: (1) intraband contiguous, (2) intraband noncontiguous, and (3) interband noncontiguous.[9] Carrier aggregation can be used in FDD or TDD modes, and supports bandwidths of 1.4, 3, 5, 10, 15, and 20MHz. **Figure 6** summarizes the types of DL-CA, different CA classes, and transmission bandwidth configurations. Different CA combinations are called out in Rel-10, Rel-11, and Rel-12 for both uplink and downlink. In Rel-12 a new DL combination is being introduced that aggregates three interband component carriers (3DL-CC). For example, aggregation of LTE bands 1-5-7 was demonstrated by Huawei and LG Uplus at 800MHz (CC = 10MHz), 2100MHz (CC = 10MHz), and 2600MHz (CC = 20MHz) to achieve 300Mbps peak throughput.[10]



CA BW Class	Aggregated Transmission BW Configuration		CC Maximum Number
	N	BW (MHz)	
A	$N_{RB,\ AGG} \le 100$	20	1
B	$N_{RB,\ AGG} \le 100$	20	2
C	$100 < N_{RB,\ AGG} \le 200$	40	2
D	$200 < N_{RB,\ AGG} \le 300$	60	3
E	$300 < N_{RB,\ AGG} \le 400$	80	FS
F	$400 < N_{RB,\ AGG} \le 500$	100	FS

CA= carrier aggregation, BW= bandwidth, N_{RB}= number resource blocks, FS= further studies

Figure 6. Illustration summarizes the different types of carrier aggregation, different CA classes, and transmission bandwidth configurations.

Carrier aggregation is supported across the LTE ecosystem in mobile chipsets from Qualcomm and Sequans with mobile devices in the Samsung® S5 and HTC One® (M8) smartphones, and base-station equipment from companies like Ericsson, Huawei, and Nokia Networks. Some examples of joint demonstrations with wireless service providers that achieve peak data rates of up to 450Mbps include Huawei and LG Uplus,[10] Ericsson and Telestra,[11] Nokia and SKT.[12] Presently DL-CA is close to ramping up worldwide in live networks so it will not be long before mobile LTE users enjoy the benefits of higher peak data rates.

Active Antenna System

AAS is the next step of the eNodeB evolution. Cellular base stations have evolved from the conventional base transceiver station (BTS), to remote radio unit (RRU), to integrated antenna radio (IAR), and now to AAS. **Figure 7** illustrates the evolutionary path where Generation II moves the radio units from the indoor enclosure at the base of a tower, up to the tower top below the antenna. RRU replaces coaxial feeder cables with fiber-optic cable interconnects. Generation III integrates the radio unit, typically 2T4R, and antenna within the radome where the radio interfaces with a cross-polarized antenna array. And Generation IV integrates multiple radio transceivers inside the antenna where each radio interfaces with a dedicated antenna element to form an array. An example is the introduction of Alcatel-Lucent's "cube lightRadio."[13]

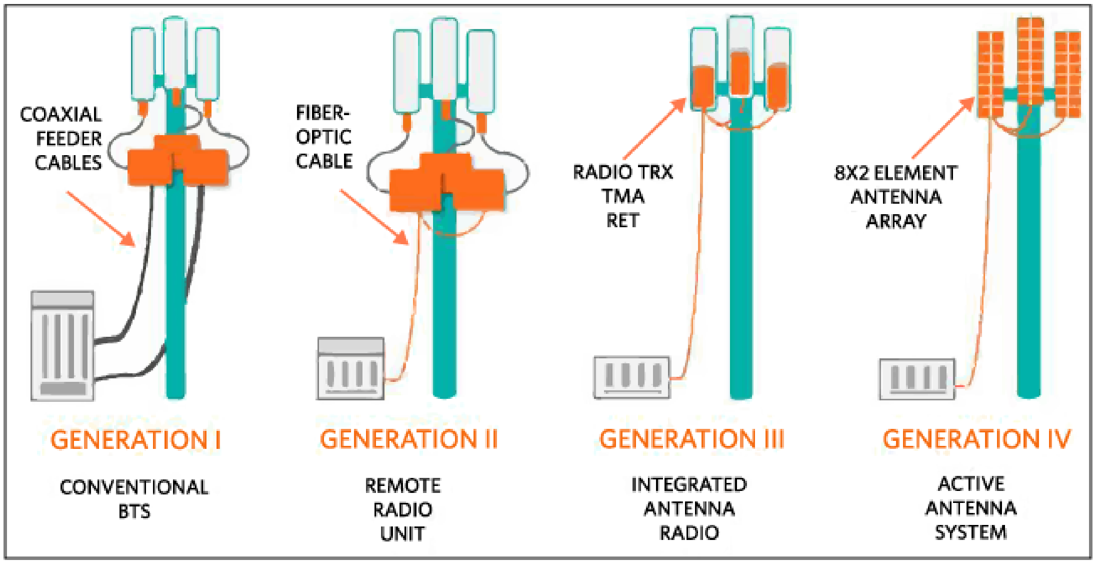


Figure 7. The evolution of base stations from the first-generation BTS through contemporary Generation IV.

Each base-station generation advanced improvements in one or more critical areas: better radio performance, lower operating power, reduced size, or faster installation time. For example, the transition from BTS to RRU saw a 50% cut in power consumption and 3dB reduction in downlink loss. The transition from RRU to IAR saw a 40% reduction in size, 8% lower power, and 1dB improvement in downlink loss.[14] The Generation IV AAS achieves yet a new, higher level of performance.

AAS is an evolutionary development that will enable macro cells to precisely focus LTE capacity to specific user groups. It will improve cell-edge performance while also reducing base-station operating power. The potential of AAS base stations lies in electronic beamforming and spatial processing techniques that produce dynamically adjustable radiation patterns. **Figure 8** illustrates the AAS structure. An array of RF transceivers and antenna elements allows electronic baseband control of phase and amplitude to shape and steer the radiated beam. This control enables single-antenna cell sector subdivision. Horizontal (azimuth) and vertical (elevation) control of the beam pattern realizes several important applications: (1) vertical sectorization(2) independent TX-RX tilt, (3) RAT tilt, (4) receiver diversity, and (5) full-dimension MIMO.

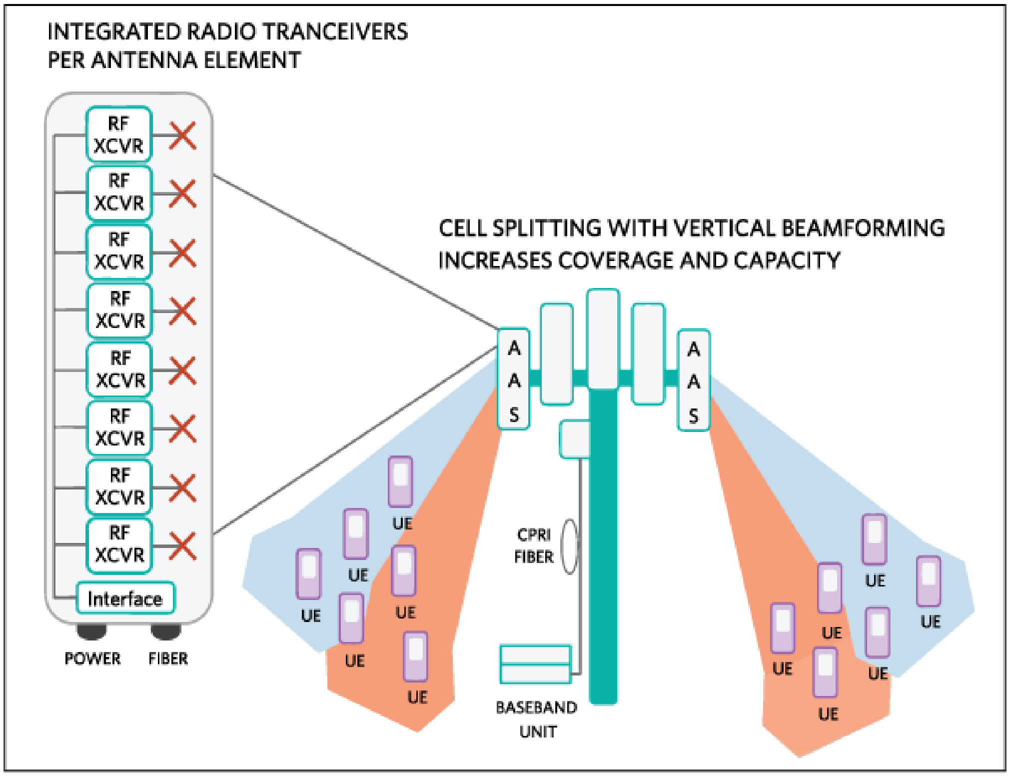


Figure 8. The structure of an active antenna system (AAS) with embedded RF (left), and AAS beamforming capabilities in a macro cell base station (right).

Figure 9 shows examples of the AAS applications that wireless service providers can leverage in macro cell base stations. With beamforming and beam steering, AAS macro cells can better utilize radio resources, adapt to changing traffic patterns, and improve the mobile users' experience. For example, independent TX-RX electronic tilt of the RX and TX beams can be used to optimize individual UL and DL paths; thus, extend mobile device battery life when the RX-TX link budgets differ. When the UL path is optimized, the mobile device transmitter's power amplifier can be set at the best possible operating power level without wasting battery energy.

AAS can bring many benefits to the LTE ecosystem. However, the RF properties of AAS base stations differ from conventional antenna systems and this must be studied in detail.

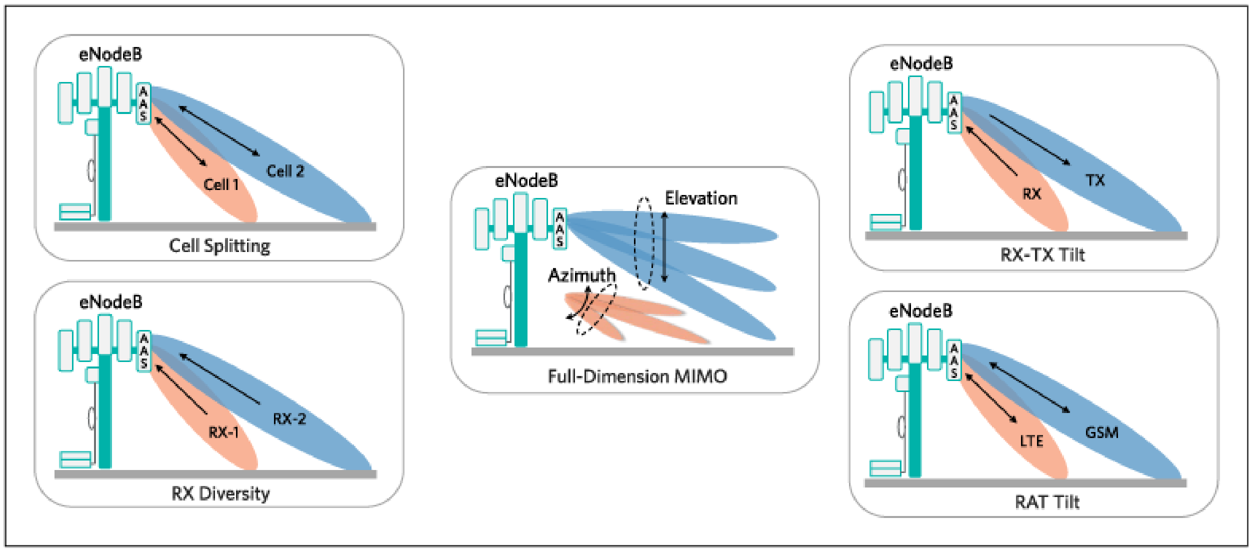


Figure 9. Several AAS beamforming and beam steering applications are possible for macro cell sites.

In Rel-12 a working group is studying AAS. A main objective of the 3GPP active antenna work item is to identify the RF requirements and conformance testing for AAS base stations. Some of the topics include adjacent-channel leakage ratio (ACLR), in-band/out-band emissions, receiver sensitivity, receiver blocker performance, and 3D channel modeling.[15] The widely recognized benefits of AAS are the primary reasons behind the 3GPP study: capacity gains by employing flexible cell splits with beam shaping and steering; elimination of cable attenuation and power losses; fewer components mounted on the tower top; and better network availability with transceiver redundancy. The advent of AAS Generation IV base stations promises higher levels of performance for macro cells and effective delivery of new 4G services like Voice-over-LTE and LTE-Broadcast.

Spatial Multiplexing with Downlink MIMO

Transporting gigabit-per-second downlink peak data rates in a 100MHz carrier aggregation band-limited system requires spectral efficiency techniques beyond high-order modulation. As wireless communication links approach the limits of Shannon's capacity theorem, the spatial dimension must be exploited and, hence, spatial multiplexing with multiple antenna configurations must be adopted. LTE Rel-8 saw the inclusion of 2X2 and 4X4 MIMO with 4-layer transmission. Rel-10 extended this to 8X8 downlink MIMO, also called transmission mode 9 (TM9). Rel-12 explores ways to optimize 8X8 DL MIMO and includes an investigation of full-dimension MIMO (FD-MIMO), complimented by AAS.

Adopting spatial multiplexing with 8X8 downlink MIMO can deliver an 8x increase in throughput without using more spectrum bandwidth. In situations where communication link reliability is important or poor signal conditions exist, then downlink spatial diversity (transmit diversity) might be employed to obtain diversity gain and improve signal-to-interference-plus-noise-ratio (SINR). Important network performance gains can be realized with MIMO spatial multiplexing or MIMO spatial diversity. However, these advanced techniques require multiple antennas at both the eNodeB and the mobile user equipment (UE). Deploying 8x8 MIMO requires eight antennas at the eNodeB and UE, as shown in **Figure 10**. Because antenna spatial separation is needed, it will be difficult to integrate eight antennas in a small-form-factor mobile device like a smartphone. However, 4X4 MIMO is practical with new advancements in antenna development like that seen by SkyCross[16] where 580Mbps peak data rates have been demonstrated. Larger-form-factor devices like data-hungry tablets and notebook PCs will have an easier time integrating eight antennas. And because it is more practical and enjoyable to view high-definition (HD) video content on large-screen devices, tablets and mobile PCs can take full advantage of mobile HD video with high-throughput 8X8 MIMO. Moreover, since mobile video is a leading driver of growth in data traffic and considered a value-added feature for wireless service providers, there is an important trend in the macro cell eNodeB to support multiple antennas with four- and eight-layer transmission.

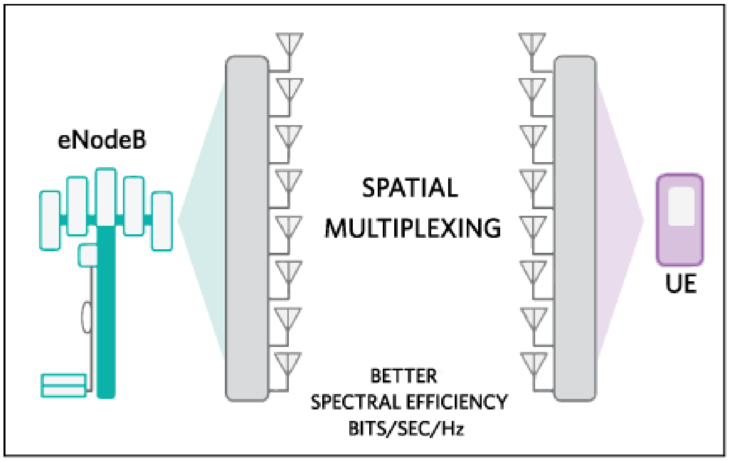


Figure 10. Spatial multiplexing with 8X8 MIMO requires eight antennas at both the eNodeB and the mobile user device.

Much of the foundation for downlink MIMO was completed in Rel-8 thru Rel-11 sessions. This included the development of transmission modes 1 thru 9, code book structure, channel state information (CSI) feedback, demodulation reference signal (DM RS), downlink control information (DCI) format, and dynamic switching between SU-MIMO and MU-MIMO. To improve spectral efficiency Rel-12 focuses on two CSI enhancements: (1) 4TX Precoding Matrix Index feedback, and (2) aperiodic feedback Physical Uplink Shared-Channel mode3-2. Rel-12 also begins initial studies of FD-MIMO.

FD-MIMO unites AAS, 3D beamforming, and spatial multiplexing to deliver efficient spectrum utilization while increasing network capacity. The possibilities of FD-MIMO are shown in **Figure 11**, where antenna beams can be precisely and independently focused on many mobile users at different azimuth and elevation planes. In Rel-10 and Rel-11 the MIMO features specifically addressed eNodeB antenna directivity in the azimuth. Rel-12 explores ways to fully utilize the spatial domain.

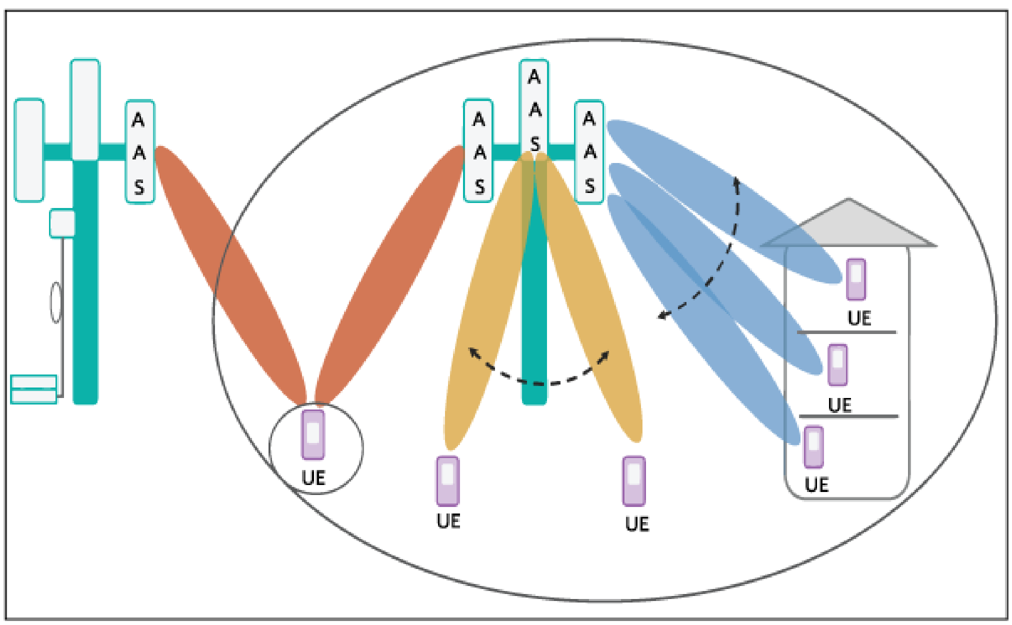


Figure 11. Applications of full-dimension MIMO (FD-MIMO) with 3D beamforming.

To realize the FD-MIMO vision, further work is needed in 3D channel modeling, codebook design, feedback enhancements, and definitions for AAS radio requirements. Nevertheless, the first step, integrating multiple wideband radio transmitter channels into a space-constrained antenna system, can be addressed with an innovative bits-to-RF solution. Part 2 of this application note reveals how direct-conversion RF-DAC technology can be embedded in AAS to reduce transmitter operating power, minimize heat dissipation, and shrink circuit board area.

Conclusion

This application note, Part 1 of this two-part series, explored the market forces that are driving global adoption of LTE-Advanced and discussed the evolution of 4G cellular base-station equipment. The application note reviewed 3GPP Rel-12 work items and relevant technology trends in eNodeB downlink transmitter applications. It explained how Rel-12 enhancements in wideband carrier aggregation, multilayer spatial multiplexing, and AAS offer many benefits to 4G networks, namely, improvements in coverage, capacity, network utilization, and peak data rates. However, the Rel-12 features introduce new analog integration challenges when designing macro cell eNodeB transmitters. To be exact, designers will need to increase transmitter channel density and deliver ultra-wideband performance with full carrier frequency agility, bound by the constraints of small size, less power, and lower system cost.

Part 2 of this application note series introduces a disruptive radio solution that can help engineers shape new RF transmitter architectures and overcome Rel-12 analog integration challenges. Part 2 focuses on novel RF DAC technology that yields a single-chip radio transmitter solution. Readers will learn how RF DAC technology offers radio engineers a way to shrink size by 60%, reduce component count by 75%, and lower operating power by 1000mW per channel.

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Glossary of Technical Terms

2G, 3G, 4G	Generations
3GPP	3rd Generation Partnership Project
4G-LTE	4th Generation Long Term Evolution
AAS	Active Antenna System
ACLR	Adjacent-Channel Leakage Ratio
ARPC	Average Revenue Per Connection
ARPU	Average Revenue Per User
BTS	Base Transceiver Station
CA	Carrier Aggregation
CAGR	Compounded Annual Growth Rate
CAPEX	Capital Expenditure
CC	Component Carrier
CSI	Channel State Information
DCI	Downlink Control Information
DL	Downlink
DL-CA	Downlink Carrier Aggregation
DM RS	Demodulation Reference Signal
eNodeB	Evolved Node B
FD-MIMO	Full-Dimension MIMO
IAR	Integrated Antenna Radio
IMT-Advanced	International Mobile Telecommunications-Advanced
ITU-R	International Telecommunication Union Radio Sector
LTE	Long Term Evolution
LTE-A	LTE-Advanced
MIMO	Multiple Input/Multiple Out
RF	Radio Frequency
Rel-12	Release 12
ROI	Return On Investment

RRU	Remote Radio Unit
TCO	Total Cost of Ownership
TM9	Transmission Mode 9
UE	User Equipment such as smartphones
UL	Uplink

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Related Parts	
MAX5868	16-Bit, 5Gsps Interpolating and Modulating RF DAC

More Information
For Technical Support: https://www.maximintegrated.com/en/support
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Application Note 6062: https://www.maximintegrated.com/en/an6062
APPLICATION NOTE 6062, AN6062, AN 6062, APP6062, Appnote6062, Appnote 6062