WIRELESS WORLD RESEARCH FORUM

5G Network Capacity

Key Elements and Technologies

Qian (Clara) Li, Huaning Niu, Apostolos (Tolis) Papathanassiou, and Geng Wu

Digital Object Identifier 10.1109/MVT.2013.2295070
Date of publication: 31 January 2014

It has been projected that, in the next decade, a mobile traffic increase on the order of 1,000 times is expected compared to what we experience today. To meet that dramatic traffic growth, next-generation mobile networks are also expected to achieve a 1,000-fold capacity increase compared to the current generation of wireless network deployments. In this article, we discuss how such capacity growth could be achieved in a ten-year time frame. We discuss the techniques that we expect to have the highest opportunity for increasing the system capacity and estimate their gains based on analysis and simulation. We observe that the main driver of capacity growth is expected to come from network architecture advancements, with heterogeneous networks and convergence of information and communication technology being two of the key techniques. We also estimate that the air-interface evolution would focus not only on improving the link and system spectrum efficiency but also on facilitating the required network efficiency improvements. This article provides insights into the communication technology evolution and

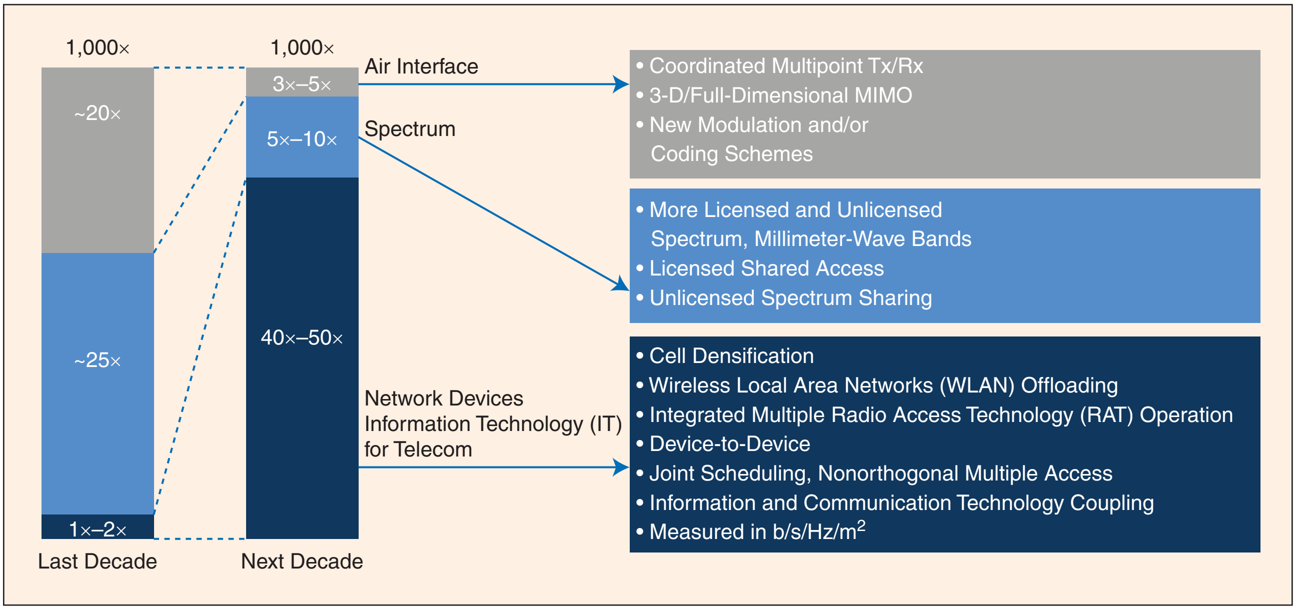

FIGURE 1 The trends of network capacity growth.

can be used as a guideline for technology development toward the fifth generation (5G).

The development of wireless communications benefits society—from science and technology to community and people's well-being. The progress and the demands in society in turn propel the innovation and the development of wireless communications systems. From 2000 to 2010, we witnessed a 1,000-fold capacity increase of wireless communications systems, with the main drivers being air-interface spectrum efficiency improvement and new spectrum acquisition. Such a capacity increase has fostered the rapid growth of the mobile Internet accompanied by various new applications and services. Looking into the next ten years of wireless communications evolution, it is expected that the continuing growth of mobile Internet applications and services will trigger another 1,000-fold mobile traffic increase [1], [2], which should be met by further increasing the capacity of wireless communications systems by 1,000 times. Considering that the capacity of currently deployed systems such as long-term evolution (LTE) Release 8/9 is already quite high, a further capacity growth of 1,000 times seems to be a very challenging task at first glance. This article gives an insight into how a 1,000-fold capacity increase could be achieved in the next decade by discussing the potential techniques and estimating their potential gains.

Figure 1 summarizes the key ingredients contributing to the capacity of wireless communications systems in the last decade and next decade. As observed for the past ten years, air-interface improvements and new spectrum acquisition have contributed to roughly 20 times and 25 times capacity increase, respectively. Technologies such as orthogonal frequency-division multiplexing (OFDM) and multiple-input-multiple-output (MIMO) have significantly improved the air-interface spectrum efficiency. Looking into the next decade, we should first observe that the air-interface spectrum efficiency has been approaching its capacity limit, and it is likely that there will be less possibility for new spectrum acquisition—we should not forget that the total licensed spectrum in use today is approximately 1 GHz. Therefore, we expect that higher capacity gains would come from the network side. Network architecture improvements as well as information and communication technology convergence accompanied by the corresponding upgrades in devices are expected to be the key drivers for the wireless communications system capacity increase in the next decade.

In this article, we present a breakdown study of the expected 1,000-fold capacity increase for wireless communications systems in the next decade. To reflect the gains from the network side, we use the network efficiency in b/s/Hz/m^2 to measure the average spectrum efficiency per unit network area. Furthermore, we elaborate on each category shown in Figure 1 by discussing specific techniques and estimating the associated gains.

The radio spectrum used for wireless communications determines the channel characteristics, which, in turn, affect the air-interface design and the network architecture. Current cellular networks mainly operate in frequency bands below 3 GHz because of the favorable channel propagation characteristics for cellular communications in those bands. As most of the frequency bands below 3 GHz are occupied, the attention on acquiring new spectrum for wireless communications systems of the next decade has shifted to frequency bands above 3 GHz and up to the millimeter-wave (mmWave) bands. In Table 1, we summarize the frequency bands expected to be assigned for wireless communications systems. For frequency bands below 6 GHz, a maximum of 2.5 GHz of

Table 1 *Gains estimated from allocating more spectra to wireless communications systems.*

Frequency	Bandwidth	Notes
Below 6 GHz	0.6–2.5 GHz	Mainly at 3.5 GHz
28 GHz	1 GHz	
39 GHz	1.5 GHz	
45 GHz	9 GHz	Both licensed and unlicensed; under planning in China
60 GHz	Up to ~7 GHz	
Total new spectrum	3–10 GHz	Considers the regional availability of new spectrum
LSA	95–150 MHz	Broadcast sharing, MNO sharing, license-exempt new bands in digital dividend, license-exempt new bands in upper UHF, military, and other public services
Existing IMT spectrum	1,177 MHz	
Gain from spectrum	3×–10×	Spectrum availability depends on regions

licensed spectrum could be potentially allocated with the largest portion being at 3.5 GHz. Moving to even higher frequency bands, one could expect allocation of 1 GHz of spectrum at 28 GHz, 1.5 GHz of spectrum at 39 GHz, and up to 7 GHz of spectrum at 60 GHz. China is currently considering allocating frequency bands at 45 GHz for both licensed and unlicensed wireless communications systems. As spectrum allocation is governed by regional regulatory bodies and policies, the potential new licensed spectrum in each region is estimated to lie in the range of 3–10 GHz. Another 95–150 GHz of spectrum could be obtained by licensed spectrum sharing (LSA), which allows wireless communications systems to use spectrum of incumbent systems without harming the incumbent system operation. Considering that, currently, 1,177 MHz of international mobile telecommunications (IMT) spectrum is in use, we can expect a 3–10 times increase in allocated spectrum over the next ten years or so.

As we can observe from Table 1, new spectrum is mostly expected to be allocated in the superhigh-frequency bands (3–30 GHz) as well as the extremely high-frequency bands (30–300 GHz), also referred to as mmWave bands, where the channel propagation characteristics are different from those of frequency bands below 3 GHz. This difference will require a new design of the air-interface and network architecture. For example, in the mmWave bands, although a shorter transmission time interval can be used because of lower frequency selectivity, cell coverage would be limited because of higher path loss, which would inevitably lead to the use of small cell sizes. In turn, small cell sizes would cause issues for mobility management and control signaling overhead. New network architectures, such as the so-called anchor-booster-based architecture, can be used to anchor all control-plane (C-plane) signaling at the wide-coverage anchor cell (typically operating at lower carrier frequencies where spectrum is limited) and offload the data-plane (U-plane) traffic to the limited-coverage booster cells (typically operating at higher carrier frequencies where more spectrum is available). Anchor-booster architecture with C-/U-plane separation can be used as a general framework for heterogeneous networks. More details on its operation can be found in [3] and [4].

Air Interface

Because of the air-interface design advances in the last decade or so, a significant improvement of the link-level spectrum efficiency has been achieved with fundamental techniques such as Turbo codes, low-density parity check codes, OFDM, and MIMO. Looking into 5G, while link-level techniques continue to evolve, we expect that air-interface design advances will be more intertwined with system-level network architecture design advances, i.e., the air-interface design needs to facilitate cooperation among the different network nodes to enable better interference management and exploit opportunistic

Table 2 *Uplink CoMP gains by joint reception (JR).*

Scenario	Cell Area Average (Mb/s)	Gain over Non-CoMP (%)	Cell-Edge User (Kb/s)	Gain over Non-CoMP (%)
Non-CoMP (CRE = 6 dB)	62.65	0	776	0
CoMP, 1 cell	79.88	28	1,153	49
CoMP, 3 cells	81.84	31	1,224	58
CoMP, 9 cells	83.33	33	1,266	63
CoMP, 21 cells	86.66	38	1,637	111
CoMP, 27 cells	88.18	41	1,950	151

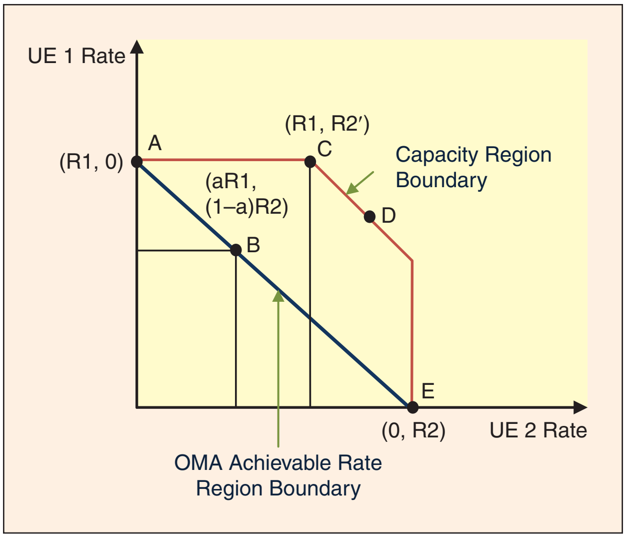

FIGURE 2 The rate regions of the two-user multiple access channel with orthogonal and NOMA schemes are plotted.

gains enabled by varying network deployments and architectures. In this regard, we expect further improvements of the air-interface efficiency from techniques such as coordinated multipoint (CoMP) joint transmission and reception, network-assisted interference cancellation and suppression (NAICS), nonorthogonal multiple access (NOMA), and three-dimensional (3-D) or full-dimensional (FD) MIMO.

The gains by cooperative communications have been demonstrated on many occasions under various channel environments and cooperation schemes [5]–[8]. LTE-Advanced systems adopted CoMP as a key performance enhancement feature. Table 2 provides our simulation results on the CoMP gains in the uplink by using joint reception (JR). We can see that the average cell throughput gain achieved by JR CoMP over non-CoMP could be up to 41% for 27-cell cooperation. For cell-edge users, the CoMP gain can be even higher and can reach 151% for 27-cell cooperation. It is noted that the CoMP gains depend on factors such as the coordination scheme, traffic type, cell distribution, and backhaul type. The CoMP schemes evaluated in LTE-Advanced Release 11 systems assume ideal backhaul links connecting the cooperating nodes with zero latency and unlimited bandwidth. However, in practice, as an operator may have backhaul links running on different media (e.g., copper, fiber, and microwave) and using different techniques (e.g., E1/T1, carrier Ethernet, and digital subscriber line) the ideal backhaul assumption may not hold in many occasions. Therefore, CoMP schemes, which can operate under various backhaul types, will need further research and development efforts.

The current wireless communications systems apply orthogonal multiple access (OMA) schemes with users being allocated distinct resources in time, frequency, or space. OMA schemes eliminate mutual interference among the allocated users and allow relatively simple transceiver implementations. However, low-complexity implementation comes at the cost of efficiency. Let us consider a simple example of a two-user multiple access channel and draw its theoretical capacity region and the rate region achieved by OMA (see Figure 2). By allowing the two users to transmit simultaneously over the same frequency band and time period by NOMA, e.g., by applying successive user data decoding at the receiver side, we can potentially reach the channel capacity boundary shown in Figure 2. In comparison, with the case of OMA, the best achievable user data rates lie along the line connecting points A and E, with each point on the line corresponding to one of the resource sharing options between the two users. Built on the idea of NOMA, opportunistic NOMA can be applied to enhance the overall spectrum efficiency. For example, let us consider a scenario where user equipment (UE) 1 and UE 2 are connected with an evolved Node-B

TABLE 3 *The gains expected from air-interface improvements.*

Technology	*Gain*	*Notes*
CoMP, NAICS, and NOMA	1.5×–2×	■ CoMP gains depend on the used coordination algorithm, cell distribution, traffic type, network loading, backhaul bandwidth, duplexing scheme, etc. ■ NAICS gains depend on the specific interference cancellation/suppression algorithm, number of Tx/Rx antennas, type of network assistance, etc. ■ NOMA is assumed to be applied with superposition coding and successive decoding for interference cancellation
3-D/FD MIMO	>2×	■ The vertical spatial domain adds one more freedom for coordination and opportunistic transmission; higher total number of antennas, e.g., 32 or 64, enable better MU-MIMO operation ■ Gains depend on the specific algorithm, number of antennas, duplexing scheme, etc.
New modulation and/or coding schemes	1.5×	■ New modulation schemes targeting at reducing the physical (PHY) overhead, e.g., filter-band multicarrier (FBMC) ■ New modulation and coding schemes (MCSs) to increase the spectrum efficiency especially in small-cell deployment scenarios having more favorable signal-to-noise ratio (SINR) conditions than typical macrocell deployments
Total gain range	4.5–6×	

TABLE 4 *The estimated network efficiency gains from network architecture improvements.*

Technology	Gain	Notes
Cell densification with optimal power control	K	Linear increase with respect to the number of cells K
Device-to-device (D2D)	$\frac{n+1}{n} \sim n$	■ Gain depends on deployment scenario, which affects the number of n (D2D pairs per macro/pico node) ■ High efficiency Wi-Fi target: At least 2× (D2D versus DL+UL) ■ In wireless display case (5-m device separation), multiple low power streams can be allowed (up to 10× improvement)
Resource scheduling and power control	1.5×–2×	■ Joint scheduling across multiple cells, advanced power control, interference mitigation, opportunistic Tx, etc. (mmWave backhaul could be an enabler for joint scheduling across small cells)
WLAN offloading (loosely coupled WLAN/LTE)	5×	Efficient use of 80- and 160-MHz channelization in IEEE 802.11ac
WLAN/LTE joint scheduling (tightly coupled WLAN/LTE)	1.5×–2×	■ Dynamic traffic steering between LTE and WLAN/second-generation (2G)/third-generation (3G) radio access technologies ■ Gains depend on technology, amount of spectrum, joint scheduling algorithm, etc.
Information and communication technology (ICT) coupling (Edge computing, etc.)	>2×	For example, transmission control protocol (TCP) packet compression (46% of packets are TCP/Internet protocol control packets with zero payload)
Total gain range	90× – 160×	Assumptions: 2× small-cell density compared to baseline (four small cells per macrocell area), n = 2 (average value of D2D pairs per macro cell), at least a few tens of clients active per macrocell, medium-to-high network loading

(eNB), while UE 1 is located closer to the eNB and UE 2 is located further away. The two UEs can transmit simultaneously in the same time period and frequency band by applying the NOMA principle, with the eNB first decoding the data transmitted by UE 1 by treating UE 2 transmission as interference, then subtracting the signal received by UE 1 from the total received signal, and finally decoding the data transmitted by UE 2. It is expected that the data rate of UE 1 would be lower in the case of NOMA compared to OMA transmission. However, as UE 1 is located close to the eNB, the impact from UE 2 interference would not lead to a significant drop of the UE 1 data rate. By canceling interference from UE 1, the decoding of UE 2 becomes interference-free, which allows UE 2 to transmit at the same rate as in the case of OMA transmission. The simulation results in [9] indicate that the application of NOMA in the downlink can achieve a 30% gain in the system spectrum efficiency. Because of the duality between the multiple access channel and the broadcast channel [10], we can expect a similar gain by NOMA in the uplink.

Other improvements regarding the air interference are expected to come from 3-D/FD MIMO and improved coding and modulation schemes. 3-D MIMO exploits the vertical spatial domain (elevation) for transmission and user scheduling, and thus, it enables the use of more degrees of freedom. Our initial simulation results show that the gain of 3-D MIMO can be at least twofold for cell-edge UEs when relatively straightforward 3-D/FD MIMO techniques are used. Additional gains are possible with more advanced 3-D/FD MIMO algorithms. Furthermore, modulation schemes such as FBMC can be applied with the advantage of reducing spectrum-side lobes, thus enabling asynchronous multiple access and reducing intercarrier interference. Table 3 summarizes our projected spectrum efficiency gains from air-interface improvements. The overall gains can lie between 4.5 and 6 times compared to the currently deployed LTE Rel 8/9 systems.

Network Architecture

As we mentioned earlier (see also Figure 1), a significant improvement in network capacity is expected to come from the deployment of heterogeneous networks and the coupling between ICT. Heterogeneous networks (HetNet) refer to network deployments with different types of network nodes, which are equipped with different transmission powers and data processing capabilities, support different radio access technologies (RATs), and are supported by different types of backhaul links. Some typical HetNet deployments include LTE-based networks with high-transmit power macro eNBs and low-transmit power pico eNBs, which may also include multi-RAT interworking and joint scheduling. To analyze the gains offered by HetNet, we categorize the techniques involved in HetNet into cell densification; D2D communications; joint radio resource and power scheduling across macro-, pico-, and D2D communications; and multi-RAT joint operation. We estimate/analyze the network efficiency gains by each technique. A summary of the considered techniques and their gains can be found in Table 4.

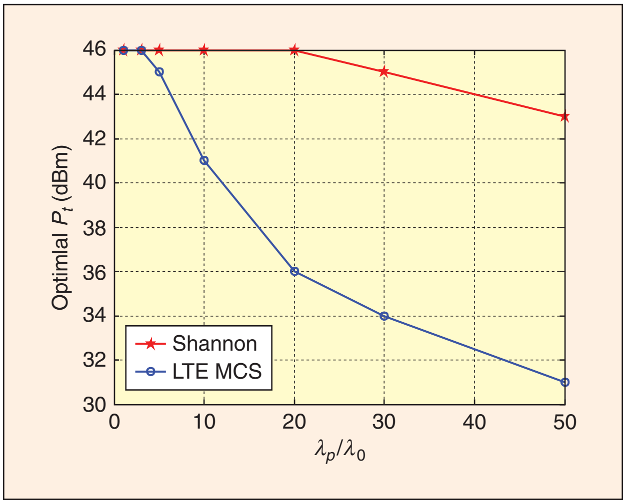

FIGURE 3 The optimal BS transmit power is plotted versus different cell density values.

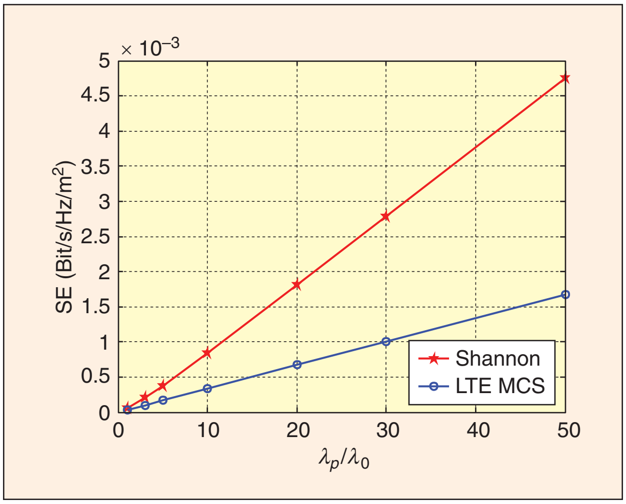

FIGURE 4 The network efficiency is plotted versus different cell density values.

The deployment of small cells with low transmission power and limited coverage increases cell density and enables high spatial and frequency reuse. The gain by cell densification can be estimated using tools from stochastic geometry. We model the base station (BS) distribution as a Poisson point process and derive the network efficiency expression, which is shown to be a function of the cell density, BS transmission power, and bandwidth allocation across the served UEs. For each cell density value and a specific resource allocation policy (e.g., considering fairness), there is an optimal transmit power value in the sense that it maximizes the network efficiency. Figures 3 and 4 plot the optimal BS transmission powers and the corresponding network efficiency versus different cell density values, respectively. The cell density value is defined as the number of small cells per macrocell area by assuming a hexagonal macrocell deployment with intersite distance equal to 500 m. It can be seen that as cell density increases, the optimal BS transmission power decreases and the achieved network efficiency increases linearly. The trends hold when the link rates are calculated using either the Shannon formula or the LTE MCSs. Despite the same trend, the network efficiency calculated using the Shannon formula is significantly higher than the one obtained using the LTE MCSs: Since the LTE MCSs only allow for a maximum modulation order of 64 quadrature amplitude modulation (QAM), the frequently encountered excellent channel quality due to the small cell density cannot be fully used when the LTE MCSs are used.

Proximity-based D2D communication is effective for traffic offloading and improving the spatial and frequency reuse. The idea is to let devices in close proximity directly communicate with each other without going through the network infrastructure. By doing so, D2D communication can potentially reuse the same frequency resources as that of the traditional infrastructure-based communication and, thus, improve the overall network efficiency. The gain by D2D communication depends on the application scenario, which determines the number of device pairs in close proximity. In scenarios such as shopping malls, railway stations, or stadiums, we expect to see a high probability of two communicating devices being in close proximity. In scenarios where the users are randomly distributed with no implicit correlations, the probability of two peers being in close proximity is relatively low. For a network with a pair of devices, the D2D gain falls into the range $((n+1)/(n), n)$. The lower bound is calculated for the case of random device distribution where the probability of two peers in close proximity is $1/n$. The upper bound corresponds to the case where all communicating peers are in close proximity. In this case, n pairs can communicate in parallel achieving full frequency reuse. Despite its dependence on the deployment scenario, D2D communication is very effective for traffic offloading and for improving spectrum reuse in densely populated deployment scenarios, which are also the most challenging communication scenarios due to the spectrum constraints they impose.

***TABLE 5** The D2D average spectrum efficiency in b/s/Hz/cell using centralized D2D pair scheduling versus the number of D2D pairs per cell.*

	One D2D Pair per Cell	*Two D2D Pairs per Cell*	*Five D2D Pairs per Cell*	*Ten D2D Pairs per Cell*	*20 D2D Pairs per Cell*
Centralized scheduling	3.2	6.45	13.8	22.1	29.8

In calculating the gains by cell densification, the impact of joint scheduling among the involved network nodes was not considered, while universal frequency reuse was assumed for simplifying our analysis. By applying joint resource scheduling and power control, we estimate an additional 1.5–2 times gain according to various available research results [11]–[13]. In the case of cochannel macro- and picocell deployment, joint resource scheduling would be beneficial in coordinating the resource usage across macro- and picocells. In the case of D2D, joint scheduling and power control can effectively avoid excessive mutual interference, ensure efficient spectrum reuse, and add power gains on top of the multiplexing gain discussed earlier. Our D2D simulation results in Table 5 show the significantly high spectrum efficiency numbers achievable with joint scheduling, even for high numbers of simultaneously active D2D pairs per macrocell area.

Current wireless communications systems are deployed using multiple RATs both in licensed and unlicensed bands, such as the Global System for Mobile Communications (GSM), high-speed packet access (HSPA), LTE, and WLANs. The operation of different RATs is independently defined by the respective specifications. However, independent RAT operation leads to suboptimal usage of the wireless resources. Multi-RAT joint radio operation is therefore needed to improve the system resource usage. For example, as GSM usage is declining, a joint radio operation would allow the GSM spectrum to be reused by LTE in high-capacity-demanding deployments with minimum impact on the GSM system. WLAN/LTE joint operation could also effectively offload traffic to unlicensed bands and reduce the traffic served by LTE. In this article, we take WLAN/LTE interworking as an example to estimate the gains by multi-RAT joint operation. We can expect higher gains by including joint operation of multiple RATs. WLAN/LTE interworking can be loosely coupled or tightly coupled. In the loosely coupled approach, whenever there is WLAN coverage, the traffic would be switched to WLAN. Assuming a 20-MHz LTE system and considering the 160-MHz channelization of IEEE 802.11 ac, the offloading gain can be as high as five times, thanks to the full utilization of the available unlicensed spectrum. On top of the loosely coupled offloading approach, further gains can be achieved by tightly coupled joint scheduling between LTE and WLAN. As the network efficiency of WLAN systems degrades with increasing number of devices, while the network efficiency of LTE improves with increasing number of devices, joint scheduling can balance the traffic load factors between WLAN and LTE according to the network load.

Table 6 presents our system-level simulation results achieved by loosely coupled WLAN offloading and tightly coupled joint scheduling. A bandwidth of 20 MHz is assumed for both the LTE and WLAN systems. The IEEE 802.11 g WLAN system at 2.4 GHz is assumed in the simulation. The results indicate that an average of 2 times gain can be achieved by joint scheduling.

THE DEPLOYMENT OF SMALL CELLS WITH LOW TRANSMISSION POWER AND LIMITED COVERAGE INCREASES CELL DENSITY AND ENABLES HIGH SPATIAL AND FREQUENCY REUSE.

Table 7 shows the traffic load distribution corresponding to the scenario of Table 6. In the loosely coupled WLAN offloading case, we can observe that 94% of the traffic has been offloaded to WLAN. In joint scheduling, which targets at maximizing the sum throughput, we can observe that the traffic is quite evenly distributed across the different network entities, which leads to the joint scheduling throughput advantage shown in Table 6. More details on the traffic steering scheme and the simulation setup can be found in [14].

In parallel with the network architecture evolution, we expect to see an increasingly tight coupling between ICT. For example, as approximately 45% of the TCP packets are control packets with zero payload, we can compress TCP packets transmitted over the air between devices and BSs so that spectrum usage can be reduced by about half. Another example is to cache information content at the network edge, i.e., serving gateways, macro-BSs, pico-BSs, for fast retrieval and access by the end user. The cached content can be selected based on its popularity and can be dynamically updated based on the statistics from past events. Edge-caching could alleviate the backhaul and backbone burden, reduce communication latency, and improve user experience. Research on ICT convergence is still in its infancy. Higher gains can be expected with well-developed schemes.

Conclusion

In this article, we present a breakdown of how a 1,000-times capacity increase can be achieved for wireless communications networks in the next decade. We estimate that the capacity gains from acquiring new spectrum and improving the air-interface are relatively limited and lie within the

***TABLE 6** The gains by tightly coupled joint scheduling.*

Rate (Mb/s)	*Loosely Coupled*	*Tightly Coupled*
5% users	0.76	1.89 (+147%)
50% users	3.06	6.92 (+126%)
Average rate	3.5	7.35 (+110%)

***TABLE 7** The traffic load distribution.*

Proportion (%)	*Loosely Coupled*	*Tightly Coupled*
LTE macro	0.06	0.24
LTE small cell	0	0.37
WLAN	0.94	0.39

range of 3–10 times and 4.5–6 times, respectively. The main driver for achieving the required capacity increase is expected to come from the network side, and we estimate gains within the 90–160-times range. The key enabling technique is heterogeneous networks, which include cell densification, D2D communication, and multi-RAT operation. Joint ICT operation would also bring additional capacity benefits as the wireless network architecture evolves. The capacity gain range estimated for each of the techniques is either based on simulation results or analytical derivation. In practical system deployments, some performance loss is expected because of issues pertaining to practical deployment. Despite that, we believe that the analysis and results in this article provide reasonable insights on how to achieve the 1,000-times capacity gain in the next decade and can be used as a guideline in prioritizing new technology development efforts.

Acknowledgment

We would like to thank Dr. Reza Arefi of Intel for his guidance regarding the projection of the allocated spectrum, Dr. Shu-ping Yeh and Dr. Nageen Himayat of Intel for providing the simulation results in the case of WLAN/LTE joint scheduling, and Dr. Guangjie Li of Intel for providing the TCP packet compression results.

Author Information

Qian (Clara) Li (liqian@ieee.org) received her B.E. and M.S. degrees in information engineering from Nanjing University of Posts and Telecommunications, Nanjing, China, in 2003 and 2006, respectively, and her Ph.D. degree in communication engineering from Nanyang Technological University, Singapore, in 2011. She is currently a senior research scientist with the Standards and Advanced Technology Division of Intel's Mobile and Communications Group. She has served as a reviewer for several international journals and conferences. She has also served as symposium cochair of IEEE GreenCom 2013; IEEE ICNC 2014; and technical program committee member of IEEE ICC 2009, 2012, 2013, and 2014; and IEEE GLOBECOM 2012, 2013, and 2014. Her research interests include information theory, communication theory, cross-layer optimization, and RAN evolution.

Huaning Niu (Huaning.niu@intel.com) received her B.E. degree from the University of Science and Technology of China in 1997, her M.S. degree from the Chinese Academy of Science in 2000, and her Ph.D. degree from the University of Washington, Seattle, in 2004, all in electrical engineering. She is currently a senior staff engineer in the Standards and Advanced Technology Division of Intel's Mobile and Communications Group. Her research interests include LTE air interface, heterogeneous networks, and RAN architecture evolution. Before joining Intel, she worked on Wi-Fi and 60-GHz technology at Samsung Research America.

Apostolos (Tolis) Papathanassiou (apostolos.papathanassiou@intel.com) is senior principal engineer in the Standards and Advanced Technology Division of Intel's Mobile and Communications Group. His main focus is on LTE PHY standardization. He has more than 50 scientific contributions to international journals, conferences, and books since 1994, and more than 100 contributions to wireless standardization bodies such as 3GPP, IEEE 802.11, IEEE 802.16, and the WiMAX Forum since 1999. Prior to his current role at Intel, he led multiple standardization efforts in ITU-R and IEEE/WiMAX Forum. Before joining Intel, he worked on multiple-antenna PHY technologies for 3G, satellite, and Wi-Fi systems.

Geng Wu (geng.wu@intel.com) is the chief scientist of MCG Standards and Advanced Technology at Intel and the head of Intel 3GPP delegation. He has more than 20 years of research and development experience in the wireless industry and contributed extensively to 2G, 3G, and fourth-generation air-interface technologies and network architecture development. His research interests include mobile computing and communication platform, heterogeneous networks, cloud-RAN, next-generation air-interface technologies, and advanced mobile services and applications. Prior to Intel, he was the director of Wireless Architecture and Standards at Nortel Networks.

References

[1] Qualcomm. (2012, Aug.). The 1000x mobile data challenge, Webinar. [Online]. Available: http://www.qualcomm.com/solutions/wireless-networks/technologies/1000x-data

[2] Cisco. (2012). Cisco visual network index: Global mobile traffic forecast update. [Online]. Available: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html

[3] H, Ishii, Y. Kishiyama, and H. Takahashi, "A novel architecture for LTE-B," in *Proc. IEEE Globe Communications Conference (GLOBECOM) 2012*, Dec. 2012, pp. 1–5.

[4] Q. Li, H. Niu, G. Wu, and R. Q. Hu, "Anchor-booster based heterogeneous networks with mmWave capable booster cell," in *Proc. IEEE Globe Communications Conference (GLOBECOM) 2013*, Atlanta, Georgia, Dec. 2013, pp. 1–5.

[5] E. C. van der Meulen, "Three-terminal communication channels," *Adv. Appl. Probab.*, vol. 3, no. 1, pp. 120–154, spring 1971.

[6] T. M. Cover and A. A. El Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inform. Theory*, vol. 25, pp. 572–584, Sept. 1979.

[7] A. B. Carleial, "Multiple-access channels with different generalized feedback signals," *IEEE Trans. Inform. Theory*, vol. 28, pp. 841–850, Nov. 1982.

[8] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity—Part I: System description," *IEEE Trans. Commun.*, vol. 51, pp. 1927–1938, Nov. 2003.

[9] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)," in *Proc. IEEE Annual Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC) 2013*, London, Sept. 2013, pp. 1–5.

[10] N. Jindal, S. Vishwanath, and A. Goldsmith, "On the duality of Gaussian multiple-access and broadcast channels," *IEEE Trans. Inform. Theory*, vol. 50, no. 5, pp. 768–783, May 2004.

[11] M. Ismail, A. Abdrabou, and W. Zhuang, "Cooperative decentralized resource allocation in heterogeneous wireless access medium," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 714–724, Dec. 2012.

[12] Q. Li, R. Q. Hu, Y. Qian, and G. Wu, "A proportional fair radio resource allocation for heterogeneous cellular networks with relays," in *Proc. IEEE Globe Communications Conference (GLOBECOM) 2012*, Dec. 2012, pp. 1–5.

[13] Q. Li, Y. Xu, R. Q. Hu, and Y. Qian, "Optimal fractional frequency reuse and power control in the heterogeneous wireless networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2658–2668, May 2013.

[14] R2-133479, Intel, 3GPP RAN2 Meeting 83bis, Ljubljana, Slovenia, Oct. 7–11, 2013.

VT