Network Densification: The Dominant Theme for Wireless Evolution into 5G

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Abstract

This article explores network densification as the key mechanism for wireless evolution over the next decade. Network densification includes densification over space (e.g, dense deployment of small cells) and frequency (utilizing larger portions of radio spectrum in diverse bands). Large-scale cost-effective spatial densification is facilitated by self-organizing networks and inter-cell interference management. Full benefits of network densification can be realized only if it is complemented by backhaul densification, and advanced receivers capable of interference cancellation.

Introduction

Mobile wireless communication has experienced explosive growth over the past decade, fueled by the popularity of smartphones and tablets. A broad consensus in the wireless industry anticipates a strong continuation of this trend for several years to come. The wireless industry has taken on the challenge of cost-effectively supporting a 1000-fold increase in traffic demand over the next decade. In this article, we explore the main technological ingredients that are likely to enable this remarkable enhancement of wireless throughput.

As observed by Martin Cooper, the celebrated pioneer of cellular communications, growth of wireless system capacity ever since the invention of the radio right up to the present can be attributed to three main factors (in decreasing order of impact): increase in the *number of wireless infrastructure nodes*, increased use of *radio spectrum*, and improvement in *link efficiency*. We maintain that these three ingredients continue to be the dominant drivers of wireless capacity growth today.

For a simple visualization of the key factors governing the performance of a cellular system, consider the following equation based on the capacity of an additive white Gaussian noise (AWGN) channel. The throughput of a user in a cellular system is upper-bounded by

$$R < C = m\left(\frac{W}{n}\right)\log_2\left(1+\frac{S}{I+N}\right) \cdots\cdots \tag{1}$$

where W denotes the base station signal bandwidth, the integer parameter n (load factor) denotes the number of users sharing the given base station, the integer parameter m (spatial multiplexing factor) denotes the number of spatial streams between a base station and user device(s), and S denotes the desired signal power, while I and N denote the interference and noise power, respectively, at the receiver.

Clearly, the signal bandwidth W can be increased by using additional spectrum, which leads to a linear increase in data capacity (all else being equal). The load factor n (≥ 1) can be decreased through cell splitting, which involves deploying a larger number of base stations, and ensuring that user traffic is distributed as evenly as possible among all the base stations. Spatial multiplexing factor m can be increased using a larger number of antennas (with suitable correlation characteristics) at the base station and user devices.

Cell splitting has the favorable side-effect of reducing the path loss between a user device and base stations, which increases both desired and interfering signal levels S and I, effectively dwarfing the impact of thermal noise N. As a result, interference mitigation is paramount for link efficiency improvement in modern cellular systems. This requires a combination of adaptive resource coordination among transmitters and advanced signal processing at the receivers.

The above ingredients for wireless capacity enhancement may be viewed under a common umbrella of "network densification." Network densification is a *combination of spatial densification* (which increases the ratio m/n) and *spectral aggregation* (which increases W). Spatial densification is realized by increasing the number of antennas per node (user device and base station), and increasing the density of base stations deployed in the given geographic area, *while ensuring nearly uniform distribution of users among all base stations*. Spectral aggregation

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refers to using larger amounts of electromagnetic spectrum, spanning all the way from 500 MHz into the millimeter wave bands (30–300 GHz). Aggregating potentially non-contiguous fragments of bandwidth across such disparate frequency bands unleashes a spate of challenges for antenna and RF transceiver design, which need to be overcome in order to support spectral aggregation.

Spatial densification and spectral aggregation between the base stations and mobile users is of little consequence unless it is complemented by densification of the backhaul, which connects base-stations to the core network. In a spatially dense network, non-line-of-sight (NLoS) wireless backhaul technologies are often needed to serve remote locations without wired backhaul coverage. At the same time, availability of high performance fiber-based backhaul (with extremely high bandwidth and low latency) in dense urban centers opens up the possibility of a cloud radio access network (Cloud-RAN) architecture with coordinated multipoint processing (CoMP). In these systems, transmit-receive signal processing for a large number of base stations is centralized at a single processor, potentially transforming a dense interference-limited wireless system into a near-interference-free system, wherein most (if not all) users can enjoy an extremely high quality of service. This technique, known as multipoint equalization (MPE), can be shown to achieve significant performance gains [3–5], provided that the Cloud-RAN covers a large number of cell sites, and sufficiently elaborate and accurate channel state information is fed back from each user to the Cloud-RAN. CloudRAN may be well suited for certain specialized deployments (e.g., stadiums/venues) where particularly high traffic demand justifies highly integrated infrastructure and large feedback overhead.

In the sections that follow, we present a more detailed overview of the main challenges and opportunities associated with different aspects of network densification. We believe that network densification as described in this article meets the 1000-fold challenge along with significant reduction in cost-per-bit delivered, ensuring the business viability of the proposed approach.

Spatial Densification

Heterogeneous Networks: Macrocells, Picocells, and Relays

Dense deployment of infrastructure nodes is a prerequisite for reducing the load-factor n in the capacity equation, and for enhancing the desired signal power S (through reduced path loss). However, deployment of additional macro base station involves significant cost and elaborate site planning. Low-power nodes (i.e., small cells, which may be employed indoors or outdoors) offer a simpler cost-effective alternative to conventional cell splitting. Outdoor small cells deployed by an operator, commonly known as picocells, typically use a transmit power of 30 dBm. Small form factor and low power rating of picocells enable much lower capital expenditure (CAPEX) and operational expenditure (OPEX) compared to macrocells. At locations without

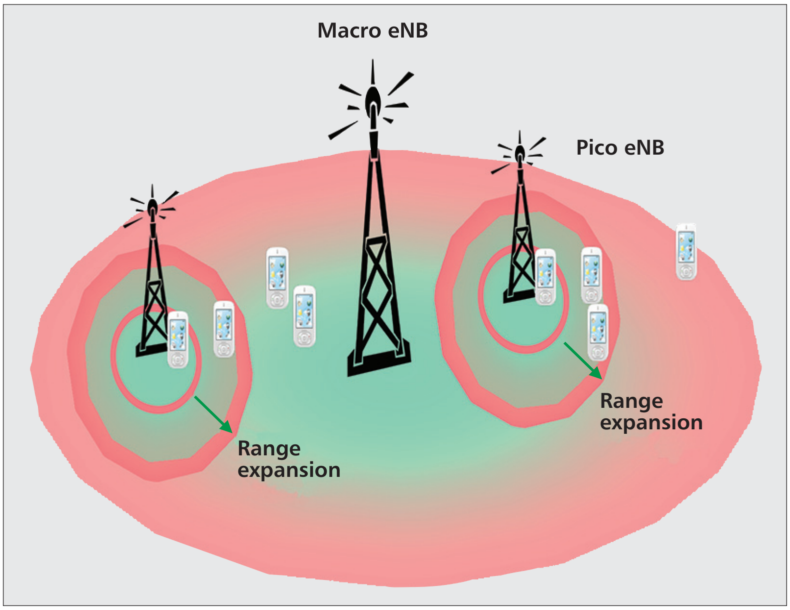

Figure 1. *Cell range expansion of low-power nodes under a macrocell.*

wired backhaul access, relay nodes may be deployed instead of picocells. A relay node uses wireless/cellular spectrum not only to provide access to mobile users, but also to backhaul data to an anchor base station with wired backhaul. It appears as a pico base station to the user equipment (UE) it serves, while appearing (mostly) like a UE device to its anchor base station.

Sharing the same carrier frequency between macrocells and small cells introduces new network design challenges. If the handoff boundary between cells is based on the received signal power at the UE, many UE devices that are very close to a picocell find themselves in the service area of a macrocell. This leads to severe uplink interference at the picocells. More important, high power transmission from the macrocells greatly shrinks the picocell coverage, leading to gross underutilization of low-power nodes. Even with optimized placement of small cells, they may become underutilized due to the temporal changes in data traffic demand. The technique of cell range expansion (CRE) is devised to address this problem.

Cell Range Expansion — As noted above, co-channel deployment of low-power nodes in a macrocellular network does not necessarily reduce the load factor n in Eq. 1. CRE overcomes this problem by biasing handoff boundaries in favor of small cells, causing most users to be served by the cell to which they are closest. This *expands* the service area of small cells, as illustrated in Fig. 1.

While CRE can significantly improve load balancing in the network and mitigate uplink interference from macro UE to picocells, it creates significant downlink interference for users in the CRE region, who are served by small cells but receive a much stronger signal from macrocells.

Downlink interference to CRE users can be overcome with resource partitioning techniques, where macrocells set aside certain *restricted resources* for the benefit of CRE users. On these

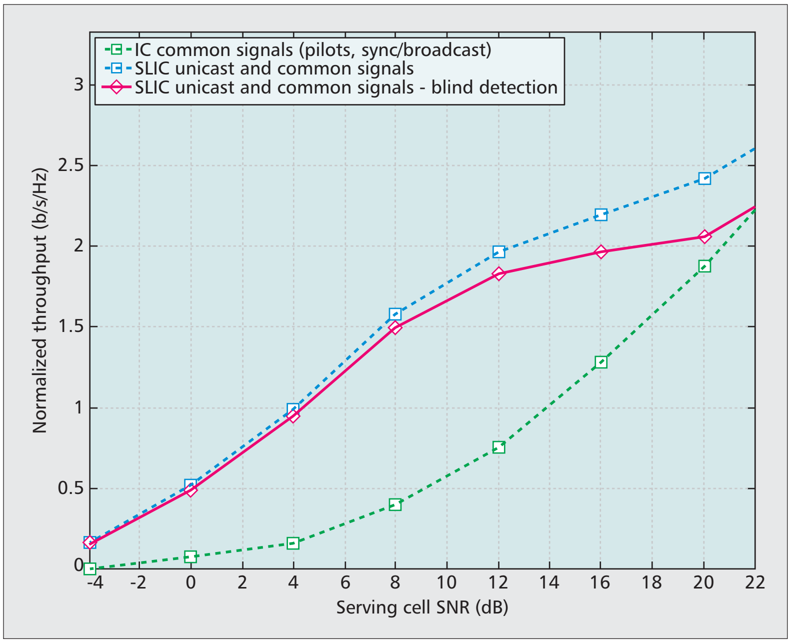

Figure 2. *Benefits of interference cancellation.*

resources, macrocells only transmit the common control/paging/broadcast channels (CCCs) and common reference signals (CRSs). Pico users in a CRE region can achieve high enough signal-to-noise-plus-interference ratio (SINR) (= $S/(I + N)$) on these resources by estimating/demodulating and cancelling the CCC and CRS from the macrocells.

Although resource partitioning creates dimension loss at the macrocells, it results in a net system gain, because dimensions lost by each macrocell are exploited by many small cells under its footprint [1].

Advanced Interference Cancellation Receivers — Dimension loss at the macrocells due to resource partitioning can be avoided if macrocells are allowed to use the restricted resources in a constrained manner (e.g., reduced power, low spatial rank, low code rate). In this case, we require more advanced receivers at the UE devices in the CRE region, where interference cancellation at the receiver is extended to encompass not only the common channels, but also unicast data/control transmissions from a macrocell.

Advanced interference cancellation (IC) of common and unicast signals includes a combination of linear and nonlinear interference cancellation techniques. Linear IC refers to spatial minimum mean squared error (MMSE) processing, while nonlinear IC involves estimating and reconstructing the interference signal at the victim receiver, and subtracting the reconstructed interference from the received signal, before decoding the desired signal. Nonlinear IC may involve estimating the interference signal at the modulation symbol level (SLIC) or at the codeblock level (CLIC). Error propagation issues associated with SLIC may be overcome by adopting a soft cancellation approach, incorporating the confidence level in estimated interference symbols. CLIC is mostly immune to error propagation effects, but requires that the spectral efficiency targeted by the interfering transmitter be consistent with the interference signal quality ($I/(S + N)$) at the victim receiver.

Both approaches require knowledge of various transmission parameters of the interfering signal, such as the modulation order, spatial multiplexing scheme, pilot type (common/dedicated), and traffic-to-pilot ratio. In addition, CLIC needs the code rate and resource allocation for each user's data. These parameters need to be either blindly estimated or obtained through network assistance. Network assistance can reduce/eliminate blind estimation complexity at the UE, but blind estimation is inevitable when UE operates with legacy networks.

Figure 2 compares the link-level performance of SLIC on common and unicast channels, with IC on common signals alone, in a one-macro-one-pico scenario with no resource partitioning. Interference from the macrocell is received by the UE at a level 16 dB above noise power, while signal-to-noise ratio (SNR) from the serving pico varies from –4 dB to 22 dB. The channels from server-to-UE and interferer-to-UE are modeled as enhanced typical urban (ETU) and enhanced vehicular-A (EVA), respectively [2]. Both serving and interfering cells use dual-Tx diversity, and the UE is equipped with two receive antennas. The red curve shows that full-IC with blind parameter estimation provides large gains over common-channel-only IC (green curve), and often performs nearly as well as the full-IC scheme with "genie knowledge" of the interference parameters (blue curve).

While we have focused this discussion on interference cancellation and centralized resource coordination/interference avoidance due to their near-term deployment prospects, advanced techniques such as decentralized coordination and interference alignment/neutralization are being actively researched, and may well find application in fifth generation (5G) cellular systems.

Neighborhood Small Cells

Picocells are mostly deployed in a (semi-)planned manner by cellular operators, incurring some cost in terms of site acquisition/rental, provisioning of backhaul, and so on. We now describe a novel deployment model of a *neighborhood small cell* (NSC), which provides a more cost-effective approach to spatial densification, and constitutes a key ingredient for addressing the 1000x challenge associated with 5G.

As illustrated in Fig. 3, an NSC network consists of small cells deployed (mostly by end users) in urban/suburban homes, small offices, and enterprises. NSC deployment involves no site acquisition and minimal RF planning, and uses existing broadband backhaul (digital subscriber line, DSL/cable) for core network connectivity. Plug-and-play user-driven NSC deployment with robust operation is achieved through self-organizing network (SON) techniques, as discussed below. These characteristics promote NSC network deployment with much-reduced cost compared to macro/pico deployment.

A key functionality of an NSC network is "indoor-to-outdoor" coverage, that is, indoor small cells providing coverage to outdoor users (e.g., pedestrians, low-mobility vehicles) in the neighborhood. Thus, NSC constitutes a coverage layer that complements an existing macrocellular network. More significantly, by virtue of cell splitting, a dense NSC network can provide huge data capacity over macro-only deployment while maintaining seamless mobility across the entire (macro-NSC) network.

Figure 4 compares downlink UE throughput performance of an NSC network (100 MHz bandwidth) relative to a macro-only (10 MHz) deployment observed in a dense urban simulation environment consisting of apartment buildings. Performance is evaluated for different NSC penetrations, where 100 percent NSC penetration implies 720 small cells per macrocell. Results show that 1000x gain is observed with 20 percent NSC penetration (144 small cells per macro) while serving 200 UE devices per macrocell. While one might expect a 1450-fold gain (10x from spectrum, 145x from node density), the gain deficit is attributed to inter-SC interference suffered especially by outdoor UE, and imperfect load-balancing between macro and small cells due to limited outdoor coverage of (indoor) small cells. Gains can be improved further using SON techniques for interference management, as discussed later. Nonetheless, the results show that dense NSC deployment, coupled with more spectrum, can provide huge gains in UE throughput and equivalently in network capacity. The key to realizing the promising gains of dense NSC networks with minimal cost lies in the use of SON techniques. SON enables spatial network densification by reducing/eliminating the burden of RF planning and enabling plug-and-play deployment by end users. Broadly, SON techniques in the following key areas are essential to realize this vision:

- Self-configuration: Network-listening and UE feedback for neighbor-cell discovery, leading to coordinated selection of operational parameters (eg., physical cell identity, tx-power, time-frequency resource sharing) among neighbors.
- Mobility management: SON-optimized handover parameters provide robust mobility in NSC deployments, coping with more challenging handover requirements than macro networks.
- Backhaul load balancing: NSCs are likely to be deployed over consumer-grade backhaul. Also, the backhaul may be shared with other devices (e.g., WiFi access points). SON maintains user quality of service (QoS) through dynamic load balancing based on backhaul bandwidth availability.

Given the promise of NSCs, it is not far-fetched to envision future NSC networks comprising multiple radio technologies (e.g., Long-Term Evolution, LTE, and WiFi) coexisting harmoniously, thanks to SON.

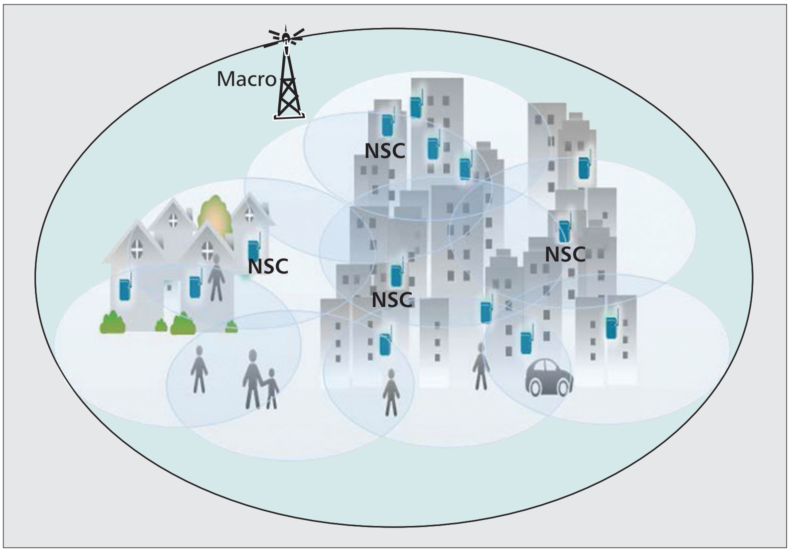

Figure 3. *Neighborhood small cell deployment.*

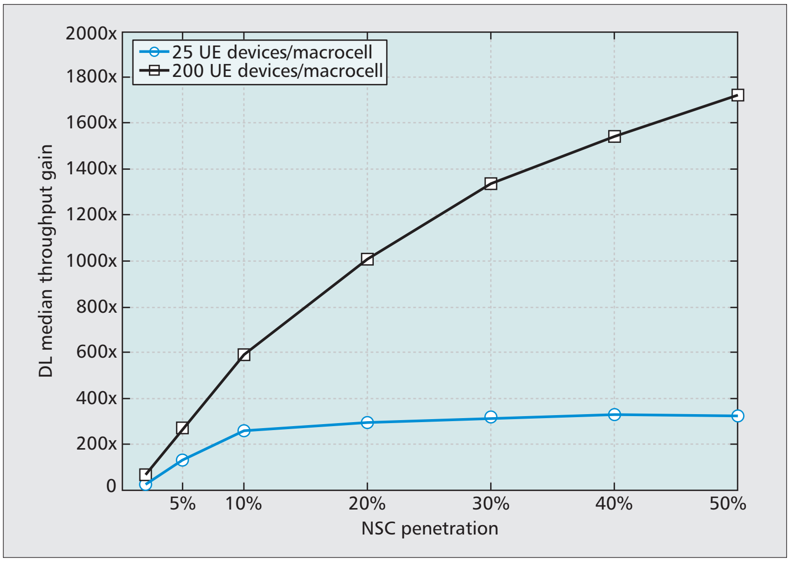

Figure 4. *Performance gains of NSC deployment relative to a macrocellular deployment.*

Device-to-Device Communications

Device-to-device (D2D) communication allows nearby devices to establish local links so that traffic flows directly between them instead of through base stations. D2D communication can potentially improve user experience by reducing latency and power consumption, increasing peak data rates, and creating new proximity-based services such as proximate multiplayer gaming. D2D communication leads to dense spectrum reuse. The base station is no longer the traffic bottleneck between the source and destination. Multiple D2D links (A-B, E-F, and G-H in Fig. 5) simultaneously share the same bandwidth, thereby increasing spectral reuse per cell beyond 1.

The ad hoc nature of D2D communication results in very irregular interference topology with large signal dynamic range. In Fig. 5, although A is closer to D than to B, A transmits directly to its desired target B rather than the nearest neighbor D, an effect called *restricted association*. This creates significant interference at D, making its SINR much lower than 0 dB, even if both links are power-controlled. In some scenarios the interference

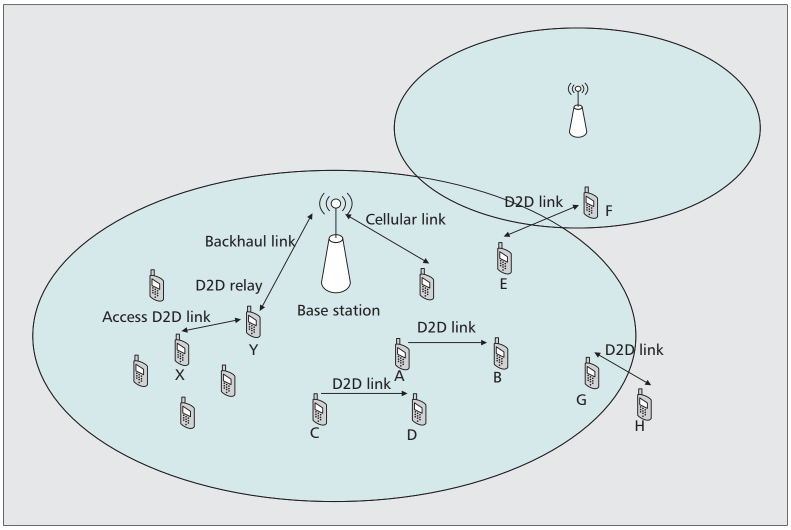

Figure 5. *Illustration of D2D-based proximal communication and multihop (relay) service.*

is so strong that even frequency orthogonalization with orthogonal frequency-division multiple access (OFDMA) is insufficient to isolate interfering D2D links because of receiver desensitization; they have to be orthogonalized in time. The carrier sense multiple access with collision avoidance (CSMA/CA) protocol used in the Wi-Fi system is designed to be robust in such scenarios, but suffers from low spectral reuse and inconsistent service [6]. D2D communication protocols designed for managed service have to address these issues. Moreover, if D2D and cellular communications share the same bandwidth, one also has to deal with interference between the two. A D2D protocol that fullfils these promises may be found in [6, 7].

In addition to enabling direct proximal communications, an interesting use case is D2D relay for traffic offloading, where a device with better geometry to the base station acts as a relay for another nearby device, illustrated in Fig. 5. If the cellular link of X is weak, a D2D link can be established between X and Y, which has a much better cellular link. A large number of UEs, including those in the sleep state, can potentially act as relays and therefore exploit multiuser shadow-diversity. Shadowing is usually uncorrelated over short distances of few 10s of meters, a range supported by D2D communication. The ubiquity of D2D-enabled devices that can act as relays exploits spatial variability of shadowing and provides an advantage akin to the user walking outside a building for better reception. D2D relay introduces new technical problems to be solved, such as discovery of candidate relays, opportunistic relay selection, interference management, multiplexing between access and backhaul links, and minimization of relay power consumption ("relays" may actually be battery-operated user devices). Furthermore, D2D relay is in essence a special example of two-hop communication, and the concept can be extended to enable multihop and more advanced cooperative communication and networking.

Spectral Aggregation

Spectrum Availability and Multiband Operation

The wireless industry is facing a spectrum crunch due to the seemingly neverending surge in demand for mobile broadband data. Traditionally, spectrum has been made available for mobile broadband usage in two distinct ways:

- Bands that can be completely cleared of incumbents, auctioned, licensed, and brought online in a reasonable timeframe. This includes the cellular bands in 700 MHz, 1800 MHz, 2100 MHz, 2600 MHz, and so on.
- Unlicensed spectrum that can support offloading from licensed bands on a best-effort basis, where fullmobility is not essential. This includes the 2.4 GHz, 5 GHz, and 60 GHz bands.

This excludes a third type of spectrum that is not allocated for mobile broadband, but is underutilized in time or across geography. The U.S. 3.5 GHz and EU 2.3 GHz bands fall under this category. In both cases, the incumbents underutilize the spectrum in both time (at the same location) and geography. In these bands, approximately 250 MHz of precious spectrum can be made available for cellular mobile broadband data [8, 9].

Even though these bands apparently cannot be cleared of incumbents in a reasonable/predictable timeframe, spectrum-sharing techniques allow them to be integrated into licensed carrier networks, to support full mobility and provide reliable QoS where and when the incumbents are not using it.

Licensed or authorized shared access (LSA or ASA) is a *licensed spectrum sharing* paradigm that allows for network-level coordination between incumbents and licensees that use the band for augmenting cellular capacity with predictable QoS. ASA is a binary system wherein the ASA spectrum rights holder has an exclusive right to use a given portion of the spectrum when and where it is not used by incumbents. At any given location and at any given time, a specific channel in the spectrum will be used by either the incumbent or a single ASA rights holder. ASA generalizes the TV white space concept, where the incumbent need not be a TV broadcaster.

An ASA controller provides all the information necessary for a licensee to operate within the interstices of the frequency band whenever and wherever incumbents are not using it, and to move off of the spectrum quickly when and where incumbents need to operate. ASA is completely transparent to the user device, requiring no protocol changes whatsoever. From its perspective, operating on ASA band should be no different from operating on any licensed band.

RF Transceiver Design Challenges

The proliferation of multiple frequency bands, high-order multiple-input multiple-output (MIMO), and coexistence of multiple radios impose several challenges to power- and cost-efficient RF front-end design. A 5G phone is expected to support some 40 wide area network (WAN) bands in addition to radios for wireless LAN (WLAN), personal area network (PAN), and FM services. This can be realized in one of two ways: (i) a large number of fixed frequency filters or (ii) high Q tunable RF filters followed by broadband RF front-ends (RFFEs). The challenge for the first approach is that filters need to decrease in size while the insertion loss of the entire filter bank is reduced. The second approach requires an RFFE that maintains RF and DC power performance and linearity over a considerably wider bandwidth.

At present, none of the best-in-class RF technologies (e.g., switched-capacitor filter banks, micro electromechanical system [MEMS]-based varactors and ferro-magnetic thin films, varactor-based tunable filters) satisfy all the above design requirements. For instance, the best performing technology for RF/microwave tunable resonators based on Yttrium Garnet (YIG) requires large volume ($\sim$1 in^3) and consumes significant power (0.75–3 W) [13].

Antennas and RFFEs in mobile devices must concurrently support WiFi and WAN operation. Segmentation and reassembly (SAR) degrades with multiple simultaneous transmissions, while nonlinearities in the Tx chain create intermodulation products that leak into and severely jam receivers in other bands. An intelligent coexistence manager is necessary for thermal, power, interference, and SAR management. A number of RF/antenna-based and systems-based approaches can be used to mitigate coexistence interference, such as:

- Adaptive trade-off between power consumption and linearity of Tx/Rx chains
- Aligning the aggressor-victim timeline whenever possible so that transmissions and receptions are synchronized (e.g., LTE-time-division duplex, TDD, and Bluetooth)
- Regenerate aggressor's Tx waveform as seen by the victim's Rx for cancellation
- Adaptive power backoff on the aggressor as a function of target victim/aggressor performance subject to maintaining the use case QoS
- Protecting important asynchronous events (like those of a connection setup) by autonomously gating off the aggressor's Tx power for the lifetime of the reception

Millimeter-Wave Technology

Most mobile cellular systems are deployed in the sub-3 GHz spectrum. One possible area of 5G study is to explore higher carrier frequency, such as millimeter-wave bands (30 to 300 GHz) recently investigated [10, 11]. Two salient features of the millimeter-wave bands are large amounts of bandwidth, enabling very high in-coverage throughput, and very small wavelengths enabling a large number of tiny antennas in a given device area.

The main challenges for millimeter-wave-band communications include large path loss (especially with non-line-of-sight, NLoS, propagation), signal blocking/absorption by various objects in the environment, and low Tx power capability of current millimeter-wave-band amplifiers. Signal attenuation may be combated using large antenna arrays driven by smart beam selection/tracking algorithms. Phase-array-based RF/analog domain beamforming can be combined with interference-aware baseband-level beamforming to ensure that the number of transceivers scales with the number of active spatial layers, rather than the total number of antenna elements at a given base station/user device.

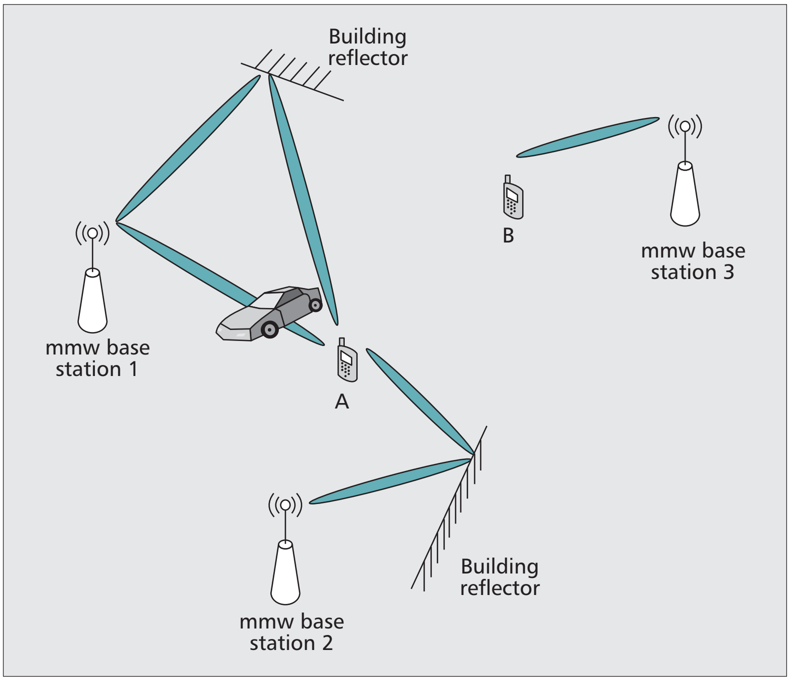

Figure 6. *Illustration of millimeter-wave mobile access.*

Highly directional beams improve the link budget and enable very dense spatial reuse through spatial/angular isolation, as illustrated in Fig. 6. This massive spatial orthogonalization leads to a very different cellular architecture where the millimeter-wave base stations can be very densely deployed with significantly overlapping coverage but no strong intercell interference. This also leads to intermittent link availability on the millimeter-wave band, which requires very fast cell switching within the millimeter-wave band, as well as tight integration and seamless mobility with sub-3 GHz 3G/4G cellular networks.

Backhaul Densification

We have seen that data throughput between the base stations and wireless (mobile) devices may be enhanced through network densification (in space and frequency). But in order to translate this into enhanced user experience, the base stations need to to be connected to the core network (and to one another) through high-capacity low-latency backhaul. We envision two main ways in which backhaul technologies would evolve to support the 5G wireless system. One approach is the Cloud-RAN architecture, briefly mentioned in the introduction, and the other consists of wireless backhaul technologies, explored in this section.

Spatial densification assumes that it is possi-

With reasonable projections on additional spectrum availability, expansion of small-cell deployments and growth in backhaul infrastructure, we believe that the cellular communication industry is well-positioned to meet the 1000x demand over the next decade.

ble to deploy small cells in locations such as lampposts, building walls, and utility poles. Providing wired backhaul to these locations may be cost prohibitive. Wireless backhaul could provide a viable solution, connecting the edge nodes (small cells) to aggregator nodes (called feeder links), and then to the gateway nodes (called aggregation links), which have fiber backhaul to the core network. Because of the channel propagation characteristics, the sub-6 GHz spectrum has often been used for LoS/NLoS feeder links, and the microwave/millimeter-wave spectrum for the LoS aggregation-links.

Potential capacity improvement techniques for wireless backhaul include:

- Exploiting large channel coherence time and high SNR to reduce pilot overhead and channel feedback rate, while operating at high modulation order such as 4096-quadrature amplitude modulation (QAM)
- Employing single-user spatial multiplexing (MIMO) on each (NLoS) feeder link, with end node locations optimized for MIMO
- Using distributed/multi-user MIMO techniques for spatial multiplexing among LoS links radiating from each gateway node to multiple aggregator nodes
- Exploiting massive spatial processing for millimeter-wave bands, promoting large beamforming/null steering gains, and dynamic spectrum sharing between access and feeder links

Millimeter-wave communication, especially in the context of wireless backhaul, provides one example of operating with high spatial multiplexing order (m in Eq. 1); another example in the lower frequency bands may be found in *massive MIMO* systems [12], where macrocells are equipped with two-dimensional antenna arrays, enabling multiple horizontal and vertical beamforming capabilities at the macrocells.

Conclusions

With reasonable projections on additional spectrum availability, expansion of small-cell deployments, and growth in backhaul infrastructure, we believe that the cellular communication industry is well positioned to meet the 1000x demand over the next decade. The path to 5G outlined in this article may seem like an enhancement and scaling of current 4G technologies with a few new components added in, but a combination of meaningful enhancements in key areas together with a few novel components can raise the overall user experience to a whole new level, inaugurating a brand new wireless universe that is truly worthy of the 5G designation.

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