A Holistic View on Hyper-Dense Heterogeneous and Small Cell Networks

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ABSTRACT

The wireless industry has been experiencing an explosion of data traffic usage in recent years and is now facing an even bigger challenge, an astounding 1000-fold data traffic increase in a decade. The required traffic increase is in bits per second per square kilometer, which is equivalent to bits per second per Hertz per cell × Hertz × cell per square kilometer. The innovations through higher utilization of the spectrum (bits per second per Hertz per cell) and utilization of more bandwidth (Hertz) are quite limited: spectral efficiency of a point-to-point link is very close to the theoretical limits, and utilization of more bandwidth is a very costly solution in general. Hyper-dense deployment of heterogeneous and small cell networks (HetSNets) that increase cells per square kilometer by deploying more cells in a given area is a very promising technique as it would provide a huge capacity gain by bringing small base stations closer to mobile devices. This article presents a holistic view on hyper-dense HetSNets, which include fundamental preference in future wireless systems, and technical challenges and recent technological breakthroughs made in such networks. Advancements in modeling and analysis tools for hyper-dense HetSNets are also introduced with some additional interference mitigation and higher spectrum utilization techniques. This article ends with a promising view on the hyper-dense HetSNets to meet the upcoming 1000× data challenge.

INTRODUCTION

Mobile data traffic has just started exploding: the amount of traffic usage has been doubling each year during the last few years with the increasing popularity of smart phones and new types of mobile computing devices. Now the wireless industry is preparing for an even bigger challenge, an astounding 1000-fold increase in data traffic expected in this decade [1].

A set of new radio access technologies are required to satisfy future requirements of 1000× capacity. The required capacity is in bits per second per square kilomiter, which is equivalent to bits per second per Hertz per cell × Hertz × cell per square kilometer. Higher utilization of spectrum (bits per second per Hertz per cell) in given frequency resources per cell is quite saturated; recent results show that at least point-to-point link throughput is very close to the theoretical limits. Utilization of more bandwidth (Hertz) is a very costly solution, unless devices can utilize additional radio access technologies for unlicensed bands with seamless aggregation and offloading. The final and probably one of the most promising frontiers to achieve the goal is to increase cells per square kilometer by deploying more cells of different types/technologies in a given area. Heterogeneous and small cell networks (HetSNets), whose goal is to maximize the utilization of existing spectrum by deploying more cells, are thus expected to be important to challenge the future of cellular networks [2].

HetSNets are networks deployed with a mix of traditional high-power macrocells and low-power smaller cells such as pico, femto, and/or relay nodes. We assume that HetSNets include wireless local area network (WLAN) and wireless personal area network (WPAN) technologies as well, so HetSNets are networks consisting of multiple radio technologies. In theory, the overall capacity scales with the number of small cells deployed in a unit area: shrinking the radius of each cell and packing more cells in a given area would actually offer more capacity and more spectrum reuse. In reality, however, as cells get closer, the hyper-densification of HetSNets is challenged in many ways. In a hyper-dense deployment, not only desired signal strength but also interference from other cells increase. Increasing other-cell interference needs to be mitigated, and a better mobility management mechanism is required as the mobile users see cell edges more frequently. Furthermore, as some privately owned small cells implement restricted access schemes, they can generate/receive strong uncoordinated interference to/from external cells sharing the same radio resources [3]. The deployment of small cells are mostly unplanned, so a network self-organizing mechanism needs to be developed. The promising performance gain by deploying more cells can only be achieved by successfully addressing these problems.

Despite the barriers, there have been many technical breakthroughs in HetSNets in recent years. The development of further enhanced intercell interference coordination in Third Generation Partnership Project (3GPP) Long Term Evolution (LTE)-Advanced systems enables the mobile stations to coordinate/mitigate intercell interference and successfully set up connections

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with small cells. Self-interference cancellation (SELIC) enables the coexistence of heterogeneous radios in the same mobile device. Expanding SELIC further to even enable full duplex radios is also being actively investigated [4]. Intelligent incentive schemes can motivate privately owned small cells to open up for wider access. Thanks to those advanced interference management and self organizing network (SON) techniques, the overall capacity enabled by HetSNets is expected to continue grow as the densification of small cell deployment increases. In this regard, several mathematical models for analyzing the hyper-dense HetSNets have recently been proposed [5–7].

The main goal of this article is to provide a holistic view of the hyper-dense deployment of HetSNets. We first compare the two approaches for future wireless systems, massive antenna and dense deployment, and present the fundamental preference for dense deployment. We review the technical challenges in HetSNets, which are due to other-cell and in-device interference, user mobility, privately owned small cells, and difficulties in performance analysis. We then provide recent technical breakthroughs to overcome those barriers. We introduce additional techniques that can be used in HetSNets and present a promising view of the hyper-dense HetSNets for the 1000× challenge.

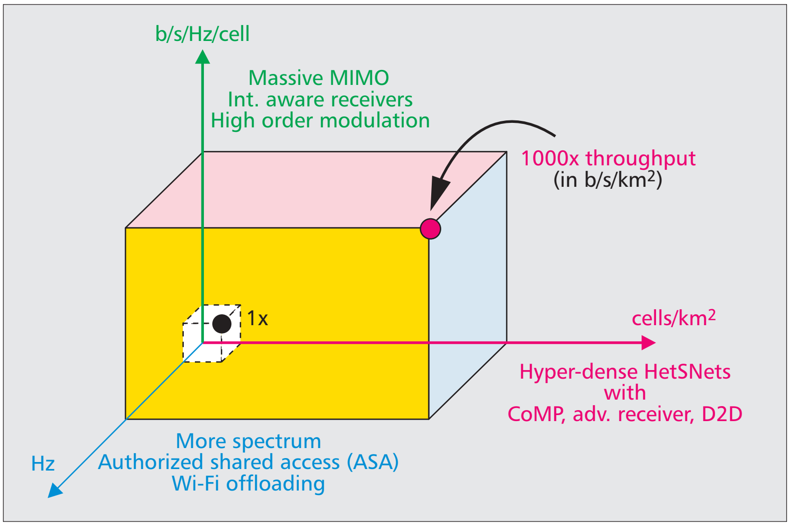

Figure 1. *The 1000× data challenge in three domains.*

Future Wireless Systems: Massive or Dense?

There have been two different approaches to future wireless systems to achieve much higher throughput. The first approach is to use more antennas at the macro base stations to achieve higher spatial gain outdoors. The second approach is to deploy more small cells to cope with increasing traffic demand both indoors and outdoors.

Massive MIMO

Massive multiple-input multiple-output (MIMO) is an emerging technology that uses a large excess of base station antennas (up to a few hundred antennas) to simultaneously serve a number of users in the same time-frequency resource [8]. In massive MIMO systems, as the aperture of the array grows with many antennas, the resolution of the array also increases. This makes the transmitted power concentrated extremely sharply into small areas, causing the transmit power to be arbitrarily small. It was thus expected that massive MIMO could provide a significant capacity gain and improve energy efficiency.

However, the performance of massive MIMO is limited by the finite and potentially correlated scattering given the space constraints [8]. The degrees of freedom of the system, solely determined by the spatial resolution of the antenna array, can be saturated to an intrinsic property of the scattering channel itself. Also, channel estimation and feedback for a large number of antennas is an inherent challenge. As a result, massive MIMO can be more attractive in time-division duplex (TDD) systems where downlink channel training and feedback do not constrain the number of transmit antennas. Unfortunately, the number of orthogonal pilots may still be limited by the finite channel coherence time even in TDD systems. This results in high reuse of pilots with adjacent cells, contaminating the pilots and thus resulting in impairments of the uplink channel estimation [9]. High deployment cost for guaranteeing the minimum antenna spacing of the large arrays with many radio frequency (RF) chains is a very practical issue. Thus, it is expected that the throughput gain and application of massive MIMO is fundamentally limited, and massive MIMO may not be a single dominant approach to achieve the ever increasing traffic demands.

Hyper-Dense HetSNets

Hyper-dense HetSNets are motivated by rethinking the network deployment principle: to bring the network close to the users to offer unprecedented capacity. There are several advantages of this approach over macrocell enhancements. First, the cost of deployment in HetSNets is much lower than that of macrocells. Unlike a macrocell, where a significant portion of the recurring cost comes from fiber to each cell site, power usage, and real estate, there is no big operating cost in user deployed HetSNets. Second, HetSNets are energy efficient as they can be utilized intelligently and opportunistically. Depending on the traffic demand, small cells can be in dormant state, so the energy consumption and interference can be minimized. Third, hyper-dense HetSNets can realize the *always best connected* principle by seamless handover and smart offloading. Proximity-based over-the-air congestion control and fast intercell load balancing in HetSNets increase the overall spatial reuse [1]. As many small cells are deployed indoors, offloading not only the indoor user traffic but also the outdoor traffic to indoor small cells may provide a huge gain.

Macro base stations can also benefit from similar approaches. Instead of deploying expensive macro base stations with many antennas and digital baseband processing units, only the radio units can be deployed in remote locations. Such

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	Massive MIMO	Cloud RAN	HetSNets
Total transmit power	≤ 46 dBm (macro)	30 dBm (per RRH)	30/20 dBm (pico/femto)
Total # of antennas	Up to 100	8 (per RRH)	4 (pico), 2 (femto, relay)
Antenna azimuth pattern	Sectorized	Omni	Omnidirectional (macro-relay)
Typical cell radius	400 m–2 km	Up to 40 km	4–200m
Required backhaul	None	Fiber access (1–10 Gb/s)	Cable (10–100 Mb/s), wireless
Operational cost	High	Medium	Low
Duplex mode	TDD only	TDD, FDD	TDD, FDD

Table 1. *Comparison of massive MIMO, cloud RAN and HetSNets.*

cells are called remote radio heads (RRHs), which are part of the distributed antenna systems (DASs). DASs/RRHs may provide additional throughput gain by filling up the coverage hole due to disruption of obstacles. The cloud RAN approach extends this on a network-wide scale. In these centrally controlled networks, extensive requirements for high-capacity fiber connections to/from the RRHs and fast adaptation capability to agile traffic demands need to be properly addressed. Despite the similarity in physical appearance, HetSNets operate in a distributed manner by allowing enough intelligence to each cell to organize and coordinate autonomously. Current deployment of millions of femtocells is suggestive of initial preference for small cells. Technology enhancements for HetSNets with distributed intelligence are actively promoting this further.

Technical Challenges in HetSNets

There are a few important technical challenges in HetSNets that need to be resolved. Such challenges include intercell interference, in-device self-interference, unplanned deployment, mobility management, privately owned small cells, and difficulties in performance analysis.

Intercell Interference (Coexistence with Another Cell)

As cells get smaller, and as more small cells are packed into the same amount of space, the mobile user may see more diverse and stronger out-of-cell interference. Strong interference between macrocells and co-channel small cells arises from the high imbalance in path loss and transmission power between two types of cells. This may cause significant degradation in the received signal quality to mobile users. In hyper-dense HetSNets, on top of existing macro-small cell interference, interference between small cells further complicates the intercell interference landscape. The geographically random, unplanned small cell deployment may generate out-of-cell interference to adjacent small cells especially in densely deployed areas.

In-Device Interference (Self-Interference)

Advanced wireless devices are equipped with multiple radios such as 2G/3G/4G, WLAN and WPAN transceivers and simultaneous utilization of them is becoming particularly important in small cells that support multiple radios [10]. Due to extreme proximity of these tranceivers operating on the same, adjacent or harmonic/sub-harmonic frequencies, the interference power coming from a transmitter (aggressor) may be much higher than the received power of the desired signal at a receiver (victim). For example, LTE bands 7 (FDD, UL: 2500–2570 MHz), 40 (TDD, 2300–2400 MHz), and 41 (TDD, 2496–2690 MHz) are immediately adjacent to the 2.4 GHz industrial, scientific, and medical (ISM) band, which can potentially cause significant mutual interference even with high-performance band-pass filteration. In addition, several LTE bands around 800 MHz could interfere with the 2.4 GHz ISM band via third harmonics and vice versa. These coexistence problems often result in degradation or failure of one or both radios. A similar problem exists for 5 GHz U-NII-band WLAN, as illustrated in Fig. 2a.

Unplanned Deployment

It is anticipated that hyper-dense HetSNets are largely fueled by unplanned deployment of residential and enterprise small cells. In this scenario, no special consideration may be given to traffic demand or interference with adjacent cells. Frequency resources may be limited in hyper-dense small cells when deployment is loosely correlated to those network demands. The small cells thus need to be capable of being configured, optimized and healed by themselves not to cause any noticeable disruption to the existing networks. Unplanned hyper-dense deployment without such autonomous processes may cause significant problems to both macro cell users and small cell users.

Mobility Management

In the hyper-dense HetSNets, mobile stations may experience more frequent handover due to smaller cell radius. For instance, with a cell diameter under 100 m and at a velocity of 30 km/h, the mobile station needs to move from one cell to the other in every few seconds.

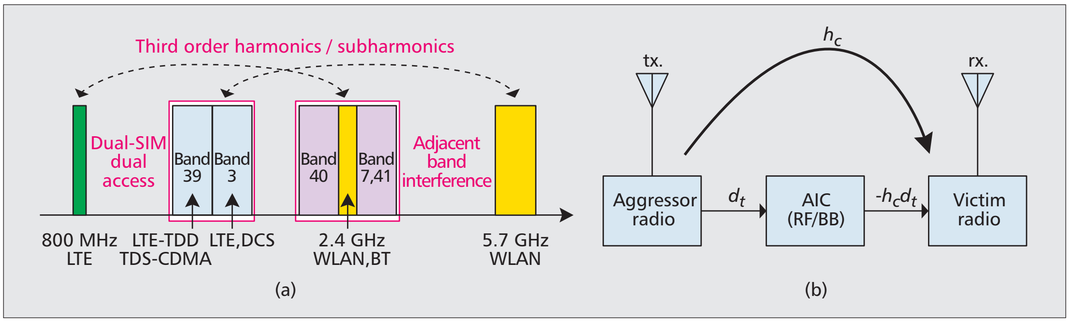

Figure 2. *Illustration of a) self-interference due to dense radios; b) active interference cancellation. In b),* d_t *is the transmitted signal from the aggressor radio, and* h_c *is the coupling channel from the aggressor radio to the victim radio.*

Many small cells, especially femtocells, are mainly owned by end users and by private enterprises. Some private users may not be willing to open up access as they are paying for the operational costs such as backhaul and electricity, unless a sufficient incentive is given.

Recent studies in LTE show that there are very frequent handover events with nearby, but not even very dense, picocells in the shared spectrum [11]. The analysis indicates that handover performance in HetNet deployments is not as good as in pure macro. Asymmetry of downlink and uplink coverage in hyper-dense HetSNets also threats the mobility management mechanism in the hyper-dense HetSNets. The downlink coverage of the macrocell is generally much larger than that of the small cells due to its higher transmit power. This difference does not hold for uplink because the mobile user is the only transmitter. If the handover mechanism is based on the received signal strength only, simultaneously addressing downlink and uplink handover needs could be challenging.

Privately Owned Small Cells

Many small cells, especially femtocells, are mostly owned by end users and private enterprises. Some private users may not be willing to open up access (e.g., because they are paying for operational costs such as backhaul and electricity) unless a sufficient incentive is given. A closed access femtocell serves only a small number of closed subscriber group (CSG) users and potentially generates a lot of interference to adjacent macrocell and small cell users and vice versa. When more privately owned CSG small cells are deployed in the hyper-dense HetSNets era, the high interference area surrounding the small cells may significantly increase. Novel incentive schemes to open up privately owned closed small cells to open access or at least hybrid access need to be developed.

Performance Analysis

A typical model for one-tier homogeneous macrocell systems is the two-dimensional hexagonal grid model, which is widely used to reduce the simulation complexity in large-scale system-level simulations. In HetSNets, however, average transmit power, base station antenna height, channel scattering, supported data rate, and base station density are different per tier, and the classical grid model can be far from reality [5]. Better mathematical modeling and performance analysis tools for multi-tier HetSNets need to be investigated. In addition, good traffic modeling tools are required to model overflow traffic, offloading, and frequent handover caused by the hyper-dense HetSNets.

Recent Technical Breakthroughs in HetSNets

Despite the issues raised in the previous section, there are recent breakthroughs that make the hyper-dense HetSNets viable. We introduce those recent achievements in this section. Note that the subsections are completely paired, so each challenge identified in the previous section is addressed in this section.

Intercell Interference Coordination/Mitigation

Intercell interference coordination/cancellation (ICIC) is one of the key enablers that make HetSNets a reality. To enable mobile users to detect and then subsequently be attached to a small cell that is transmitting at a much lower power than the nearest macrocell, time-domain resource partitioning is widely studied in LTE/LTE-Advanced. Specifically, predefined subframes are periodically vacated from the macrocells except for only minimal reference and control signals, so the small cells can assign resources for the designated users with less macrocell interference. Such a subframe is called an almost blank subframe (ABS). Furthermore, advanced mobile receivers with interference cancellation capability enable a large cell detection bias (e.g., 9 dB or higher) so that a mobile can detect and camp on nearby small cells. As a result, small cells can enlarge its coverage and further offload macro traffic. Further enhancements of ICIC include non-zero power ABS for macro users with good channel conditions and rate matching around the cell-specific reference signal to avoid interference cancellation at the mobile station. This time domain partitioning enables the co-channel deployment of small cells with macrocells, avoiding any inefficient bandwidth segmentation.

MultiFlow is a flow-level technique being actively investigated for hyper-dense HetSNets [1]. It enables mobile users to receive multiple downlink data streams from multiple cells. As typically the traffic load is uneven and changes with time and location, MultiFlow balances load and improves cell edge performance by allowing mobile users to receive multiple signals from multiple small cells. Instead of causing interference to each other, with MultiFlow, the mobile

	LTE eNB (macro)	LTE femto	Wireless LAN	Bluetooth (Class 2)
Bandwidth [MHz]	9	9	20	1 (79 CH)
Tx. power [dBm]	46	20	16	4
Noise figure [dB]	2	5	7	7
Noise power [dBm]	–102.4	–99.4	–94.0	–88.0
Desired cancellation [dB]	144.4	115.4	103.0	85.0

Table 2. *SELIC requirements for different systems (10 MHz system bandwidth is assumed for LTE).*

users can have additional receive diversity with interference suppression.

Self-Interference Cancellation

There have been several efforts on avoiding the multiradio cross-interference problem by carefully coordinating allocated resources to different radios in either frequency, time, or power domain. However, these often lead to compromised performance in each radio due to restrictions in radio resource utilizations (e.g., one radio can use only a subset of time slots). A more advanced approach is to conduct SELIC using the knowledge of the self-generated interfering signal. Therefore, an efficient SELIC approach is to employ an active interference cancellation (AIC) architecture as shown in Fig. 2b. SELIC can happen in baseband (BB), RF, or simultaneously in BB and RF.

SELIC can also be used to enable a full-duplex wireless system that uses the same frequency channel at the same time for both transmission and reception [4]. However, as the self-interference is extremely strong, the cancellation requirement can be prohibitive. Table 2 tabulates the SELIC requirements for suppressing the self-interference below the noise level for different systems. It is clearly observed that the smaller the cell size and transmit power, the less stringent the SELIC requirement. Therefore, HetSNets can potentially migrate to adopt more aggressive duplexing techniques for small cells.

SON and Cognitive/Docitive Networking

In self-deployed hyper-dense HetSNets, any newly plugged in small cells ought to be self-configured, while all existing cells need to optimize parameters autonomously in response to periodically observed RF conditions. When equipment malfunctioning and outage is detected, self-healing mechanisms need to be triggered to temporarily compensate for the outage while awaiting a more fundamental and permanent solution. SON is a technological enabler of such functionalities and is being introduced in 3GPP LTE-Advanced to simplify and automate the initial provisioning, operation optimization, and maintenance of mobile networks.

As adaptiveness and autonomy are the two main features for the interference management by a SON, research on *cognitive* femtocells has already started. Cognitive femtocells can dynamically sense spectrum usage by macrocells and adapt the transmissions to optimize the overall usage of the spectrum. In cognitive femtocells, the slow convergence speed and less precision problems are the remaining issues and thus need to be solved. Those issues are actively studied using a more intelligent *docitive* networking concept, where nodes effectively teach other nodes with the prime aims of reducing cognitive complexity, speeding up the learning process, and drawing better and more reliable decisions [12]. The early stage investigation in [12] shows that docitive networks may be a facilitator for the efficient management and utilization of limited spectral resources.

Advanced Mobility Management

To help mobile users have faster handover only when necessary, several advanced mobility management schemes are investigated. One simple solution is user grouping, where stationary users are served by small cells while mobile users are allocated to the macrocell. A more advanced form of mobility management is the formation of virtual cells by clustering cooperating hyperdense small cells. Mobile users can see the clustered cells as a single distributed cell, so a handover event is triggered only at virtual cell boundaries. Another technique is adaptive handover, which changes the hysteresis level according to the mobile speed. The hysteresis level can be dynamically adjusted so that mobile users can have a faster or slower handover if necessary. Neighbor list management can also be enhanced. Adjacent cells can share neighbor lists (e.g., whitelist or blacklist) or other information to negotiate and manage appropriate handover across clusters of small cells and the macrocell.

Intelligent Incentive Schemes

To open up privately owned small cells for wider usage, many intelligent incentive schemes have been proposed and investigated. A practical realization of such intelligent incentive schemes is "Fon" (http://corp.fon.com/en/this-is-fon/easy-to-join/), which forms a large WiFi network with over 5 million hotspots worldwide. By sharing a private user's WiFi resource, the user obtains access to the entire Fon network. To enable this, Fon uses two dedicated WiFi signals, one private and one public. The private signal is encrypted just for exclusive subscribers, while the public signal is password protected but accessible by registered Fon users. Fon is one successful incentive scheme that motivates users to open up their resources for wider usage. This approach is essentially an instance of a cooperative game. A broader range of game theoretic approaches such as a coalition game and Stackelberg game [13] are being considered for intelligent incentive schemes.

Tractable Mathematical Model

To model K-tier hyper-dense HetSNets, the location of small cell base stations can be drawn from a stochastic process because most small cells are deployed in unplanned positions. A Poisson point process (PPP), which is useful mathematical tool based on stochastic geometry, provides an accurate tractable analytical model [5]. Recently, repulsive cell planning strategies based on the Matern hard core process (MHP) where the constituent nodes are forbidden to lie closer than a certain minimum distance have been proposed [6, 7]. MHP is a thinning of the PPP ensuring a desired minimum distance between base stations. Specifically, distributed control [6] and centralized control [7] of minimum separation distance in MHP enables the number of active base stations to be adjusted, improving the coverage probability, throughput, and load balancing. The two multicell modeling methods, PPP and MHP, are compared and illustrated in Fig. 3. As shown in the figures, MHP makes the base station distribution more uniform than PPP and the coverage probability for a given signal-to-interference-plus-noise (SINR) requirement higher. Further advantages of the MHP approach such as improved load balancing capability are analyzed in [6, 7]. In reality, how to promote/enforce the minimum distance in small cells remains an open problem.

The 1000× Challenge: Hyper-Dense HetSNets

There are multiple ways to reach out to the 1000× throughput (in bits per second per Hertz per square kilometer), with different mixes of spectrum (Hertz), spectral efficiency (bits per second per Hertz per cell), and hyper-dense deployment of HetSNets (cells per square kilometer).

Enabling Technologies

We present the performance gain of many enabling technologies, focusing on the performance comparison between massive MIMO and hyper-dense HetSNets. In theory, massive MIMO achieves high throughput by achieving a high beamforming gain, while hyper-dense HetSNets improve the performance by bringing base stations closer to the target mobile stations. With a massive antenna array at the base station with appropriate transmit beamforming such as matched filter (MF) or minimum mean square error (MMSE), the effective SNR increases linearly with the array size N as long as the size of the antenna array is scaled accordingly [8]. In hyper-dense HetSNets with N small cells per unit area, the average distance from the base station is decreased by $\sqrt{N}$ so $\sqrt{N}^{\gamma}$ gain can be achieved where γ is the path loss exponent. Typically, γ is greater than 2 in most propagation conditions (especially in indoor environments). Therefore, the gain achieved by bringing the network closer to the mobile station $N^{\gamma/2}$ is greater than the massive array gain N.

In Fig. 4a, throughput performance of massive MIMO and hyper-dense HetSNets are presented for $\gamma = 4$. In massive MIMO, the deterministic equivalent model based on random matrix theory [8] indicates that the average rate is saturated at acertain point due to the effects of pilot contamination and correlated scattering [9] as indicated by the black dashed line in Fig. 4a. In hyper-dense HetSNets with the same number of users ($K = 8$), the network throughput scales to a higher value as the hyper-densification takes place. We also plotted the scenario

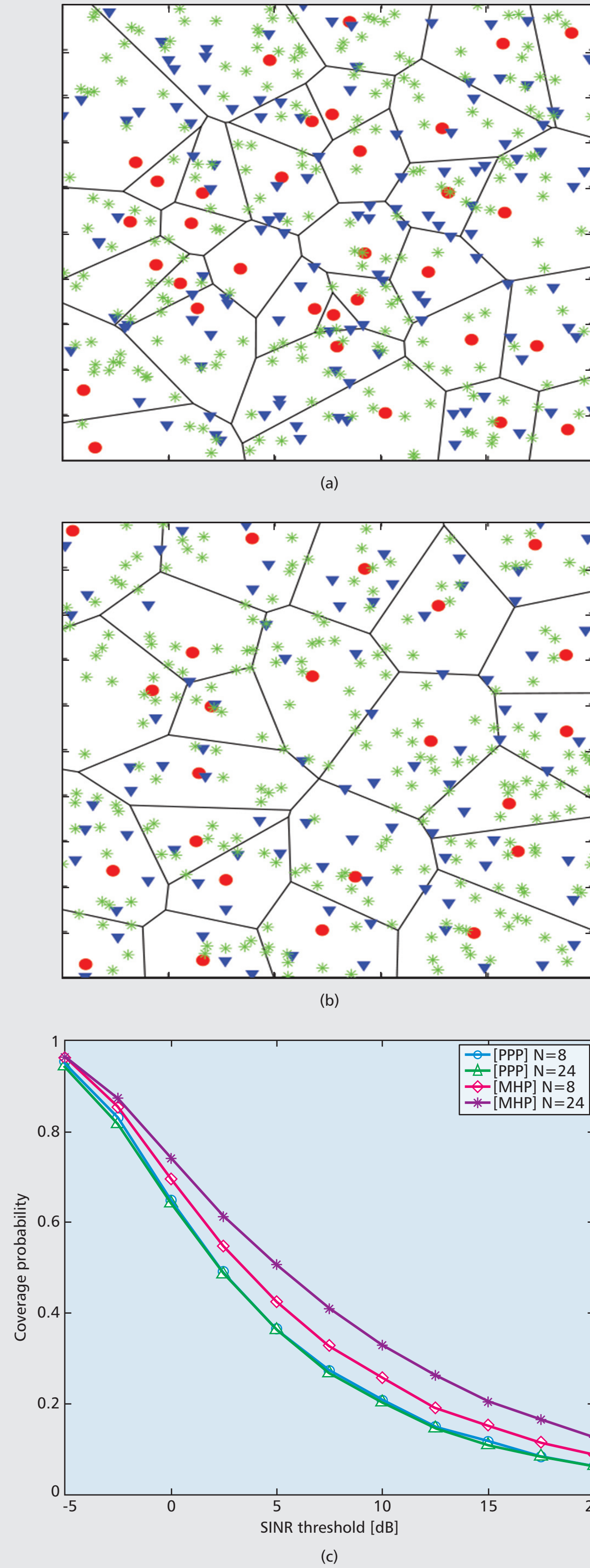

Figure 3. *An illustration of base station distribution for three-tier (red: macro, blue: pico, green: femto) HetSNets in a) PPP; b) MHP with Voronoi tessellation of macrocells; c) their cell coverage performance comparison. In both cases, $\lambda_3 = 4\lambda_2 = 8\lambda_1$, where λ_i is the ith tier's base station density. In MHP, the minimum distance in each tier is inversely proportional to its transmit power, and the cell coverage performance is improved as the number of cells (N) in a unit area increases.*

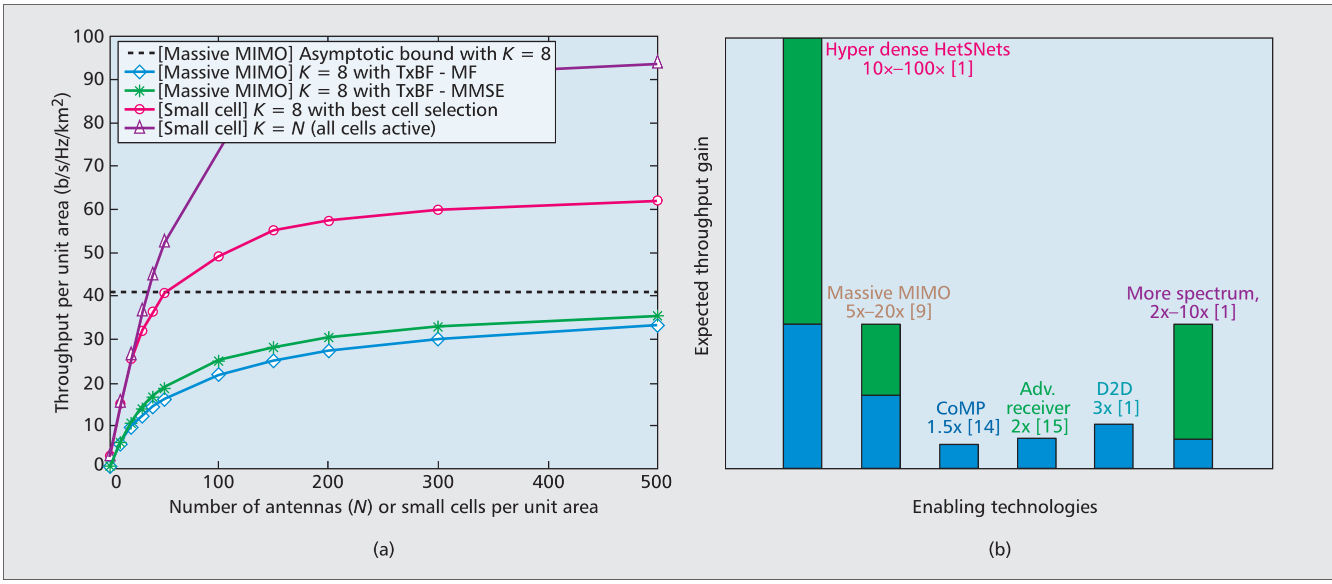

Figure 4. *a) Performance comparison: massive MIMO (number of users per cell K = 8, number of cells L = 4, and intercell interference factor = 0.1) vs. dense small cells (one tier, base stations are distributed by MHP with minimum distance 85 m, path loss exponent λ = 4); b) multiple paths to the 1000× data throughput. In a), "best cell selection" means that each user selects the nearest base station, and the unchosen base stations are turned off.*

where the number of users scales according to N (i.e., $K = N$), where a significantly higher gain is observed. The performance gain of hyper-dense HetSNets can be improved further with novel adjacent-cell interference mitigation schemes [1, 2]. Note that there might exist a fundamental throughput scaling limit in hyper densification due to distinct channel and interference characteristics, growing overhead (e.g., handover) and this is an interesting area for further research.

In addition to massive MIMO and hyper-dense HetSNets, there have been many parallel and independent efforts to attain a higher throughput. Coordinated multipoint transmission and reception (CoMP) [14] and advanced receiver techniques [15] target a higher utilization of spectrum (bits per second per Hertz per cell). Direct communication between mobile stations that enables packets to flow directly to the destination in a single hop (instead of two-hop transmissions via a base station) achieves additional throughput gain [1]. Activities to achieve more unlicensed spectrum and authorized shared access (ASA) improve the data throughput by utilizing more bandwidth (Hertz) [1]. Despite those achievements, any of the single technical advances alone cannot meet the data traffic demand and may not provide a higher gain than hyper-dense HetSNets. Nonetheless, many techniques can be used with hyper-dense HetSNets to provide additional aggregated throughput gain, as illustrated in Fig. 1.

The 1000× Challenge

The projected throughput gains of different enabling technologies are presented in Fig. 4b. Note that the numbers presented in Fig. 4b are rough estimates based on the current status of the technologies. With further technological advances, a higher gain can be achieved. At this point, it seems that it would be hard to reach the 1000× via a single technology.

Despite its roughness in terms of expected throughput at this stage, it has been advocated that the hyper-dense deployment of HetSNets may provide throughput gain up to hundreds [1]. Thanks to the advancements in interference management technologies, the capacity scales with small cells deployed up to certain points. If users are non-uniformly distributed, and more small cells are deployed in areas with higher user density, the gain could be higher. Furthermore, dense deployment makes higher spectrum bands more attractive, while providing sufficient indoor coverage. As more intelligence will be endowed to small cells by better self-organizing and self-optimizing capabilities, and with the catalyst that opens privately owned cells for wider access, the gain of hyper-dense HetSNets may reach a scale of 1000.

Note that the gains in Fig. 4b critically depend on the scenarios and may not be independent. In fact, advances in a certain technology may degrade the performance gain of other techniques. For instance, massive MIMO may improve the system throughput several times but also reduce the gain from the advanced receiver due to significantly reduced interference to mobile users. The aggregated gain of CoMP and advanced receiver is not just a multiplication of two individual gains [15]. Furthermore, the gain achieved by device to device is originated from the strong demands for direct data exchange among users. The amount of gains achieved by more spectrum and ASA depends on the amount of new spectra and the popularity of shared access worldwide. Despite these facts, HetSNets with novel supplementary techniques can address the 1000× challenge. Hyper-dense HetSNets is indeed the key enabler with its promising gain.

Remaining Issues in Hyper-Dense HetSNets

Despite the promising gains, there are some further issues need to be resolved as the densification of HetSNets progresses. Some major issues are listed below.

•Limits of hyper-densification: The fundamental limits of the hyper-densification in HetSNet are not fully understood. Would the reuse of the capacity in hyper-dense HetSNets grow indefinitely as long as the user density grows accordingly? Or would it saturate at some point due to distinct interference characteristics, channel properties, and/or growing overhead (e.g., handover overhead)?

•Guided unplanned deployment/operation: As evidenced in [6, 7], enforcing a certain minimum distance between cells is desirable for better coverage and load balancing. Practical ways of promoting/enforcing minimum distance separation between small cells during an unplanned deployment process or during operation (e.g., by intelligent activation and deactivation [7]) are highly sought for best utilizing hyper-dense HetSNets.

•Novel incentive schemes: Due to the universal coverage of the macro layer, small cell users maintain connectivity even when they are outside the small cell. Therefore, a Fon type of incentive scheme that offers wider coverage may not be a persuasive approach in the hyper-dense HetSNets. Practical incentive schemes and technologies for opening up the privately owned small cells are crucial for successful hyper-densification.

Conclusions

In this article, a holistic view of hyper-dense HetSNets is presented. Among two possible approaches to the future network, massive antenna deployment and densification of small cells, the fundamental preference for hyper-dense HetSNets is shown first. Then the technical challenges in HetSNets are discussed, and the solution to each challenge is provided. The keys of the breakthroughs include intercell interference coordination/mitigation, self-interference cancellation, intelligent self-organizing networks, and advanced mobility management techniques. Several supplementary techniques were then introduced, showing that the 1000× data throughput could be achieved by aggregating those techniques together with hyper-dense HetSNets. As we have presented only a holistic view in this article, more rigorous feasibility and coexistence studies with real-world verifications should follow.

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As more intelligence will be endowed to the small cells by better self-organizing and self-optimizing capabilities, and with the catalyst that opens privately owned cells for a wider access, the gain of hyper-dense HetSNets may reach a scale of a thousand.