Multiple smaller base stations are greener than a single powerful one: Densification of Wireless Cellular Networks

Agrim Gupta, Ish Jain, Dinesh Bharadia
{*agg003,ikjain,dineshb*}*@eng.ucsd.edu*
University of California, San Diego

Abstract

5G and cellular networks would become 1.4% contributors to the carbon footprint, almost on par with 2% of the aviation industry, and is only on the trajectory of further increasing their carbon footprint. Wireless base-stations are one of the major contributors to the operational carbon footprint, as a consequence of transmitting at high power levels to achieve the required communication range and throughput. In order to further keep up with the increasing data rates, and more users getting connected, typical approaches make the existing base stations even more sophisticated, like going to massive MIMO architectures, or mmWave communications, the earlier requiring many more antennas and electronics, and the latter operating at high mmWave frequencies where power amplifiers are difficult to design. Instead, much simpler hardware can be used at lesser transmit power requirements if the base station deployment is densified, with the key idea being that numerous simpler base stations can equivalently do the job of a single sophisticated base station. This dense deployment also ends up saving the power cost of transmitting at higher signal levels, since the smaller base stations need to blast lesser power over the air. The key reason is that this dense network of base stations suffers from less environmental attenuation due to shorter links, thus requiring significantly less power to offset these environmental losses. Further, this densification strategy can be a scalable way of achieving the next generation cellular capacity, where networks can be densified as response to user demand. However, doing so would require addressing numerous challenges and opportunities in designing such networks, articulating the architecture, algorithm, and deployment-level challenges to drive the next decade of research toward greener cellular networks.

1 Introduction

Mass implementation of wireless networks like 4G-LTE has been one of the biggest technological achievements of the past decade, and has revolutionized day-to-day life, as people are always connected to go [1]. This was made possible because of increased reliability, better throughput, and robustness of these wireless networks, almost matching the metrics of equivalent wired networks, at the same time allowing for portable wireless connectivity. However, wireless networks still expend roughly 10 times more energy per bit than wired networks [2], which leads to the wireless industry contributing to 1.5% of the carbon footprint, almost comparable to that of the aviation industry [3, 4].

Wireless base-stations form one of the highest contributor towards the operational carbon footprint of the wireless industry. These base-stations consume a lot of power to transmit signals at sufficiently high power in order to reach far-located clients, as well as in setting up multiple antenna hardware for MIMO, to handle the interference caused by multiple simultaneously communicating clients. Both these problems are unique to wireless networks, as with wired networks communicating over cables has lesser attenuation and multiple users do not typically share the cables. With the next-generation wireless networks, in order to connect more and more devices, are, in fact, the base station are made more sophisticated by requiring even higher number of antennas for massive MIMO, or going to higher mmWave frequency bands to get more spectrum. This increased sophistication leads to higher power bills, with Massive MIMO ends requiring to run hardware for massive number of antennas [5–7], and at high mmWave frequencies, the RF hardware becomes highly lossy and inefficient [8–11].

Hence, the need of the hour is to somehow meet the increased bit-rate and user scalability demands in a sustainable manner. One insight could be to not further sophisticate the base-stations further, and instead use very simple hardware at low transmit level, but use a lot more of these simpler base stations to do the job of a more sophisticated single base station. Increasing the number of base stations would allow connecting more users, as well as improve the overall throughput metrics by dedicating the base station to particular users which would reduce contention across multiple users connected to a single base station. A natural question is that though individually each of these smaller base stations consume less power, wont the total power consumption summed across this network of smaller base stations be comparable, or more than the single base station? However, our key insight is that this densification actually comes at lower power costs, since the smaller base stations end up saving much more power due to communicating at lower transmit levels, than the increased power consumption as a result of operating these multiple base stations.

Fundamentally, the reason why denser base-station deployments end up saving on power consumption lies deep-rooted in how wireless signals actually propagate in real-world scenarios. Wireless signals ideally die out in strength as they travel R distance as R^2 in line of sight (LOS) settings. However, in realistic urban settings with buildings/trees and other objects, which makes the problem non-LOS (nLOS), the statistical data fitting show the signals dying out as R^3 instead of R^2. That is, the path loss towards the edge of cellular coverage becomes insanely large due to R^3 dying out statistics [12–15], with a user located at the coverage edge ($r = R$) would spend 8 times more power than a user located at the mid-way ($r = R/2$). Hence, it makes sense to densify the base station deployments such that the overall distances between base stations and users decrease and wireless networks don't overburden the power amplifiers at base stations into compensating for extreme path losses due to the complex environment of operation.

From a deployment viewpoint, as base stations densify, there are both incredible opportunities and unique challenges. Due to base station densification, these will serve a lesser number of users per base station. As a consequence, these smaller base stations would require a lesser number of antennas or less bandwidth requirements than traditional base stations. However, at the same time, a challenge would be to create efficient data backhauling and decoding strategies for these smaller base stations. For instance, although the denser base stations would handle a fewer number of users, the number of handoffs will be higher since the users will be much more mobile and going to-and-fro base stations than what a traditional base station serving a larger area would see, which would end up requiring a fast, efficient coordination between these multiple base stations. In addition, managing and coming up with these many smaller base stations would be a challenge, as it is going to be difficult to manage 100s of base stations scattered around than a centralized single base station. However, this can be made easier via incentivized benefits to the public and maintaining a neighborhood wireless base station by individuals can be promoted similar to the latest trends with Helium LoRa network [16–18].

Hence, in this short paper, we first discuss how base station densification reduces the power consumption in wireless networks by bringing base stations and devices closer. Then we discuss the deployment challenges, opportunities, and incentives for the dense base station paradigm and draw some conclusions about our insights.

2 How base station densification saves transmit power

In typical LTE macro base-stations, power amplifiers generating the required transmitted signal levels to reach far-off clients make up to more than 50% of the power consumption (Fig. 1). To show how base station densification can reduce these transmit power requirements immensely, we consider a simple example shown in Fig. 2(a). Here, The red base station is serving an area with radius R whereas the 4 smaller base stations serve area with half the radius $R/2$. Usually, the wireless signal path loss (PL) depends on the propagation distance d and frequency f and typically can be simplified into the following form, $PL(d,f) = \frac{K}{f^2 d^\gamma}$ with γ being the path loss exponent and K being a constant.

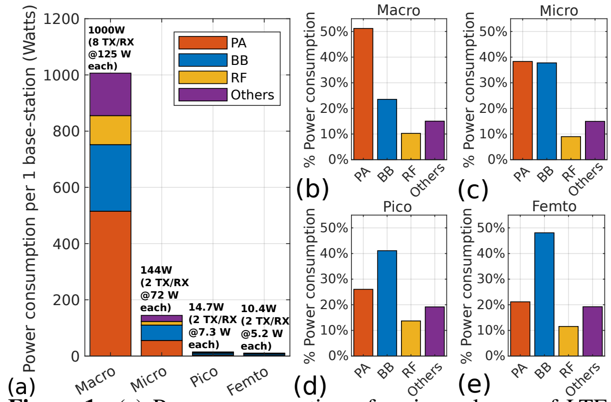

Figure 1: (a) Power consumption of various classes of LTE base stations per consumption category with PA denoting power consumed by power amplifier for transmit signal level, BB denoting power consumed by baseband processing, RF denotes RF circuits power consumption and others denote cooling and mains power consumption for mechanical aspect of base station, (b-e) shows the percentage contribution of each category for macro-micro-pico-femto base station.

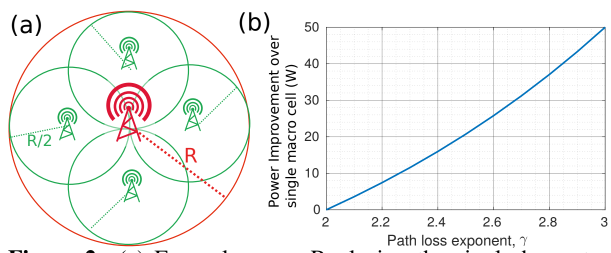

Figure 2: (a) Example case: Replacing the single base station (red) serving R distance coverage into 4 smaller base stations (green) serving $R/2$ each (b) As path loss exponent increases, densification leads to power savings due to lower transmit power requirements

Hence, the red base station would face path loss of $PL_R = \frac{K}{f^2 R^\gamma}$ in the worst case, whereas for the four smaller green base stations, the path loss would be $PL_G = \frac{K}{f^2 (R/2)^\gamma} = (PL_R)2^\gamma$. Hence, to maintain the same received power at user devices, the green base station can transmit at $2^{-\gamma}$ lesser power than the red base station. Thus, the total power expended by the 4 greener base stations would be $2^{2-\gamma}$ that of the single red base-station,

$$\frac{P_{tx}^R}{P_{tx}^G} = 2^{-\gamma}4 = 2^{\gamma-2}$$

The path loss exponent γ is always >2, with free space

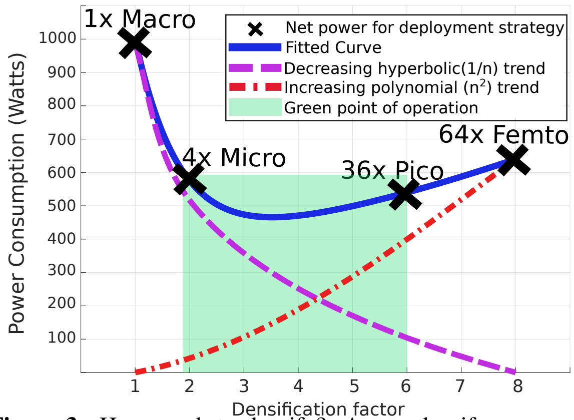

Figure 3: How much to densify? As we densify more and more the power reduction effect saturates, and infact going more denser the other power components start dominating

LOS channels with no buildings/trees etc having $\gamma \approx 2$, however in typical urban nLOS setting $\gamma \approx 3$, depending on the density of urban setting and other environmental clutters [12–15]. Thus in a LOS setting with $\gamma = 2$, the four smaller green base stations would transmit the same amount of power as the red base station, however as $\gamma \to 3$, due to higher scaling of path losses, the 4 smaller base stations would infact expend 2x lower power combinedly than the single red base station. This is because with $\gamma = 3$ the PL trends are favorable towards smaller distances and the cubic losses due to covering higher distances amount to higher transmit powers and hence more burden on the PAs. The total power saving due to the toy example densification of $R/2$ as shown in Fig. 2 (a) as γ varies is shown in Fig. 2 (b).

Generalizing it to smaller radius than R/n, where $n = 2, 3, 4, \ldots$, we infact get the ratio of powers to be $\frac{P^R_{tx}}{P^G_{tx}} = n^\gamma/n^2 = n^{\gamma-2}$. Hence, we can keep splitting the radius and densify the base station deployment in order to relax the transmit power requirements further and further. However, this assumes that the power calculations are dominated by the PA transmitted power. In addition to PA power, there is power spent in ADCs/DACs, and up/downconversion at the receiver. Hence, to identify the green point of densification requires careful analysis of the total power consumed at a base station.

3 LTE case-study, how much to densify?

Having shown how densifying base-station deployments can relax the transmit power requirements substantially, we now show a case study to evaluate where this relaxation breaks down and what is the green point of densification we need to target.

We take the power consumption metrics reported for a single macro/micro/pico/femto base-station [19] and evaluate the total power used across the network of smaller base stations required to replace a single macro base station. The total power follows the trend shown in Fig. 3. Basically, we get summation of an $1/n$ decreasing trend and a n^2 increasing trend. The $1/n$ decreasing trend is explained via the transmit power calculations, from the red-green toy base station example earlier, as we densify with n^2 base stations to replace a single macro base stations, the net power required is $n^{2-\gamma}$ times that of macro base station, hence a decays of K_1/n if $\gamma = 3$, where K_1 is the transmit power of a macro base station. However, due to densification, the other power components, like basic baseband processing, RF front end power consumption doesn't get relaxed, as each smaller base station still needs to perform the required signal processing to decode users' data. Hence, there is an increasing trend of $K_2 n^2$, where K_2 is the minimal power required to do basic tasks at each smaller base station. Clearly $K_1 >> K_2$, and hence, the effects of the increasing trend start showing up as we densify more and more, where the n^2 term starts dominating the power calculations.

Hence, this shows the presence of a green point of densification, beyond which is not beneficial to densify more and more. This is because densifying further gives diminishing returns on transmit power, but you need to invest more power in just operating these numerous base stations. From the available data on power calculations of typical LTE base stations, we can see that this green point occurs between micro and pico base stations, and from femto onwards the power requirements infact start showing upward trends. The calculation of total power requirements follows similar steps as our red-green base station toy example, where we compare the maximum tranmsit power of these 4 levels of base station to calculate the ratio of areas covered as compared to macro base station, and then use this to calculate how many smaller base stations would be required and finally multiply this number with the net power consumption.

The numbers for power consumption for various levels of LTE base stations are taken from [19]. LTE macro base-station with 8 TX-RX chains consumes about 1000 W power, leading to 125 W energy per antenna [20] to transmit at $43-46$dbm power and 10-20 MHz bandwidth. Power amplifier consists of about 50% of this power (64 W), with next major component being the baseband processing amounting to 24% (30W), and then the power consumed in the RF hardware being 10% and the rest 16% is from cooling hardware, DC-DC power conversion inefficiencies etc. Comparatively, a LTE micro base-station, consumes about 72 W energy per antenna, to transmit at about 8 times lower power, $37-38$dbm, and similar $10-20$ MHz bandwidth. Note that, as a consequence of having 8 times lesser transmit power requirements, the PA power consumption reduce from 64W to 27W, however, the baseband processing power requirements remain similar to macro level, decreasing only slightly from 29 W to 27W. Since micro base stations transmit 8 times lesser power, with $\gamma = 3$ they would cover 2 times lower distance. Hence, we would need $2^2 = 4$ such base stations to cover the area similar to the macro base station with the net power requirements would be $4 * 2 * 72$ W to get similar 8 multiplicity, with 2 RF chains per micro base station and 4 such base stations, which amounts to $576W$ power, much lesser than the 1000 W power consumption of the macro base station.

Processing similarly for pico/femto base stations, we see, that pico/femto base stations with TX power 21, 17 dBm respectively, that is about 160, 400 times lower. Hence, pico base station would cover a radius of $R/160^{1/3} = R/5.5 \approx R/6$, that is, it would require $6^2 = 36$ such pico base stations, whereas, femto base station would cover $r/400^{1/3} = R/7.37 \approx R/8$, that is would require $8^2 = 64$ such base stations. Today, the pico/femto base stations consume about $15/10$ W respectively, and hence the total requirements for pico deployment would be $15 * 36 = 540$ and for femto it would be $10 * 64 = 640$W. Clearly, beyond the pico-level, the costs of operating these n^2 smaller base stations would start outweighing the diminishing benefits available from densification. Also as a consequence of densification, the setting would become more LOS which would make $\gamma \to 2$ and then the net available gains will start to flatten even more. However, this example of splitting the radius more and more to densify the base stations show how such simple strategies can be used to address the transmit power problem in urban non-LOS settings.

4 Challenges and open problems

Till now, we have seen how densifying the base station deployment helps reduce the transmit powers and thus addresses the operational carbon footprint challenge of the wireless industry. However, it comes with several challenges and opportunities to create a highly optimized sustainable network of small base stations. We divide the challenges into three categories, RF architectural challenges to build highly efficient small base stations, algorithmic challenges to manage the base station network and deployment challenges behind actual operation of these 100s of base stations.

4.1 Architecture & Hardware challenges:

As we add smaller base stations to reduce the transmit power requirements, it opens up new low-power operation point of PAs, as well as opportunities to design efficient RF circuits. Optimizing the power consumption at circuit level would shift the green point further to more denser deployments, since the power lost in circuits get multiplied by the 100s of base stations deployed.

Design low-power PA with high efficiencies In macro base stations, the PAs have very high transmit power requirements which tend to introduce non-linearities. Therefore, PAs are designed to operate in a back-off region, where the response is more linear, however, this is not optimal from an energy efficiency point of view. Hence, till now, PA requirements have kept on just increasing, and as a consequence PAs have to operate in back-off regions and artificially reduce their output powers to keep linearity. However, as the PA's net output power requirements lower with densification, there would be a unique opportunity to operate them at high efficiency, as well as linear regimes.

Direction for optimizing RF circuits energy efficiency: As clearly seen from Fig. 1 (b)-(e), the power consumption of interfacing electronics and baseband processing starts dominating the power calculations for smaller base-stations as compared to a macro base station. Till now, as the PA used to dominate the power consumption metrics, optimization of RF circuits did not garner much research effort. However, with smaller base stations, highly power efficient RF circuits would create incentives to densify more and more by reducing the fixed circuits cost which is paid per small base station.

4.2 Algorithms & Compute challenges

A network of smaller base-stations if managed well can improve the user experience since typically in single base-station network there is a lot of contention amongst its users. With densification, users can now multiple base-stations around them, and the base-stations can collaborate among themselves to handle the massive challenges of handover management, inter-user interference, improvement of data rates via collaborative decoding amongst base-stations, as well as on-demand flexible softwarized control over smaller base-stations depending on user traffic.

Managing fast and frequent handovers: A mobile user in a small cell deployment has a higher chance of switching from one base station to another, and fairly quickly as well, causing a handover between two base stations frequently. Typical handover is a hard and cumbersome process where the entire state of the user's connection has to be migrated from one base station to another so that the higher TCP and application layers don't get interrupted in this process [21,22]. However, it is also more likely that the user is in the coverage range of multiple spatially close base stations at a time due to small cells. Thus, akin to content caching mechanisms, handover mechanisms can maintain shared states between spatially close base stations to aid the handover process.

Handling inter-user interference: As cell size shrinks further, the users can receive and transmit to multiple base stations in the vicinity. If the base stations are sharing spectrum resources, then they would cause severe interference to each other. For instance, the base station would receive signals from both its intended user and many other unintended users in its vicinity that are causing interference to the data of the intended user. However, there exist various techniques which can aid this challenge, for example, interference alignment techniques [23], or using constellations smartly such that far-off users causing interference get mapped to different constellation points [24].

Collaborative decoding at base stations: As base-stations densify, there would be more overlapping regions. It means that more than one base station could hear the user's signal and can cooperate opportunistically to improve the user's data rates [25]. Each base station can partially decode the user's data packet and assign a confidence value in their decoded bits. Multiple base stations can combine their data at the switch or the router connecting the base stations and jointly improve the decoding performance [26, 27].

Flexible Densification: By efficient software control over this vast network of small base stations, the network can be densified 'on-demand'. That is, if there are less users in an area, some base stations can be selectively turned off to prevent wastage of power. However, this would require active sensing of users' spatial location, and this is already part of 5G [28, 29], as well as older wireless networks like LTE [30]. In addition to localization, the flexible densification would also require softwarized control over these many base-stations as well as a scalable management system of same at a central node orchestrating the network.

4.3 Deployment Challenges

Finally, apart from the architectural and algorithmic challenges, there would be key deployment challenges which would need to be addressed. For example, such vast network of base stations would require social incentivisation, multiple verticals of society to accept and maintain these base stations. Further, it would require efficient silicon and energy management since this network of base stations would require a lot of electronics and a significant amount of distributed power, which needs to be handled in a sustainable and renewable manner.

How to deploy small cell base stations: With small cells comes many base stations that need to be deployed with a high density in a geographical area. A natural question is where and how the base stations can be deployed? Deploying on public infrastructures such as community buildings, lampposts, and parking lots would require bureaucratic Governmental procedures to procure these areas for base station deployment. And still, a large residential area would be left out where there is no or little public infrastructure. Another idea is to incentivize residential users to deploy a base station at their home or roof-top. We have already seen the success story of Helium networks for LoRaLAN (Long Range Local Area Network), one of the largest open-source networks for connecting IoT devices. The incentive of deploying 4G wireless RAN is in terms of mining the Helium cryptocurrency based on some notion of their RAN coverage [18]. Similar incentives can be used for small cell base stations. This small cell network will benefit from cable backhaul at every residence.

Optimize energy-per-bit through incentives: There are many ways a small cell network can optimize energy-per-bit with different degrees of optimization in different situations, such as low or high network load or based on the density of deployment. To understand the design trade-offs in different situations, it is required to monitor the energy consumed per bit and take appropriate action to optimize the trade-off. The energy-per-bit can be monitored at the edge and can be used to incentivize users to reduce the carbon footprint in their base stations, similar to how Helium [18] incentivizes based on coverage.

Explore renewable source of energy and electronics for small cell base stations: Small cell base station consumes less power and can be installed in a large residential area by providing some incentives to residents. These base stations can further use renewable sources of energy such as solar-powered to reduce the carbon footprint in wireless technology [31]. With low energy requirements at the base station, a solar-powered base station is an attractive solution in most geographic locations. Although the energy demands of this network of base stations are relaxed, putting so many base stations would require a large number of electronics, which can potentially create e-waste if not managed properly. Hence, this silicon management with the network of base stations would be as important of a challenge.

5 Conclusion and Discussion

In this short paper, we show how base-station densification can be a possible approach to create sustainable wireless networks which scale well with number of users. The key insight is that instead of relying on a single sophisticated base station expending power to reach far-off clients, the same job can be done more flexibly and with lower power via multiple smaller base stations with simpler hardware and transmitting at reduced signal levels. However, there exists a green point of densification, beyond which there are diminishing returns on power savings and the net power starts scaling up just as a consequence of managing more and more number of base stations. We show this green point of operation lying between micro and pico cells in existing LTE base stations via a case study. Further, we delineate the hardware, software and deployment level challenges and opportunities going ahead with this idea of reducing power consumption via base station densification.

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