Evolving mobile networks towards 5G. A framework to infer the state of connectivity infrastructure in dense urban areas.

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Abstract

Despite the growing trend towards the use of big data methodologies, the application of such techniques to inform telecommunications policy is still relatively limited. Although the deployment of mobile broadband networks is primarily driven by market forces, policy-makers and governments play an important role, particularly with regards to spectrum allocation and regulation. However, decision-makers usually lack data-driven insights to guide these processes.

In this paper we propose a methodology to (i) infer the state of connectivity infrastructure and (ii) understand how Mobile Network Operators (MNOs) have combined spectrum resources and network densification to deploy 4G services. The methodology draws on crowdsourced data from a mobile app, including received signal power (RSRP) and received signal quality (RSRQ).

Using UK data from 2017, we apply this method to Greater London to illustrate the capabilities of the framework. The results suggest that mobile broadband networks are only capacity-constrained in dense urban areas with MNOs adopting different strategies to deal with network congestion. *MNO1* and *MNO3* rely on larger spectrum portfolios, while *MNO2* and *MNO4* depend more on network densification. Interestingly, MNOs sharing the same capacity-expansion strategy do not necessarily share sites nor have spectrum on similar frequencies.

We also find that in suburban areas mobile networks are still primarily coverage-constrained, where data suggests MNOs have favoured lower frequency spectrum, while avoiding the deployment of higher frequencies for cost reasons. The implications of these findings are discussed with regard to the roll-out of 5G networks.

1 Introduction

Ubiquitous and high-capacity connectivity has been recognised as pivotal for economic and social development. Many of the enabling technologies upon which we are pinning our hopes for solving major national and global challenges, such as the Internet of Things or Industry 4.0, depend on reliable capacity and coverage from wireless networks.

The first standardisation efforts of 5G culminated in the Release 15 of the 3GPP, frozen by mid-2018, which allows both Non-Standalone (NSA) and Standalone (SA) modes for enhanced Mobile Broadband (eMBB) services. While NSA will require using some specific functions of 4G networks to work properly, SA equipment can be deployed on greenfield scenarios. The Release 16, expected by the end of this year, will assist the development of new use cases, including Ultra-Reliable and Low Latency (URLL) communications (3GPP, 2019).

Regardless of the operating mode (NSA or SA) and use case for the 5G network, in developed countries this new digital infrastructure will be built on top of existing assets, such as macrocellular sites or fibre cables (Oughton et al., 2019). In addition, the deployment strategies developed by Mobile Network Operators (MNOs) will be highly conditioned by the strategies that they have followed with the previous generation, including their existing sites, spectrum portfolios and infrastructure sharing agreements.

There is extensive literature on the technical aspects of 5G, and the targeted technology evolution is well understood within the standardisation community (see, for example, Andrews et al. (2014)). However, there is limited knowledge and understanding of the roll-out of 5G infrastructure, the extent to which legacy networks might condition the deployments, and the related policy ramifications.

There have been a few recent analyses of 5G deployment. For example, Wisely et al. (2018) undertake a techno-economic analysis of the deployment of 5G for enhanced Mobile Broadband (eMBB) in the area of Central London. The authors model different network densities at 700 MHz, 3.5 GHz and $24-27.5$ GHz and test several deployment options to assess both capacity and cost. The work concludes that the cost of massive increases in capacity (in excess of 100 Gbps/km2) will require investments 4 to 5 times higher than LTE roll-out.

Oughton & Frias (2018) also undertake an analysis of the cost, coverage and roll-out implications of 5G infrastructure in Britain under different demand scenarios (up to 50 Mbps per user) and deployment capital intensities (ranging £$1.5-2.5$ billion). The authors conclude that for the business-as-usual scenario, 90% of the population is highly likely to be covered with 5G by 2027, although deployments would be unlikely to reach the final 10% due to exponentially increasing costs.

Finally, Schneir et al. (2019) assess the business case for 5G mobile broadband in three boroughs of central London for the period 2020-2030. The results of this study suggest that there is a positive business case for 5G eMBB (10 Mbps with 95% availability), although the results are very sensitive to traffic growth.

All the studies referred to above lack accurate and scalable input data on the state of existing infrastructure. Yet this information is crucial for both academics and policy-makers to gain valuable insights on the deployment of wireless networks.

We still have a limited number of examples of where big data methodologies have been applied to help inform public policy, particularly with regard to telecommunications. This is surprising given the importance of decisions in this sector, as they can affect spectrum allocation, regulation and ultimately the roll-out of mobile broadband services.

As MNOs begin to deploy the fifth generation of mobile communications technologies, there is an opportunity to use crowdsourced data to further investigate past roll-out strategies, including how sunk costs may affect future deployment. These insights can guide governments and policy-makers in their decisions towards the roll-out of 5G.

The objective of this paper is to assess the extent to which it is possible to infer the state of connectivity infrastructure and the deployment strategies using crowdsourced measurements. Specifically, we address the following four research questions:

1. How much information about the existing network infrastructure can we extract from crowdsourced mobile measurements?
2. What are MNOs' deployment strategies in current networks?
3. What incentives do they have to deploy 5G? What strategies might they follow?
4. What are the ramifications for policy-makers and regulators?

Using crowdsourced measurements from a popular mobile app, we utilise the received power strength (RSRP, *Reference Signal Received Power*) and the received quality (RSRQ, *Reference Signal Received Quality*) of LTE mobile signals for the four MNOs in the Greater London area. This region provides a very high number of data records, with very comprehensive coverage, providing unique insight into the quality of service experienced by users.

The paper is consequently structured as follows. Section 2 presents the theoretical background and related work on mobile network deployment strategies and infrastructure inference using crowdsourced measurements. Section 3 describes the methodology for the geographic classification of the data, collected variables, and scenarios. Section 4 shows the results and Section 5 discusses the policy implications towards the deployment of 5G. Finally, Section 6 concludes the paper.

2 Theoretical background and related work

This Section discusses the theoretical background of capacity-expansion strategies in wireless networks (2.1) and presents the existing work based on crowdsourced measurements that relates to this research (2.2).

2.1 Capacity-expansion strategies in mobile networks

The growing demand for mobile broadband services has dramatically increased the traffic in mobile networks over the last decades. Expanding network capacity has historically been addressed via three network expansion techniques including (i) densifying the network, (ii) increasing available spectrum for mobile and/or (iii) using more advanced technologies with higher spectral efficiencies.

With 4G deployment, all these options have been utilised to cope with exponentially increasing traffic demand. For example, LTE technologies provided a $3.12\times$ spectral efficiency improvement over the previous generation[1] (Real Wireless, 2012). While the contribution of new spectrum bands for mobile use has been approximately $2\times$ over the past decade (Frias et al., 2017), network densification has at least contributed to a factor 4 [2]. However, MNOs rely on capacity-expansion strategies to different extents, depending on several factors, such as market share, spectrum portfolio or the convenience of passive infrastructure sharing agreements.

As indicated above, network densification has historically contributed to enhancing network performance to the largest extent, as it, in turn, allows for further reuse of limited spectrum resources. However, despite delivering immediate capacity gains, it also presents several challenges. As network throughput depends on the Signal to Interference and Noise Ratio (SINR), rather than on the received power, interference reduction is key to expedite network throughput, not only on average but particularly for the cell-edge users. Larew et al. (2013) showed that, in a plausible grid-based urban deployment, the base station count could be increased in a given area from 36 to 96, decreasing the inter-basestation distance from 170 meters to 85. This increased the cell-edge rate from 25 Mbps to 1.3 Gbps. Moreover, Shah et al. (2019) tested system performance in Ultra Dense Multi-Tier cellular networks, with the results suggesting high dependency of the system capacity, spectral and energy efficiency on the SINR, channel densification and cell load.

The challenges for the deployment of Ultra-Dense Networks (UDN) are not purely technical. As more base stations are delivered, there is a practical geographic constraint on the placement of new base stations. This scenario was explored by Gruber (2016), who evaluated the scalability issue by simulating different user distributions, street widths and antenna beam widths and how they affected the maximum average user throughput. Finally, network densification faces important challenges from an economic perspective, as ever more infrastructure needs to be placed, while many MNOs in advanced nations are experiencing static or declining revenue growth.

Inversely, capacity-expansion strategies based on additional spectrum resources do not have the problem of the physical constraints of site placement, as the new spectrum is typically integrated into the existing network with the addition of a new carrier module to the existing base station or a new Base Station (BS) into an existing site. Such an upgrade option also makes this alternative highly cost-efficient, as it allows the reuse of existing sunk costs, particularly physical infrastructure and backhaul fibre.

[1] Comparing LTE Rel-9 to HSPA Rel-5.

[2] We could not estimate this contribution for the UK, since Ofcom stopped maintaining the base stations database (Sitefinder). Instead, we have used the data from the Spanish regulator (CNMC). In Spain, there were 27,382 UMTS base stations in 2008. In 2018, the sum of UMTS and LTE stations reached 106,753.

However, spectrum is not an asset that can currently be acquired on-demand [3]. Generally, the acquisition of new licensed spectrum is a slow and tedious process. The new spectrum bands can take years to identify and release, and the allocation is made though controlled competitive processes in which, often, policy-makers pursue market balances.

Additionally, not all spectrum bands have the same propagation properties, with lower bands typically showing better propagation characteristics for building penetration and non-line-of-sight situations, whereas higher frequencies often provide more bandwidth. Indeed, MNOs may perceive different capacity gains for the same spectrum depending on their previous spectrum portfolio (Frias et al., 2017).

2.2 Related work

Gathering measurements on the performance of the deployed mobile infrastructure used to require extensive and time-consuming measurements campaigns. However, as smartphones have become comprehensive platforms for data collection through open Application Programming Interfaces (APIs), it has become feasible to collect large datasets of measurements, including data on the performance of mobile networks.

The processing of crowdsourced mobile measurements and traces[4] has opened new research horizons and allows researchers to address questions that had remained unsolved or unexplored previously. The disciplines that have begun to use crowdsourced traces for research are very diverse and range from urban planning to business development or public policies (see, for example, the literature review presented by Steenbruggen et al. (2015)).

In the field of telecommunications infrastructure research, several studies have already provided relevant insights leveraging crowdsourced traces, although they have not been used to inform policy. For instance, Cainey et al. (2014) present a model that captures the relationship between the download throughput of LTE networks and other network variables, such as signal quality, signal strength, time and mobile operator. They conclude that signal strength is not the best predictor for user download speed in LTE networks, being the throughput more correlated with signal quality.

Malandrino et al. (2016) investigate the initial deployment strategies of LTE networks for the operators in Boston and Brooklyn using crowdsourced measurements. The authors' found that in November 2014, contrary to intuition, LTE deployments were driven by improved coverage rather than enhanced network capacity.

Koutroumpis & Leiponen (2016) investigate the relationship between mobile coverage and social and economic factors in the United States using crowdsourced data. The authors found out that average income, population, geography and education are the main drivers for mobile coverage. Not surprisingly, low-income regions are found to receive 15% less coverage compared to their affluent counterparts.

[3] It is worth noting that real-time spectrum auctioning based on distributed ledger technology is starting to be analysed (Weiss et al., 2019).

[4] We call trace a set of mobile measurements where the devices can be tracked.

Malandrino et al. (2017b) use large-scale traces to compare the performance of different 5G caching architectures in mobile edge computing on vehicular traffic demand and study how such performance is influenced by recommendation systems and content locality. The analysis was undertaken using 81 million records in the San Francisco Bay area in October 2015. Their findings suggest that mobile-edge caching provides relevant benefits for vehicular networks.

Malandrino et al. (2017a) present a highly aggregated methodology to assess the extent to which current networks could cope with future traffic demand in the city of San Francisco, and the effectiveness of the existing strategies[5] to improve network capacity. Their findings suggested that LTE networks in San Francisco would still need substantial capacity improvements to face the load increase forecasted for 2020, which is not surprising given that meeting demand is a moving target.

3 Method

We use crowdsourced measurements gather from the Opensignal mobile app collected in February 2017 in the UK. As different areas may show heterogeneous propagation environments and traffic demand, deployment strategies may differ. Therefore, we classify the areas into different geotypes in Section 3.1, before presenting the spectrum allocation porfolios of the four UK operators in Section 3.2. We also review briefly the evolution of the spectrum management framework to justify the assumptions on the spectrum bands that are currently being used for 4G. Finally, Section 3.3 describes the variables that we use in the crowdsourced dataset and how we process them, and Section 4.

3.1 Geotypes

We constrain our analysis to the area of Greater London as there is substantial data available covering this geography. However, we use a national classification previously used by Mason (2008) in which British postcode sectors are categorised into seven geotypes. The seven geotypes are categorized based on a minimum population density as per the division presented in Table 1, where the bottom geotype aligns with the 90th population percentile for coverage purposes. Having classified the postcode sectors following this method, we then extract the units for Greater London.

Figure 1 shows the resulting spatial distribution of geotypes in the postcode sectors of Greater London. As it may be noticed, most of the sectors belong to geotypes 1 to 3, with 4 being only present in outer areas. Expectedly, the distribution of measurements across geotypes is not homogeneous, with most of the crowdsourced measurements having been taken in the densest areas.

Table 2 shows the distribution of measurements across geotypes. As geotypes 4 and 5 comprised only 3.3% and 0.2% of the samples, respectively, they were excluded from the analysis as results are not necessarily statistically representative.

[5]The strategies include deploying MIMO basestations, refarming 10 MHz spectrum, introducing Coordinated Multipoint (CoMP) technologies and using Almost-Blak subframe (ABS) techniques.

Geotype	Min pop density (people/km^2)
Geotype 1	7,959
Geotype 2	3,119
Geotype 3	782
Geotype 4	112
Geotype 5	47
Geotype 6	25
Geotype 7	0

Table 1: Geotype classification used. Source: authors based on Mason (2008)

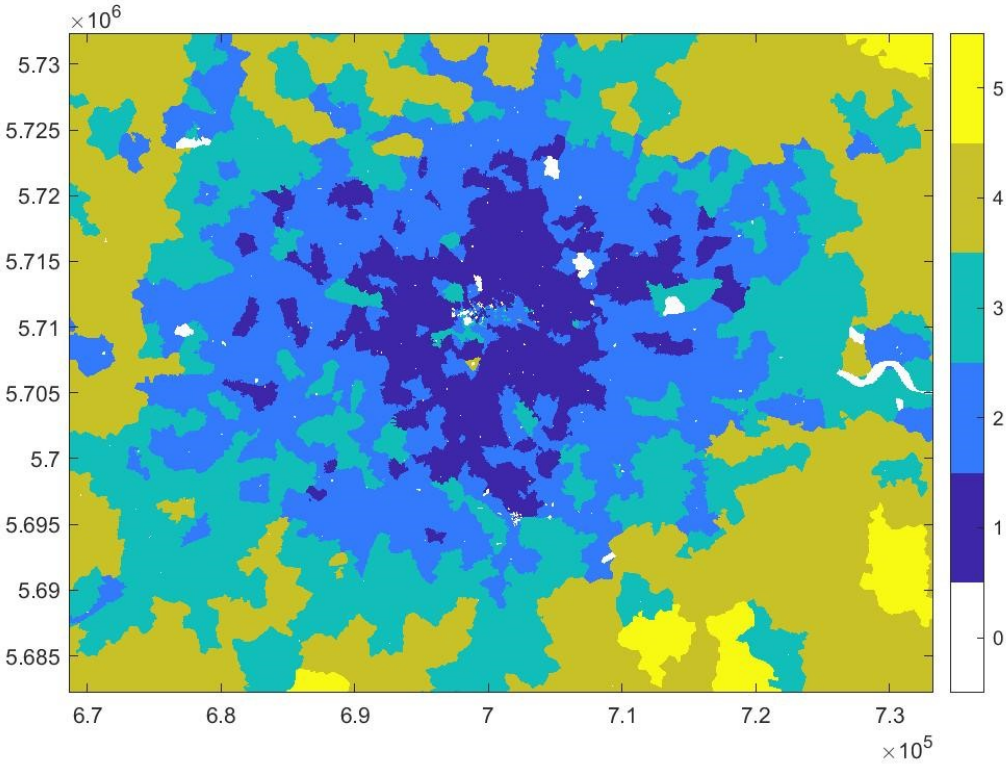


Figure 1: Spatial distribution of the geotypes in the Greater London area.

Geotype	Number of measurements	Proportion
Geotype 1	5,913,025	37.8%
Geotype 2	6,663,844	42.5%
Geotype 3	2,327,790	14.9%
Geotype 4	520,266	3.3%
Geotype 5	28,807	0.2%
Total	15,453,732	100%

Table 2: Number and proportion of measurements per geotype.

3.2 The mobile market and spectrum allocation in the UK

In terms of revenues and number of subscribers, the UK mobile sector is one of the largest in Europe. MNOs with major market shares include *MNO1* (21%), *MNO2* (26%), *MNO3* (28%), and *MNO4* (12%) (Statista, 2018). Other Mobile Virtual Network Operators (MVNOs) comprise the remaining 13%, mainly offering alternative low-cost offers. Currently, 2G, 3G, and 4G technologies are in operation across the UK by all operators although 4G roll-out is yet to cover some rural areas. Although premises coverage of both 3G and 4G is over 70%, geographic coverage lags behind with 4G at approximately 40% of UK landmass (Oughton et al., 2018).

The UK makes an interesting case study because, unlike other countries in Europe, the distribution of spectrum across network operators is very asymmetric. While *MNO1* and *MNO2* have usage rights in low-frequency bands, *MNO3* and *MNO4* primarily rely on high-frequency spectrum. Additionally, for some of their sites, *MNO1* and *MNO2* share a network of passive infrastructure under the joint venture *Cornerstone* (CTIL). Likewise, *MNO3* and *MNO4* have a similar sharing agreement through the joint venture *Mobile Broadband Network Limited* (MBNL). These asymmetries in the configuration of spectrum resources provide an interesting case to study how different MNOs have developed deployment strategies to expand network capacity.

Like in all European countries, in the UK, LTE networks were primarily introduced using the harmonized bands of 800 MHz and 2600 MHz, where no previous mobile services had been deployed. These bands were allocated to MNOs through a joint auction in 2013 by Ofcom (2013). The allocation of frequencies resulting from the competitive process is illustrated in Figure 2. It is worth noting that the block of 2×10 MHz acquired by *MNO2* was the only one with a coverage obligation, which might have conditioned their deployment strategy.

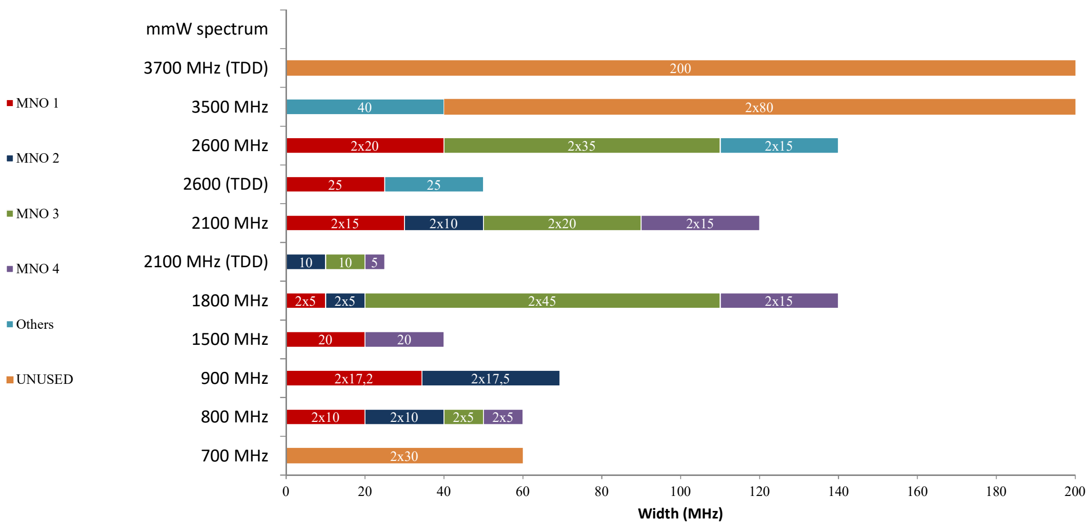


Figure 2: Spectrum distribution across MNOs in the UK.

The GSM legacy bands of 900 MHz and 1800 MHz were also soon available for LTE deployments in the UK. These bands, as per the *GSM Directive* (ECC, 1987) could only be used to deploy GSM technology until the repeal of this norm in 2009 by the European Parliament (2009). The authorization process to deploy technologies other than GSM in these bands was undertaken along with a spectrum reallocation aiming to safeguard competition and ensure fair access to spectrum resources. These redistribution processes were known as *refarming*.

The UK regulator permitted the use of UMTS technology in 900 MHz and 1800 MHz bands since January 2011 and September 2012, respectively, following *MNO3* request to included 4G networks in the allowed technologies in the refarmed bands. *MNO4* was also allowed to deploy the 4G network from September 2013 using the 2x15MHz that were divested from *MNO3* as a result of the refarming processes. Although all bands are now technology neutral, 2100 MHz is still used for 3G services, as this is the spectrum band in which they were originally deployed.

The World Radiocommunications Conference 2015 (WRC-15) identified several spectrum bands that have subsequently been harmonised, including 700 MHz, 1.5 GHz and 3.4 – 3.6 GHz[6] (Manero, 2016). At the moment, governments have already allocated a portion of this spectrum. In the UK, the 3.4 -3.6 GHz band was auctioned in April 2018 along with the 2.3 GHz spectrum harmonised in Europe. The bands of 700 MHz and 3.6 – 3.8 GHz are still to be auctioned. Ofcom closed the public consultation on the award of these bands in March 2019 and the process is expected to take place in 2020.

Finally, MNOs will be able to acquire mmW frequencies in the mid-run. Different portions of spectrum in the range between 24 GHz and 86 GHz have already been identified to conduct compatibility studies by the ITU-R so that their potential use for 5G networks can be further discussed in the next WRC, in November 2019. Although mmW signals experience orders-of-magnitude more path loss than the microwave signals currently used in most wireless systems, they have the potential to offer multi-gigabit-per-second data rates at a lower cost than previous technologies (El Ayach et al., 2014) (Murdock et al., 2012).

3.3 Network measurements variables

For this research, we have only used three network measurements at the User Equipment (UE): Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) and the extended Cell Global Identity (eCGI) of the BS to which the UE is attached.

The Cell-specific Reference Signals (CRS) in LTE are signals that are broadcasted by the BSs on certain times and frequencies, as illustrated in Figure 3. They are used by the UE to estimate the channel characteristics and demodulate the information signals (Dahlman et al., 2014).

The RSRP measures the received power from the Reference Signal on a 15-kHz bandwidth. It is a direct measurement, typically provided in dBm. Table 3 shows the RSRP values that the UE reports to the BS

[6] Note that technically, the 700MHz band had been identified at WRC-2012, but it was confirmed at WRC-15. Also, the 1.5 GHz band (1,427-1,518 MHz) was globally allocated to IMT, although the 1452-1492 MHz portion had already been harmonized for Supplementary Downlink (SDL) in Region 1.

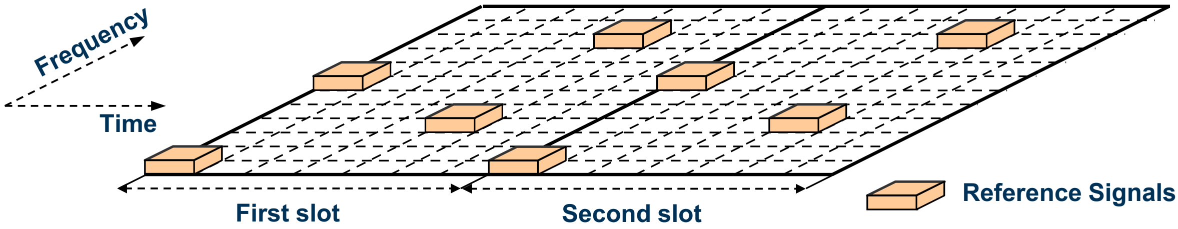


Figure 3: Illustration of the Cell-specific Reference Signals in an LTE network. Source: based on Dahlman et al. (2014)

according to the measurement. The maximum reported value for RSRP in LTE is -44 dBm, while users with RSRP below -140 are in outage.

Reported value	Number of measurements	Unit
RSRP_00	$RSRP < -140$	dBm
RSRP_01	$-140 \leq RSRP < -139$	dBm
...	...	dBm
RSRP_99	$-44 \leq RSRP$	dBm

Table 3: Number of proportion of measurements per geotype.

The RSRQ is an estimate of the quality of the signal, as it is calculated as the ratio between the RSRP scaled by the number of resource blocks used (N) and the total received power (Received Signal Strength Indicator, RSSI), which measures the average received power observed in the whole bandwidth of the cell and therefore contains interfering signals. Equation 1 shows the calculation (in natural units).

$$RSRQ = \frac{N \times RSRP}{RSSI} \tag{1}$$

Finally, we use the eCGI to estimate the BS density within the area. It must be noted that the eCGI is unique for each radio unit or carrier and therefore a typical three-sector multi-carrier cell will show several eCGIs.

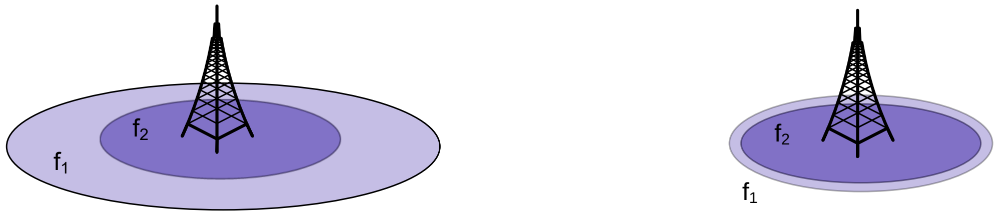
In this paper, we derive the BS density from the number of eCGI ‘seen’ from any one pixel in a grid covering Greater London. The procedure is as follows.

1. We create a grid of P pixels indexed $i \in \{1, \ldots, P\}$ sized 800×800 m covering the area under study (Greater London).

2. We count the number of different eCGI seen in each pixel of the grid.

3. We calculate the density of observed eCGI in each pixel of the grid, $\hat{d_i}$, using the area of each pixel (A_i)

4. We calculate the real average BS density D dividing the total number of BS (eCGIs) in Greater London by the total area.



(a) Large cell

(b) Small cell

Figure 4: Illustration of the propagation differences between frequencies in multicarrier BS in large and small cells.

5. As the same BS may be seen from various pixels, we scale the estimated BS density $\hat{d}_i$ with the real average BS density D so that the average of the real BS density (d_i) matches the real average BS density D. We denote the adjusted BS density per pixel as d_i. This is illustrated in Equation 2.

$$d_i = \frac{\hat{d}_i}{\sum_{i=1}^{P} \hat{d}_i / P} D \tag{2}$$

4 On information inference from the selected variables

As explained above in Section 3.3, the received power metric (*RSRP*) measures the received power from the reference signals (CRSs). As indicated, the received power depends on the carrier frequency, since the frequencies show different propagation properties, and other propagation phenomena (i.e. obstacles, multipath, etc.). In general, the closer the user to the BS, the higher the received power. On the contrary, users at the cell-edge will receive low levels of received power. Therefore, we can infer several characteristics of the structure of the network deployed using the RSRP, specifically the cell relative size and the spectrum used, as described next.

Figure 4 show two cases of deployment of multi-carrier BS, which is very common in operators that hold spectrum in different bands. Figure 4a represents a large cell, where the cell radius is large enough for the propagation differences across frequencies to come up. In this case, the distribution of received power in either carrier will be different. Therefore, when the measurements at the UEs in the cell are added together, these different RSRP distributions will overlap, resulting in small peaks (local maxima) coming up in the aggregate RSRP distribution. On the contrary, Figure 4b represents a small cell where we may not perceive any major differences on the received power, as the propagation differences across bands will be negligible.

Additionally, small cells should present higher levels of RSRP, while large cells should present lower levels, tending to -140 dBm. Note that the concept of large and small is also relative to the frequency band. The average cell size is likely to be smaller for higher frequencies due to poorer propagation.

Regarding the RSRQ, it is possible to infer how *congested* the network is, as it the metric includes interference. This allows us to remove the bias of the dataset, as the measurement at the UE measure the cell load through the interference.

5 Results

This section presents the results, which show the extent to which it is possible to infer an MNOs' deployment strategy from the crowdsourced network data to answer the research questions articulated at the beginning of this paper.

5.1 Information inference from the received power in dense urban

Figure 5 shows the RSRP histograms of the four MNOs in the UK market, with notable differences across them. Firstly, for the MNOs holding larger parts of the low-frequency spectrum (*MNO1* and *MNO2*), RSRP values below -120 dBm are very unlikely. On the contrary, *MNO3* and *MNO4*, which only hold 2×5 MHz of the sub-1GHz spectrum, show a larger probability of low received power, in the range 140 – 120 dBm. Naturally, providers deploying at high-frequency bands might compensate for the poorer propagation properties with network densification, as we review later on.

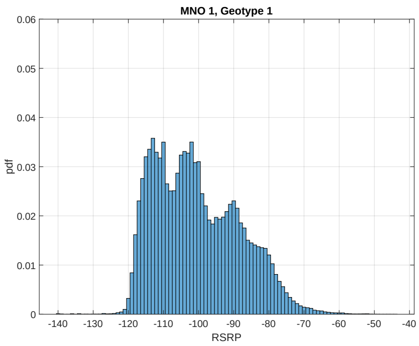
Secondly, the modes of the distributions for the MNOs with and without large low-frequency spectrum show substantial differences. While the most frequent RSRP values for *MNO3* and *MNO4* are around -100 dBm, for *MNO1* and *MNO2* are around -112 dBm. This is also an additional reason for high-frequency spectrum MNOs (*MNO3* and *MNO4*) not to further densify their networks since their average received power is relatively good.

Thirdly, there are substantial differences across the specific MNOs. Even if the results in Figure 5 are for dense urban environments in central London (Geotpye 1), *MNO1*'s network looks coverage-constrained, since cell-edge values ($\sim$ -120 dBm) are most frequent and there are noticeable peaks that indicate that cell size is large and capacity is probably provided through carriers at several (if not all) their spectrum bands. Note that *MNO1* has the larger spectrum allocation, with $2\times52.2 + 20$ MHz across LTE spectrum bands[7].

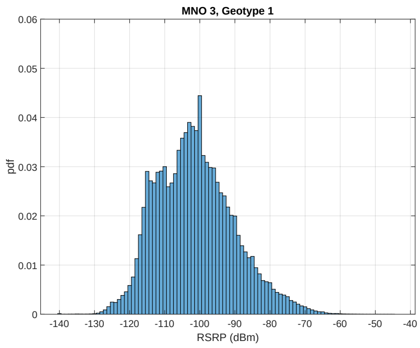
In contrast to *MNO1*, the RSRP distribution of its infrastructure-sharing partner, *MNO2*, is slightly wider with fewer emphasised components in low RSRP values. Moreover, the probability of received signal power over -80 dBm is much larger. This suggests smaller cell ranges, which is consistent with less bandwidth and the absence of the peaks that reveal the carriers at different spectrum bands. Additionally, it is also possible that these carriers are only used in specific areas, for which a more granular analysis is required.

On the other hand, in addition to the relatively smaller cell sizes highlighted by the measurements below -120 dBm, the smoother RSRP distributions of *MNO3* and *MNO4* suggest that the cells are very small

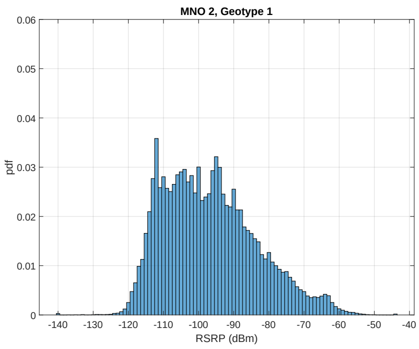
[7] We assume that 2×25 MHz at 2100 MHz frequencies are still used for 3G coverage. 1500 MHz was not still in use in 2017.



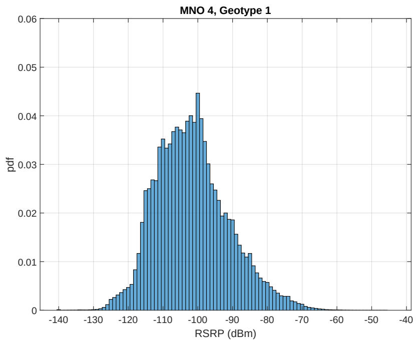
(a) *MNO1*



(b) *MNO3*



(c) *MNO2*



(d) *MNO4*

Figure 5: MNOs' RSRP histograms in Geotype 1.

and/or the propagation characteristic differences across spectrum bands are limited in the cell ranges measured. Specifically comparing *MNO3* and *MNO4*'s distribution, it is possible to notice two peaks in *MNO3*'s distribution, which very likely correspond to their combined LTE deployment at 1800 MHz and 2600 MHz. *MNO4* would only be using their 1800 MHz spectrum, which would provide this smooth distribution. These results suggest that *MNO3* and *MNO4* may not be using their low-frequency spectrum at 800 MHz in dense areas, as the bandwidth is small compared to their high-frequency spectrum and the differences across bands will be negligible.

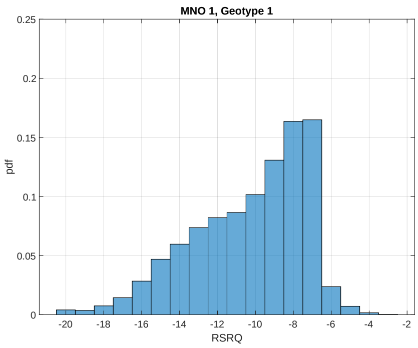
5.2 Information inference from the received quality in dense urban

From the received power analysis undertaken in the previous section, we have inferred information from relative cell sizes and use of spectrum bands. However, these variables are not always good predictors for service quality, as described in Section 2.

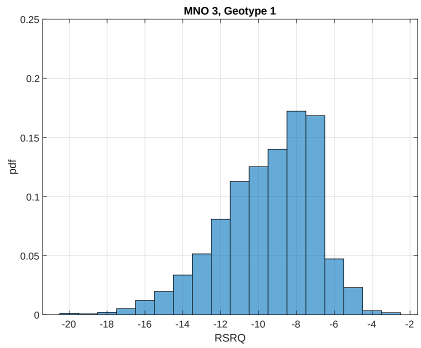
Figure 6 shows the RSRQ histogram of the four MNOs in the PCSs labeled as Geotype 1.

There are significant differences between the four operators. While *MNO1* and *MNO3* show high signal quality (RSRQ) values, with measurements of -7 and -8 being the most frequent, *MNO2* and *MNO4* present more symmetric RSRQ distributions, with lower mode and mean values.

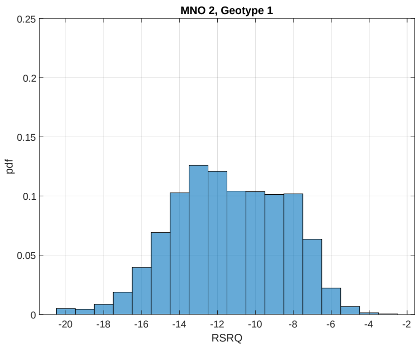
These results are very consistent with the findings presented in the previous section since *MNO1*'s and



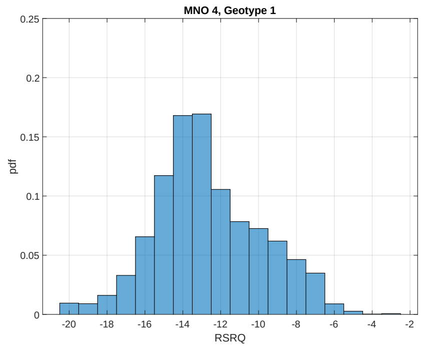
(a) *MNO1*



(b) *MNO3*



(c) *MNO2*



(d) *MNO4*

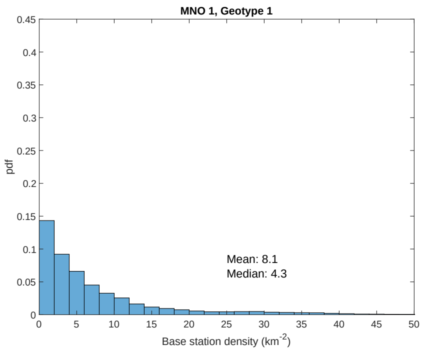
Figure 6: MNOs' RSRQ histograms in Geotype 1.

MNO3's networks are rather coverage-limited due to the large bandwidth that both hold. This large bandwidth allows them to have proportionally fewer users per MHz and even allocate users to spectrum blocks in a way that minimises interference, i.e. minimising the number of users per carrier. Additionally, their large spectrum resources allow them to deploy relatively large cells (to their respective frequency bands).

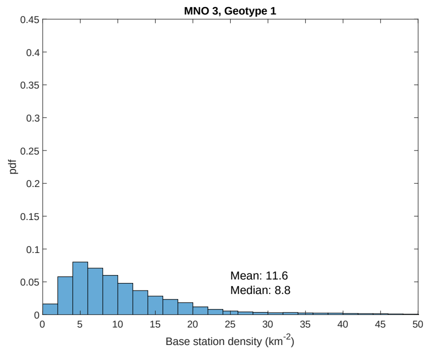
On the contrary, *MNO2*'s and *MNO4* average RSRQ may be downgraded by the higher interference that users received due to high network load per MHz. It is important to note that these lower RSRQ values do not necessarily entail worse overall performance. Signal quality is only a proxy for the spectral efficiency, and therefore, the technological capacity to transmit information. The throughput (bit rate) that the user perceives also depends on the bandwidth of the cell and the number of users that share that bandwidth, which in turn relates to the cell size. Therefore, lower RSRQ values would need to be compensated by increased BS density to provide the same throughput.

5.3 Information inference from the base station density in dense urban

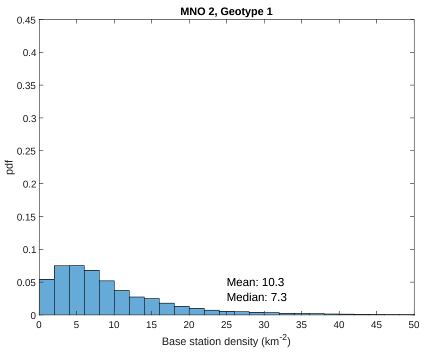
Figure 7 shows the number of BSs that we have estimated as per the method described in Section 3.3. In these Section, BSs are not to be confused with sites. In terms of BS identifiers (eCGI), each sector and carrier has its own unique identification number. Therefore, from the UEs perspective, in multi-carrier and or sectoral deployments, several BSs are deployed in the same site. Each sector is uniquely



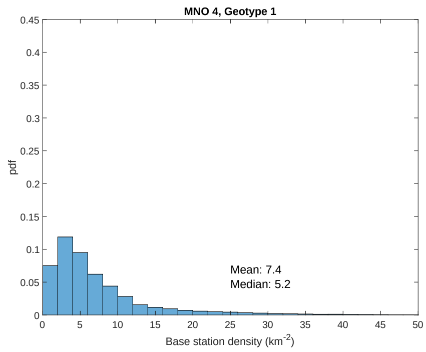
(a) *MNO1*



(b) *MNO3*



(c) *MNO2*



(d) *MNO4*

Figure 7: MNOs' Base Station density histograms in Geotype 1.

identified, as well as each carrier (either in the same or in different frequency bands). In this regard note that, for example, in the *MNO3* network, two or three different base stations will be sensed in the 1800 MHz band, as the maximum LTE carrier es $2{\times}20$ MHz and the operator has $2{\times}45$ MHz available. Therefore, the BS densities must be interpreted in a comprehensive way and not only as of the opposite of covered areas.

The highest density of BSs can be found in the networks of *MNO2* and *MNO3*, although for different reasons. With *MNO3* the number of BSs is very high due to their large bandwidth in both 1800 MHz and 2600 MHz, where they need several carriers. On the other hand, according to the spectrum allocation and considering that we exclude the 2100 MHz band, *MNO2* cannot deploy more than three carriers per sector site[8]. This is, therefore, indicating that despite having spectrum in the lowest frequencies, their network is mainly capacity-limited and therefore they need to densify the network and reduce the cell size to spatially reuse spectrum to a larger extent.

Unlike *MNO2*, *MNO1* has large bandwidth, and as per their spectrum portfolio the possibility to deploy four carriers. Its site density is lower. Finally, although the BS density of *MNO4* would, at first sight, look low, the number is relatively high when considering they can only use two carriers to provide services, which make for only $2{\times}20$ MHz in total. Table 4 shows the *adjusted* average BS density, where we estimate the BS density taking into account the number of carriers that each MNO is likely to be using

[8] At 800 MHz, 900 MHz and 1800 MHz.

at each spectrum band based on the previous findings.

	MNO1	*MNO2*	*MNO3*	*MNO4*
Max number of carriers	4	3	6	2
Average BS density	8.1	10.3	11.6	7.4
Adjusted average BS density (multi-carrier BS density or physical site density)	2.025	3.43	1.66	3.7

Table 4: Average adjusted site density per MNOs.

5.4 Network characterisation in suburban

In this section, we review the same results as above but for urban and suburban areas (Geotype 2 and Geotype 3) and assess the differences compared to dense urban environments (Geotype 1). As the user density and propagation environment differ, the results show notable differences.

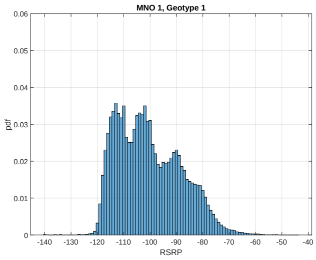
Figure 8 shows the RSRP per operator and geotype. Rows indicate the operators and columns show the geotypes from dense urban on the left (Geotype 1) to suburban on the right (Geotype 3).

We can note that, in general, as we move from dense urban to suburban, the standard deviation of the RSPRP tends to decrease and concentrate more on values around -110 dBm. This is because as cell sizes increase, the relative weight of RSRP values in the range of -120 to -110 dBm is proportionally higher, since path losses increase with distance.

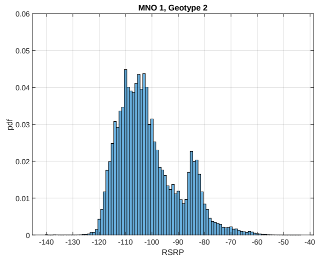
Additionally, as traffic demand decreases, networks become more coverage-constrained (rather than capacity-constrained), and therefore it may not be necessary to use all available spectrum. This becomes particularly clear in the case of *MNO1*. We can note that number of peaks, which indicate the number of carriers at the BS, decrease as we move from Geotype 1 to Geotype 3. This suggests that less bandwidth is needed in such an environment. In Geotype 3, the operator is probably using only low-frequency spectrum, which is enough in terms of bandwidth, and therefore peaks in the distribution are no longer noticeable.

On the contrary, in the densest networks such as *MNO2* or *MNO4*, the multi-carrier peaks were not as well defined in dense urban because of the small cell sizes. As we move to suburban areas, these peaks are more noticeable because the cell size is now large enough for the propagation differences across providers to have an impact.

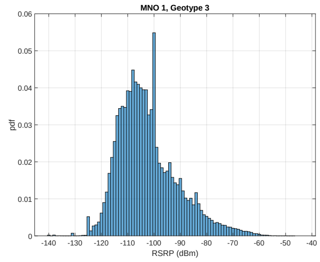
Regarding the signal quality indicator, Figure 8 shows the RSRQ distributions across providers and geotypes. They tend to equal in suburban areas, where the network load decreases and therefore interference lowers. It is worth noting that the operator having the 'best' RSRQ distribution is *MNO3*. This is probably because the operator may still use a large fraction of their 1800 MHz bandwidth, as the $2{\times}5$ MHz in sub-1GHz bands would not suffice. *MNO4* is in a similar position, but their RSRQ distribution is not so like *MNO3*'s because they only hold one-third of the spectrum at 1800 MHz.



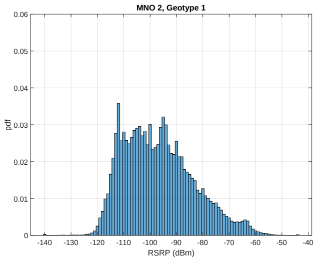
(a) *MNO1* - Geotype 1



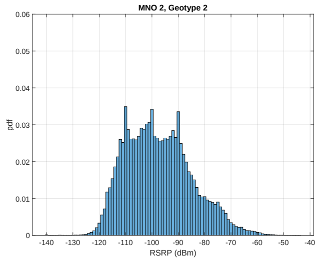
(b) *MNO1* - Geotype 2



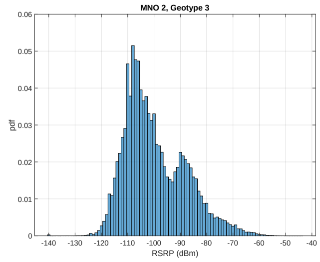
(c) *MNO1* - Geotype 3



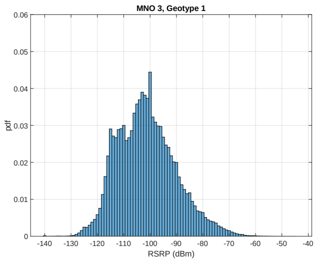
(d) *MNO2* - Geotype 1



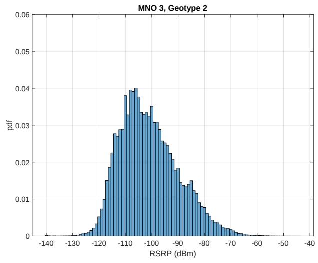
(e) *MNO2* - Geotype 2



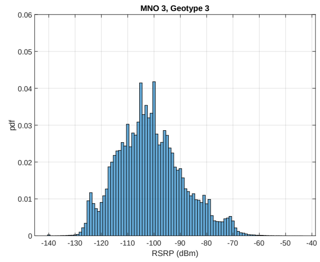
(f) *MNO2* - Geotype 3



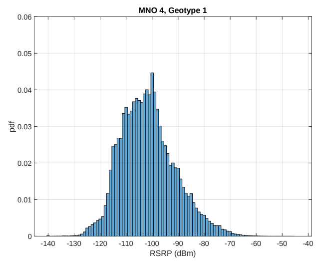
(g) *MNO3* - Geotype 1



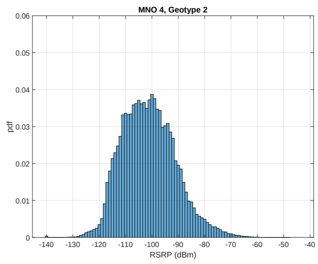
(h) *MNO3* - Geotype 2



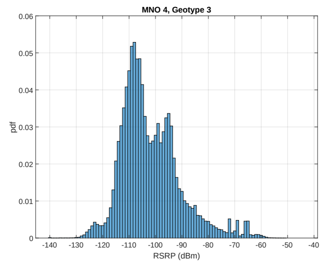
(i) *MNO3* - Geotype 3



(j) *MNO4* - Geotype 1



(k) *MNO4* - Geotype 2

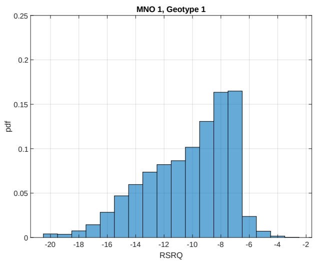


(l) *MNO4* - Geotype 3

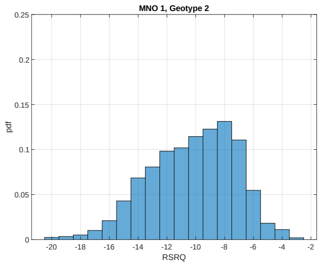
Figure 8: RSRP comparison across geotypes.

Alternatively, providers holding wide spectrum at low-frequencies, namely *MNO1* and *MNO2*, can avoid deploying high-frequency carriers in most of their sites in Getoype 3, as their networks become more coverage-constrained. This is consistent with the results of the RSRP discussed above. Consequently, their RSRQ distribution is less centered on the highest values.

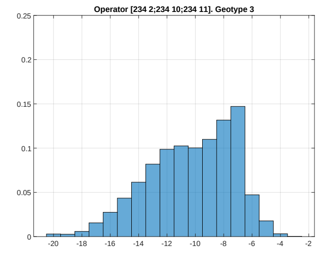
Finally, Figure 10 shows the differences in BS density across operators and geotypes.



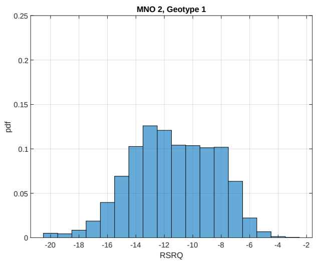
(a) *MNO1* - Geotype 1



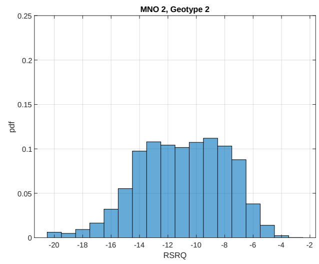
(b) *MNO1* - Geotype 2



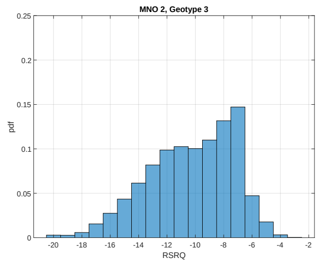
(c) *MNO1* - Geotype 3



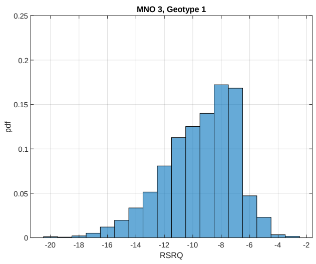
(d) *MNO2* - Geotype 1



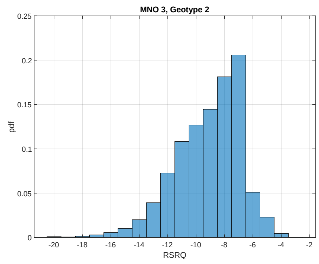
(e) *MNO2* - Geotype 2



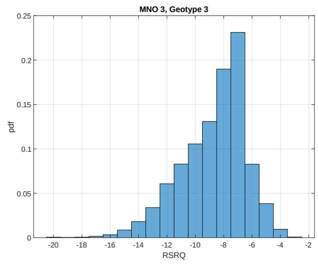
(f) *MNO2* - Geotype 3



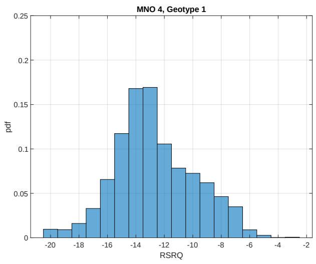
(g) *MNO3* - Geotype 1



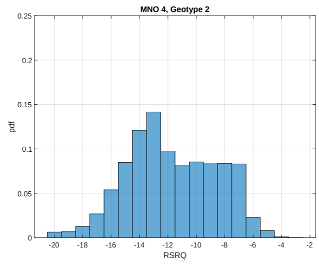
(h) *MNO3* - Geotype 2



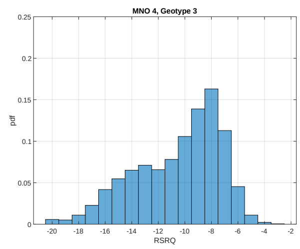
(i) *MNO3* - Geotype 3



(j) *MNO4* - Geotype 1



(k) *MNO4* - Geotype 2



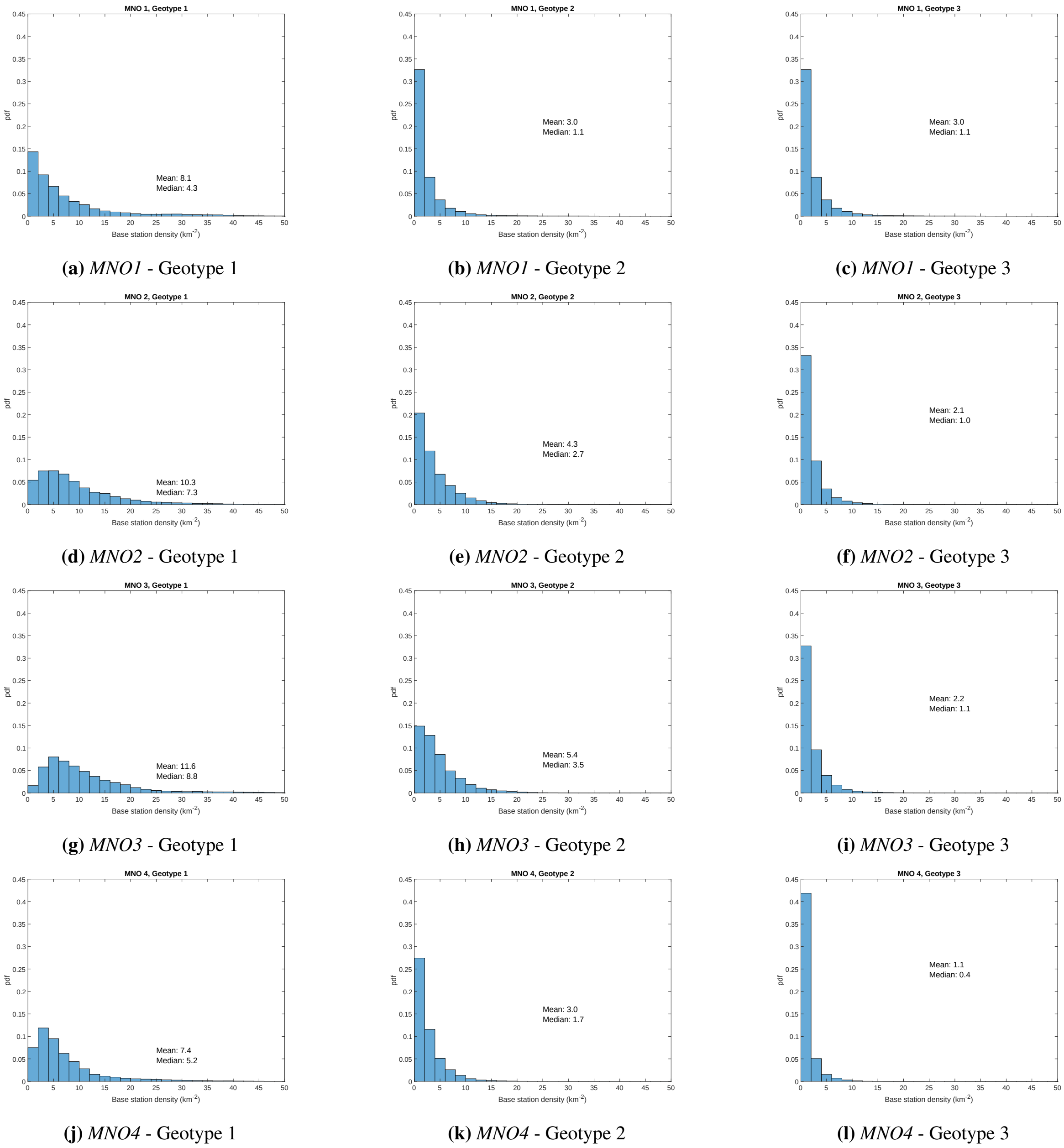
(l) *MNO4* - Geotype 3

Figure 9: RSRQ comparison across geotypes.

6 Discussion

The analysis in the previous sections shows that using metrics of received power (RSRP) and received quality (RSRQ) we can infer the BS density, the network load and the spectrum usage. Based on these, we can also identify the strategies that each MNO has followed to deploy 4G, i.e. how they have combine spectrum resources and network densification under several scenarios.

In the UK, despite the passive infrastructure sharing agreements between providers, the connectivity infrastructure shows remarkable heterogeneity, as different spectrum resources have led to unique de-



(a) *MNO1* - Geotype 1 **(b)** *MNO1* - Geotype 2 **(c)** *MNO1* - Geotype 3

(d) *MNO2* - Geotype 1 **(e)** *MNO2* - Geotype 2 **(f)** *MNO2* - Geotype 3

(g) *MNO3* - Geotype 1 **(h)** *MNO3* - Geotype 2 **(i)** *MNO3* - Geotype 3

(j) *MNO4* - Geotype 1 **(k)** *MNO4* - Geotype 2 **(l)** *MNO4* - Geotype 3

Figure 10: Base station density comparison across geotypes.

ployment strategies.

The results show that there is no single way to deploy broad coverage and high-capacity 4G networks and the way the spectrum allocation conditions the strategy followed has substantially changed. Typically, the interdependency between spectrum access and deployment strategy has been presented as a dichotomy between high and low frequencies: since high-frequency spectrum presents worse propagation properties, MNOs deploying their network in these bands require more BSs than those using low frequencies. This has been true for a long time because there have been very specific circumstances: single band deployments and primarily coverage-constrained networks.

With the explosion of the demand for mobile data traffic in the last decade and the identification and allocation of new spectrum band for mobile, the spectrum portfolios ever more heterogeneous. Contrary to the above-described simplistic view of network deployments, in this work, we have proven that in a data-centric connectivity business, MNOs have adopted more sophisticated deployment strategies.

As one of the most challenging aspects of QoS in capacity-constrained networks is interference, MNOs have followed different capacity-expansion strategies to deal with congestion, combining network densification, frequencies and bandwidths in various dissimilar ways.

We have shown that in dense urban environments, some MNOs have adopted a strategy based on (high-frequency) large bandwidth that reduce interference and enables larger cell sizes at the expense of deploying multi-carrier BSs, while others with more modest bandwidths prefer network densification that enables larger spectrum reuse as a way to compensate the poorer signal quality and higher interference that results from smaller bandwidths.

Interestingly, as of February 2017, when the data were collected, suburban areas were not so capacity-constrained, as the RSRP and RSRQ distributions differ from those in urban areas. Cell sizes are larger, BS density is smaller and MNOs with broad bandwidth may dispense with higher-frequency carriers.

These results provide insights on the extent to which each operator is more likely to expand its network's capacity relying on strategies that combine differently spectrum integration and network densification. It is worth to note noting that infrastructure sharing agreements between providers do not restrict the preferred capacity-expansion strategies, as their spectrum portfolios are considerably different. Although the operators sharing part of their passive infrastructure tend to be more focused on similar frequency bands (*MNO1* and *MNO2* capture most of the low-frequency spectrum, while *MNO3* and *MNO4* use primarily high-frequencies), there are remarkable differences between the deployment strategies of partners in the same sharing agreement. Hence, *MNO1* and *MNO3* rely on larger spectrum, while *MNO2* and *MNO4* do on network densification. Interestingly enough, MNOs sharing the same capacity-expansion strategy do not share sites nor have spectrum on similar frequencies.

The different network expansion strategies that operators have followed in the deployment of 4G networks have resulted in substantially different networks, generating path dependencies that will undoubtedly influence the strategies that operators will be able to follow to deploy 5G networks. It remains to be seen to what extent current networks will have to be densified to meet the demand for 5G services since this still presents a high degree of uncertainty.

Operators are already acquiring spectrum for the deployment of 5G networks, which will be placed at the extremes of the frequency range currently used, resulting in an even more distant combination between low (700 MHz) and high (3.4−3.8 GHz) bands. In addition, frequencies with worse propagation characteristics (mmW) will not be available in the short term, and therefore the 700 MHz and 3.5−3.6 GHz bands can easily be integrated into current locations.

The initial demand of 5G will predictably be small, with the networks being initially limited by coverage. Against this background, 700 MHz spectrum would have to play an important role. However, in the

UK and other countries, this spectrum will not be available in the short term, and therefore, MNOs, particularly those with most congested networks have strong incentives to start 5G deployments for enhanced Mobile Broadband Services (eMBB) using high frequencies in the range 3.4˘3.8 GHz.

Judging from the network situation in the suburban areas of the Greater London area, generally more limited by coverage than by capacity, the announced 5G deployment, which probably covers these areas, seems to be more motivated by business rather than by technical issues.

7 Conclusions

In this paper we have presented a methodology to infer the state of connectivity infrastructure and MNOs' deployment strategies using crowdsourced data from a mobile app. We have only used measurements of received power (RSRP) and received quality (RSRQ), which are provided by the UE along with the cell identifier (eCGI) and GPS location for the measurement.

We conclude that it is possible to infer relevant information on the BS density, spectrum use and network load. Analysing the RSRP probability distributions, we can identify spectrum usage through the peaks that come up in multi-carrier BSs. Moreover, based on the RSRQ, we can infer the network load, as the metric accounts for received interference. This reduces the bias of the dataset and provides more general information on the state of the network.

Based on data from 2017 for Greater London, our findings suggest that networks are only capacity-constrained in dense urban areas, where the MNOs have adopted different strategies to deal with congestion, combining network densification, frequency band and bandwidth in different ways.

We have shown that in dense urban environments, some MNOs have adopted a strategy based on (high-frequency) large bandwidth that reduce interference and enables larger cell sizes at the expense of deploying multi-carrier BSs, while others with most modest bandwidths prefer network densification that enables larger spectrum reuse as a way to compensate the poorer signal quality that results from smaller bandwidths. In the UK, *MNO1* and *MNO3* rely on larger spectrum, while *MNO2* and *MNO4* do on network densification. Interestingly enough, MNOs sharing the same capacity-expansion strategy do not share sites nor have spectrum on similar frequencies. Regarding suburban areas, mobile networks still look primarily coverage-constrained, where MNOs may dispense with high-frequency spectrum.

These analysis provide valuable insights on the state of connectivity infrastructure, the deployment strategy that each MNO has followed, as well as the path dependencies that their existing infrastructure impose towards the deployment of 5G networks. We argue this information should be used to inform telecommunications policy.

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