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Cost Analysis of a 5G Network with Multi-Tenancy Options

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Abstract

5G networks are envisioned to provide consumers and industry with improved transmission performance and advanced communication possibilities. To deliver the promises on ushering fast downloads and low latency, the mobile network operators are called upon for formidable investment in network upgrades, the lion's share of which is expected to be in the radio access network (RAN). One option for operator investment relief consists in sharing resources, RAN and backhaul, by means of a mobile service provider (MSP) that would have access to the joint infrastructure of multiple infrastructure providers and offer services to its tenants. This article calculates the cost savings via multi-tenancy of a 5G network architecture. The study was performed within 3 boroughs of central London, UK, for the period 2020-2030. The results show cost advantages to operators when using a multi-tenancy scheme compared to incurring the investment severally.

Keywords: 5G, multi-tenancy, costs, 5G NORMA

1 Introduction

The future 5G systems will bring new opportunities to citizens in terms of communications possibilities. With the deployment of 5G it is expected that communications will be faster, ubiquitous, more reliable and will enable a number of novel services that will contribute to the economic growth of countries and regions, e.g., vertical industry-grade services and vehicle-to-everything (V2X) communications. Expected technical features of 5G, will enable the creation of different business opportunities (NGMN, 2015). For example, 5G will provide end users with an improved user experience in terms of high user throughput of at least 25 Mbit/s downlink and uplink, lower and stable end-to-end latency, improved coverage outdoors as well as indoors, higher area wide network capacity. In (NGMN, 2015) it is explained that the wireless transmission for a number of applications should be of up to more than 1 Gbit/s and have a low end-to-end latency down to 1 ms.

The standardisation body 3GPP will finish the first 5G Standard in 2018 –Release 15–, and over the last few years different features of the future 5G network architecture have been investigated. One possible feature of the 5G network architecture is multi-tenancy. This concept has been studied in the European research project 5G NORMA. One of the core features of the 5G NORMA architecture is the multi-tenancy option based on the network slicing approach (5GNORMA D3.2, 2017). This means that different tenants like industrial enterprise customers or mobile virtual network operators will provide services through a shared network infrastructure layer hosted by one or more infrastructure providers (InP), resulting in new or changed roles in the business model.

The study of economic aspects plays an important role when operators decide to rollout a specific technology. In this sense, the analysis of cost aspects of multi-tenancy in a 5G environment is a study area that deserves the attention of operators, vendors, public authorities, consultancy firms, academia and analysts. A few authors have worked on the topic of the cost of mobile network sharing, such as (Mölleryd et al., 2014), (WIK-Consult, 2016) and (Khan et al.,

2011). However, according to the knowledge of the authors, so far little published research is available regarding the cost of 5G networks. Some results of the cost of a multi-tenancy 5G network have been provided in (Rendon Schneir et al., 2016; Oughton & Frias, 2016).

Passive network sharing whereby mobile network operators share site locations, towers/structures at these locations, antennas and site facilities like backhaul and power already exists today. Active network sharing where active network equipment as well as sites, structures and antennas are shared are also possible through Multi-Operator RAN (MORAN) and Multi-Operator Core Networks (MOCN). These active sharing techniques have been standardised in 3GPP (3GPP, 2017) with MORAN requiring dedicated carriers between sharing operators while MOCN includes spectrum sharing. A few options of network sharing are described in (GSMA, 2012) and (WIK-Consult, 2016). However, multi-tenancy in 5G NORMA networks takes this sharing to another level with infrastructure, equipment, inter-site connectivity and spectrum potentially being used to flexibly provide, at a much more granular level than currently, the processing, storage and connectivity for a mobile service provider (MSP) to implement end to end mobile services or “network slices” for multiple tenants each delivering their own target services over the network (NGMN, 2016; Samdanis et al, 2016). The key disadvantages to active network sharing in current cellular networks is that settings of the shared sites must be a compromise between the different parties sharing. In a multi-tenant 5G network the virtualisation of network functions and partitioning of these between network slices means each party can control how their service is delivered via the network resource available and hence have better control over user experience.

The aim of this article is to contribute to the study of the cost implications of a 5G network based on the 5G multi-tenancy concept. The research question that will be addressed in this study is the following: ***What level of cost savings can we expect multi-tenant 5G networks to deliver beyond today’s cellular networks with largely dedicated infrastructure per MSP?***

The purpose of the article is to provide an answer to this question by using a cost model derived for 5G. The cost model has been exemplarily constructed for the centre of London in the United Kingdom as a typical dense urban area. The cost model represents a major new development taking into account network function virtualisation (NFV) and a flexible, adaptable architecture that supports multiple service types, but is also consistent with existing cost modelling of a 4G/LTE system. We model the impact of virtualisation and a more flexible 5G architecture by dimensioning sites and equipment in line with a cloud RAN (C-RAN) architecture for macrocell sites in the area. Moreover, the demand per antenna site is translated to required general purpose processing (GPP) cores and hence equipment requirements at intermediate edge cloud sites.

The rest of the article is organised as follows. In the next section, we describe technical aspects related to our study: the simulated study area, the implementation of 5G and the multi-tenancy approach employed. We then describe features of the cost model, i.e. the cost modeling tool and the number of sites employed. We present the results of the cost assessment in terms of capital expenditures (CAPEX) and operation expenditures (OPEX). Finally, the conclusions are provided.

2 Technical Aspects

2.1 The simulated study area

For the purpose of this research we prepared a system level simulation that takes into account coverage and capacity in a central London study area. Our cost model maps demand spatially and temporally within the central London study area examined. It then selects site locations and the capabilities of these sites to dimension a relatively optimised virtualised 5G network that meets coverage requirements for the target services and provides capacity in the right locations to meet these spatial and temporal variations in demand.

The simulation study area is defined as the union of the following three central London boroughs, UK: Kensington and Chelsea, City of Westminster, and City and County of the City of London. It consists of an inhomogeneous mesh of roads, a blend of road types (quiet/busy, medium speed/pedestrian), and of business/residential districts. A buffer of 500 m around the study area was considered to avoid edge-effects. Fig.1 shows the study area.

We assumed that thoroughfare segments in this region generate traffic that needs to be served by the network as our focus in this assessment has been on outdoor mobile demand. The study area contains the following demand sources: 108 km of A roads, 29 km of B roads, 390 km of minor roads. Here A roads are the highest tier of non-motorway classified roads, B roads are the second tier of non-motorway roads, and minor roads cover all other roads below these two tiers. We ignored traffic that is generated at tunnelled thoroughfare as this is typically covered by tunnel specific deployments. Thus, for example service in the underground transport is not part of this study. We accumulated the demand generated from each source at the centre of pixels of size 25x25 m. Coverage and capacity were assessed at the centre of each pixel.

Fig 1. Study area in London in solid line, buffer area with dashed line.



2.2 Implementation of 5G

In the central London study area we dimension a virtualised, flexible 5G network to carry the outdoor enhanced mobile broadband (eMBB) demand of two eMBB mobile operators (see Fig. 1). We assume demand growth in line with Cisco VNI mobile data forecasts for the UK (Cisco, 2016) and applied to our study area considering the residential population and uplift in working hours for commuters. Our modelling of the more flexible 5G architecture assumes a C-RAN like network implementation with network functions virtualised as much as possible. This requires deployment of so called site chains towards the core network of antenna sites, with remote radio heads, and intermediate edge cloud sites, providing the baseband processing and remainder of the radio protocol stack for multiple antenna sites. In 5G NORMA site chains mean the series of sites required to form an end to end connection and consist of the antenna site, edge cloud site and central cloud and interconnections between these. In the scenarios and results presented here all core network processing is done in the central cloud and not directly modelled. We translate the demand being carried by each antenna site into processing requirements in terms of the number of GPP cores required which we in turn use to estimate volumes of cabinets and servers required at each edge cloud site or “aggregation node”. Our dimensioning of equipment to date focuses on user plane (U-plane) processing requirements.

We simulated eMBB services for up to 4K live streaming of video for users using consumer portable devices, with a minimum downlink throughput of 10 Mbit/s, 87% cell-edge coverage confidence, corresponding to 95% cell-area confidence. The network providing the service consisted of a number of small cells in Distributed RAN (D-RAN) configuration and macrocells with C-RAN configuration based on the virtualised 5G NORMA architecture as described above (5G NORMA D3.2, 2017).

In the results presented here, we assumed that the modelled service had an end to end delay requirement that was within the latency of the C-RAN site chain modelled. We do not explicitly model packet delays within the simulation model. Instead the model supports different site chain configurations with radio protocol stack processing or application servers being located more centrally or at the antenna site depending on the category of service and latency required. However, in the results presented here we do not exercise this ability to dimension network equipment to support low latency.

We simulated a network evolution from 2020 to 2030 to meet growing traffic demand but also considering spectrum and spectral efficiency (SE) evolution over this time period. We also modelled network evolution over a warm up period from 2017 to 2020 to get the starting site volumes and specifications for 2020. By site specifications we refer to the number of sectors, bands, antennas per band and bandwidth available to a site. The simulated network consisted of antenna sites (3-sector macrocell sites, 2-sector small cell sites), the transport of antenna sites towards edge cloud sites, edge cloud sites, and the transport of edge cloud sites towards the central cloud. We did not simulate traffic at the core network in the central cloud.

The assessment link budgets were prepared for 2x20 MHz at 800 MHz, 2x40 MHz at 2100 MHz, and 1x40 MHz at 3.5 GHz TDD configuration 5, to assess outdoor coverage at sub 1GHz, low (from 1400 to 2600MHz), and medium frequency bands (from 3.4 to 3.6GHz). We did not model millimeter Wave (mmWave) bands. We assumed that uplink is served by sub 1GHz and low bands.

The macrocells had variable specifications. In 2017 they were equipped with cross polarised antennas (2x2 MU-MIMO) and had access to 2x20 MHz at low band, corresponding to average single user goodput of 15 Mbit/s/cell. In 2020 they can upgrade to 2x40 MHz at low band if required by demand in the area, corresponding to average goodput of 30 Mbit/s/cell. By 2030 they can if demand requires be equipped with up to 4 antennas in sub 1 GHz/low-band and up to a 64-element active-antenna in the medium band, with access to 105 MHz for downlink (DL) across all bands and average goodput of 120 Mbit/s/cell. The upgrade option of a macrocell was compared against other network improvement options by means of maximisation of the merit, which was defined as served demand over cost. Because of the spatially-inhomogeneous traffic demand, at any given simulated year there was a diverseness of macrocell capacity installed in the network. From 2019 we assume that all macrocells are with C-RAN configuration; since this analysis considers costs from 2020 onwards the migration cost from D-RAN to C-RAN for the macrocells is not part of this study.

The small cells had also variable specifications. We assumed that the small cells are on different channels from the macrocell layer. In 2020 they were equipped with cross polarised antennas (2x2 MU-MIMO) and had access to 1x20 MHz at low band. By 2030 they could have been equipped with up to 4 antennas in low and medium bands, with access to 60 MHz for DL in total. The replacement option of a small cell was compared against other network improvement options by means of maximisation of merit. At any given simulated year there was a spatial diverseness of small cell capacity in the network. All small cells are in D-RAN configuration.

For both macrocell and small cell layers, we assumed that the capacity is based on the SE values as stated in (5GNORMA D2.2, 2016). These include taking reported SE simulation results and applying factors for example for MIMO order and non-full buffer traffic. For example, a headline mean SE per cell for 2x2 MU-MIMO FDD of 2.62 bit/s/Hz is multiplied with a factor of 0.65 to correspond to non-full buffer, more realistic traffic mix. We also assumed that the cells get loaded up to 65%; for example, 65 Physical Resource Blocks (PRB) in 20 MHz channel were utilised for data and overhead. We further assumed that 24% of the resources are needed for non-data channels. By multiplication of the quantities listed above, the headline SE of 2.62 bit/s/Hz corresponds to good put of 15 Mbit/s/cell.

We assumed that edge cloud sites can be located at the existing 32 incumbent fixed telecoms exchange sites in the area. Based on economies of scale a C-RAN architecture is profitable when there is a considerable aggregation at the edge cloud site. To achieve such a level we calculated that the study area should include 6 edge cloud sites, chosen randomly from the 32 exchange locations. Each edge cloud site was then serving on average 22 macrocell sites in 2020, and an increasing number of antenna sites thereafter. We calculated the maximum Euclidean distance between antenna and edge cloud site at 3.5 km. Taking the route of the fibre into consideration, based on the G.826 routing factor of 1.5, the maximum fibre length would not exceed 5.3km (ITU-T G.826, 2002). The one-way latency in 5.3 km of fibre is only 26 μ s (0.026 ms). Therefore, even CPRI-based transport with latency requirements of 250 μ s could be supported by fibre in this dense urban scenario if 6 (out of 32) incumbent exchanges are used as the edge cloud sites (CPRI, 2015).

2.3 Multi-tenancy

The 5G NORMA network architecture supports multi-tenancy. Within the context of 5G the MSP provides the end to end connectivity and network functionality to support the mobile services requested by multiple tenants with their individual service requirements. The MSP accomplishes this by using sites, equipment and inter-site connectivity provided by one or more InPs. In single tenant networks a particular infrastructure set is used by only one tenant. However, in multi-tenant networks the same infrastructure set can be used by the MSP for more than one tenant to implement the end to end network functionality required to support the services being provided by each tenant in their individual network slices.

While sharing of network infrastructure and equipment costs can be realised already with today's networks, as discussed earlier, 5G multi-tenant networks take sharing to another level. Within 5G multi-tenant networks resources can be shared at a more granular level than today. Also MSPs can implement their own sets of virtualised network functions on the shared network resources and as such can have more control and less compromise in terms of the quality of experience delivered.

The multi-tenancy approach employed is shown in Fig. 2. Fig. 2a and 2b show the cases where the Mobile Network Operators (MNOs) 1 and 2 have the functions of tenant, MSP and InP. Fig. 2c represents the multi-tenancy case where a MSP has a service level agreement (SLA) with InP₁ and InP₂. This MSP then offers end to end eMBB mobile services to two tenants each of which have the demand of our two original MNOs in Fig. 2a and 2b. To assess the savings from multi-tenancy we conducted three simulation runs: one run for MNO₁ where it had the role of MSP₁ and InP₁, one run for MNO₂ where it had the role of MSP₂ and InP₂, and one run with two tenants sharing infrastructure via one MSP. In the first two runs shown in Fig. 2a and 2b InP₁ and InP₂ each have equal amounts of spectrum available but do not share spectrum with each other. In Fig. 2c the site locations of InP₁ and InP₂ are both available to the MSP with spectrum also shared between these two infrastructure sets so that sites in Fig. 2c can use double the spectrum of sites in Fig. 2a or Fig. 2b if needed to keep pace with demand in the area.

In this third run we assume that the multi-tenant network is implemented from 2019 with shared spectrum carriers, tower/masts and antennas, RAN, servers at edge cloud sites and backhaul/transport. Costs associated with existing sites are shared, as well as those for new sites and site-upgrades. Both macrocells and small cells are shared. The above assumptions mean that at the start of 2019 the MSP utilises the combined infrastructure from InP₁ and InP₂, with some sites collocated and others offset. In case of collocation the MSP can provide access to double the spectrum quantities of the individual owners.

In the third run, for network improvements from 2020 to 2030 the MSP is allowed to explore the option of a new site or upgrading existing macrocells with double the spectrum quantity to meet the growing demand. These options are compared against other network improvement options, via a merit calculation as explained in the previous section. Table 1a summarises key assumptions about the three cases. The MSP aggregates the processing in the same 6 edge cloud sites as InP₁ and InP₂, but previously separate equipment rooms can now be combined although the amount of servers that the MSP requires are likely to be equal to the sum of the servers from the independent owners.

Fig 2. 5G Multi-tenancy scheme: a) Mobile Network Operator 1; b) Mobile Network Operator 2; c) Mobile Service Provider

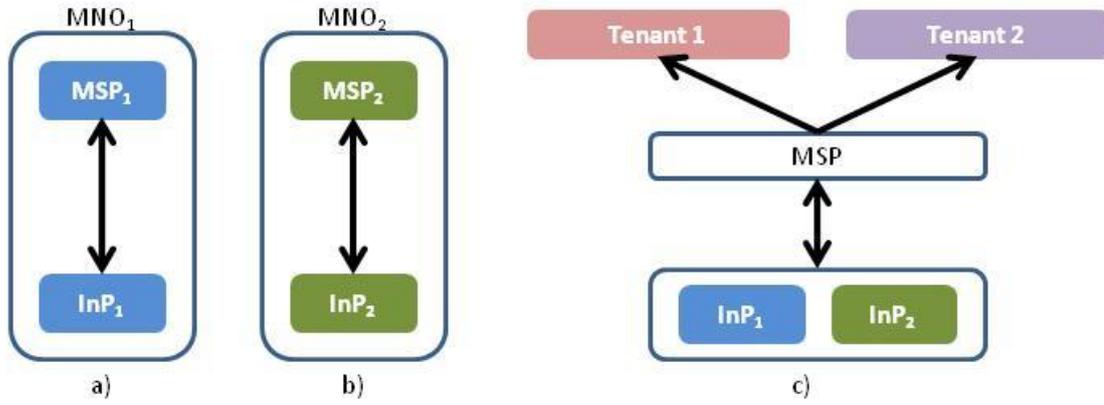


Table 1. a) Main assumptions b) Cost elements, c) Relevant Unit Costs

a)

	MNO1	MNO2	MSP
Number of macrocell sites, start of 2020	134	130	264
Number of small cell sites, start of 2020	252	153	409
Number of edge cloud sites	6	6	6
Market penetration	18%	17%	35%

b)

	Macrocell	Small cell	Edge cloud
CAPEX	Civil works and acquisition	Civil works and acquisition	Processing servers
	Antennas/feeder	Antennas/feeder	Cabinets
	RF front end and base band	RF front end and base band	--
	Labour	Labour	Labour
	Transport	Transport	Transport
OPEX	Rental	Rental	Site rental
	Rates and utilities	Rates and utilities	Cabinet rent and utilities
	Licensing and maintenance	Licensing and maintenance	Licensing and maintenance
	Transport	Transport	Transport
	Vendor services		Vendor services
			Operating overhead

c)

Unit cost	£k
OPEX macrocell site C-RAN 2x2 MIMO 40 MHz	38
CAPEX macrocell site C-RAN 2x2 MIMO 40 MHz	97
OPEX small cell site D-RAN 2x2 MIMO 20 MHz	5.3
CAPEX small cell site D-RAN 2x2 MIMO 20 MHz	12
OPEX edge cloud site with 15 servers*	54
CAPEX edge cloud site set up costs in 2019	150
CAPEX edge cloud site for 2 additional servers**	11.6

* A typical edge cloud site has 15 servers in 2020

** A typical edge cloud site adds 2 servers in 2020

3 Cost Model

3.1 Overview of the cost modelling tool

We employed a cost and demand/coverage/capacity tool, CAPisce (Real Wireless, 2012), to simulate the network and service demand. In each modelled year the demand module of CAPisce forecasts and distributes the demand into the demand sources (spatial-), and into hours of the day (temporal-distribution). The coverage and capacity module serves the generated

demand based on the current network deployment. Any leftover demand needs to be served by implementing network improvements (new/upgrade antenna sites) and improvement options are ranked by a merit function. Mathematically, this is a nonlinear constrained discrete optimisation problem. It is constrained because the leftover demand has to be served by the network improvements. It is discrete because the infrastructure owner can only choose from specific set of improvement options, for example the number of antennas for a macrocell is discrete.

Because network improvements are selected based on minimum cost over benefit, CAPisce implements different network improvements at different locations. The choice of improvement can depend on the extent of the area that lacks coverage, for example by choosing between a new macrocell or small cell. The amount of leftover demand will most likely define the bandwidth and number of antennas required on the antenna site and the amount of additional servers needed at the edge cloud, if any. Proximity to upgradeable antenna sites may mean that CAPisce selects an upgrade over a new site.

Table 1b summarises the cost elements that were included in the analysis. Table 1c shows unit costs for some example site specifications. configurations. All costs are relevant to 2020 unless stated. Network dimensioning and costs focus on U-plane processing costs for the RAN and exclude control plane signalling, network orchestrators or controllers, core network applications and wider business and administrative costs.

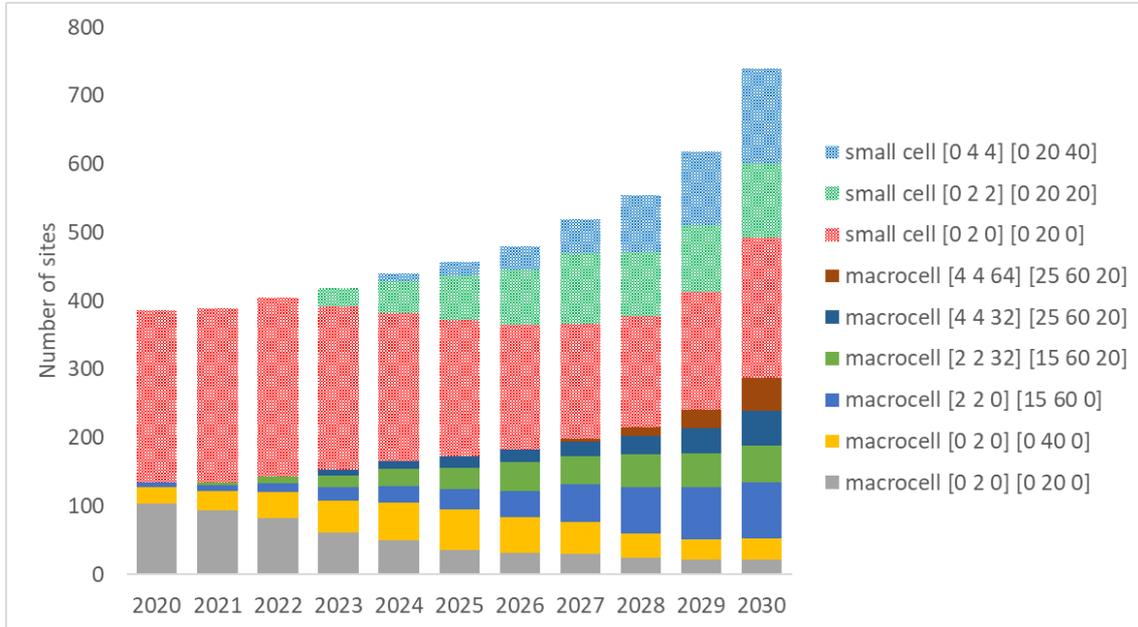
3.2 Number of sites

As demand increases the network requires more sites with improved capabilities. However, all demand notspots (i.e., areas with insufficient coverage and/or service) are different and so there is not a single network improvement that suits all notspots.

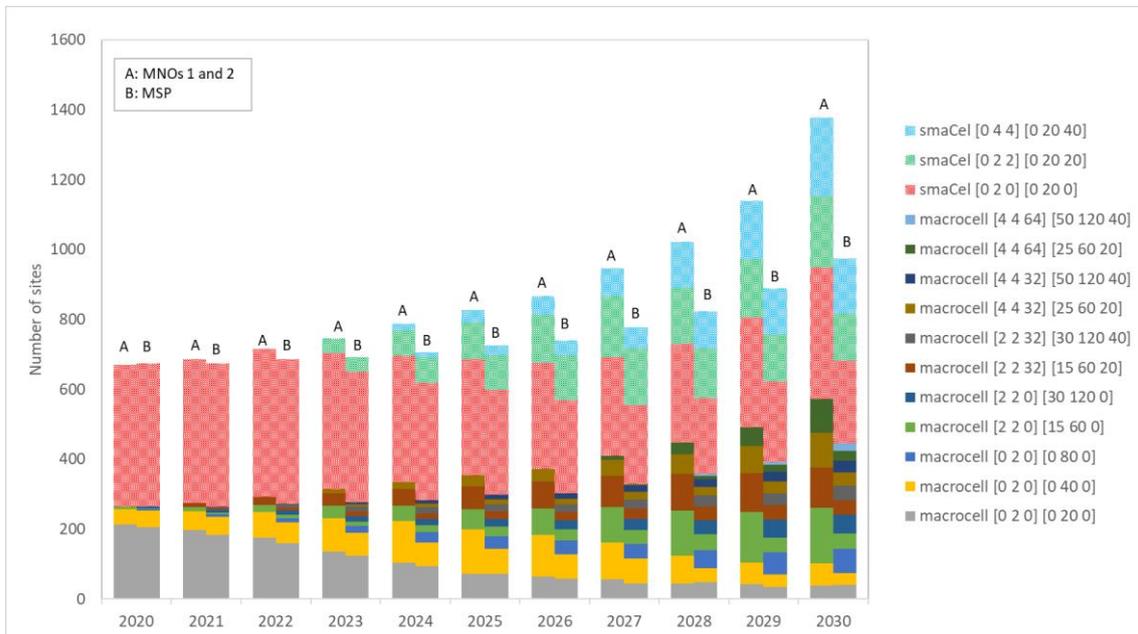
Fig. 3a shows the site count breakdown for InP_1 . The first pair of square brackets contains information about the number of antenna elements, whereas the second pair of square brackets contains information about the available bandwidth in MHz for each frequency band. In each pair of brackets there are three values that correspond to the three frequency bands employed: sub 1GHz, low (from 1.4 to 2.6 GHz) and medium (from 3.4 to 3.6 GHz). Here we see that low capacity sites decrease in volume over time but are still present in the network even in 2030 due to the spatial distribution of the demand. The SE in any given year is a blend of the efficiency that corresponds to all modelled site specifications in that year. We can see that any given year a range of network improvements that are most cost effective depends on the type of the demand notspots to be tackled. For example, in 2021 equipping macrocells with medium frequency has similar preference to installing new small cells. In 2023 swapping older small cells for those that support medium frequency are preferred to equipping macrocells with more antennas in the lower bands.

Fig 3. Number of sites: a) MNO_1 ; b) MNO_1 and MNO_2 (A) and MSP (B). The first bracket in the legend provides the information of the MIMO order at the sub-1GHz, low and medium bands respectively, while the second bracket contains the information about the bandwidth in MHz available at each band.

a)



b)



Sharing the network resources means that macrocells can have double the amount of spectrum, compared to the individual InP case. Sharing causes the site count to drop, compared to the individual case, and this is expected because the network is mainly capacity limited. The site count does not get halved by sharing, even after 10 years which equals to the lifetime of a

macrocell. This is because the demand increase may not justify the additional cost of supporting a greater bandwidth. Note that more bandwidth and antennas will increase both CAPEX and OPEX but may not lead to a proportional increase in site capacity particularly as the order of MIMO increases. In this case a new site may be a more cost effective option still. Fig. 3b shows the number of sites when each of 2 tenants has their own dedicated infrastructure set vs. when the two tenants work together by:

- Making sites in their existing individual infrastructure sets multi-tenant and hence capable of serving demand from either tenant. These sites may remain equipped with the spectrum holding of the original single infrastructure set or be upgraded to have the spectrum of both infrastructure sets to address demand notspots.
- Deploying new multi-tenant sites with the spectrum of both original infrastructure sets if required to address demand notspots.

This is a brownfield type roll out based on the existing individual infrastructure sets and improving the capacity of these existing sites or adding new sites over time as needed.

4 Cost Assessment

The cost evolution over time is shown in Fig. 4a, whereas Fig. 4b shows the total CAPEX and OPEX of the two options over the 10 year period compared. Fig. 4a shows that for all the years the total cost per year of the multi-tenancy scheme is lower than the cost of the sum of the individual solutions. Fig. 4b shows that the cost reduction is 14.9% for combined CAPEX and OPEX values. The net present value (NPV) was not used to derive the results shown in Fig 4b.

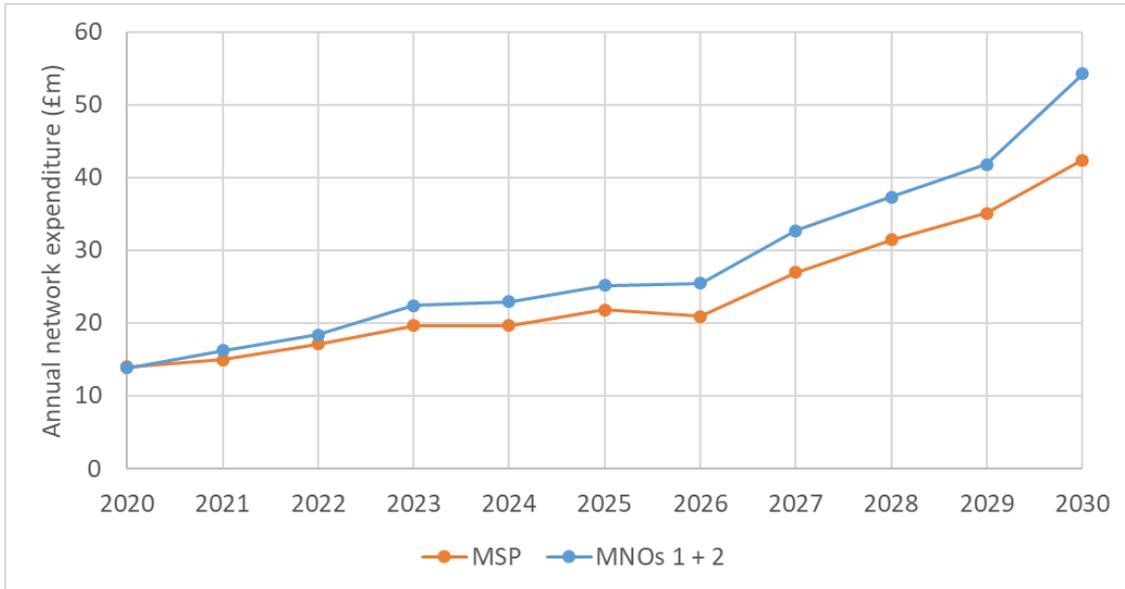
Providing eMBB services via a multi-tenant network shows some cost advantages. Sharing of sites, equipment, spectrum and site transport means that some costs, such as site acquisition and rental, can be split in half for the two MNOs, but other costs, such as active equipment, potentially remaining as duplicates due to the sites being equipped with double the spectrum and hence capacity if needed. The main savings arise from this potential to share some of the CAPEX and OPEX of these multi-tenant macrocell antenna sites which hold double the spectrum quantity, compared to individual sites. On the other hand, the CAPEX and OPEX of the edge cloud sites scales more with resource utilisation, so there is reduced gain from sharing.

Because sharing is assumed to begin in 2019 and the macrocells have a lifetime of 10 years, savings from sharing materialise over an extended period of time. Cost savings when all macrocells have been refreshed to potentially take advantage of carrier pooling, i.e. in the last year, 2030, is 21.8%.

While LTE-A networks will arguably be able to evolve to include the same air interface enhancements and additional spectrum as a 5G NORMA network, we would expect the 5G NORMA architecture to facilitate faster roll out of these enhancements due to the virtualisation and centralisation of network functions and the ability to co-ordinate resource usage across a number of antenna sites to form network slices providing a more seamless experience. Additional features such as multi-connectivity in multi-tenancy 5G networks may improve the coverage confidence and reliability of service giving the user a more consistent and better QoE that will improve their willingness to pay and hence potential for incremental revenues from 5G over LTE-A networks.

Fig. 4 a) Total CAPEX and OPEX over time; b) Total Cost of Ownership for 2020-2030

a)



b)

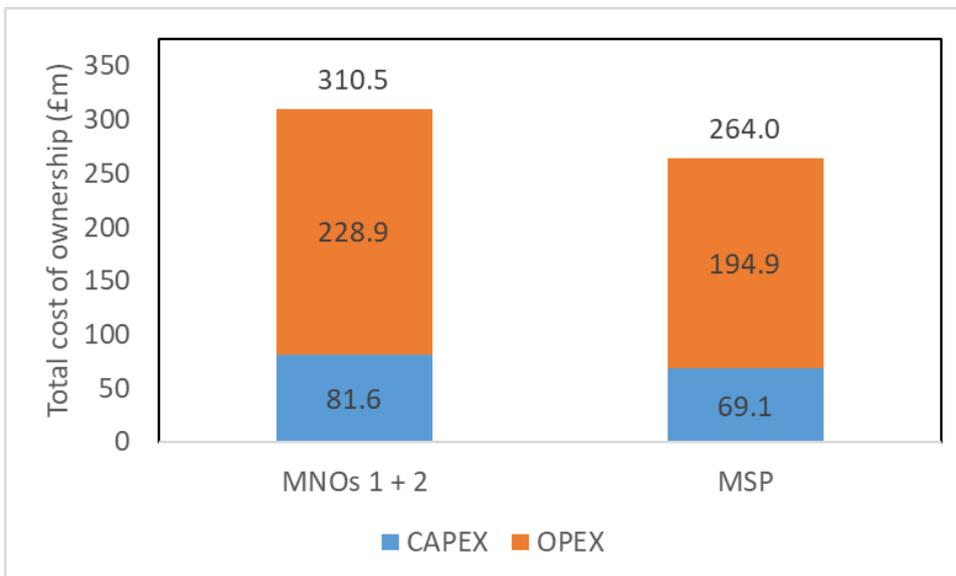


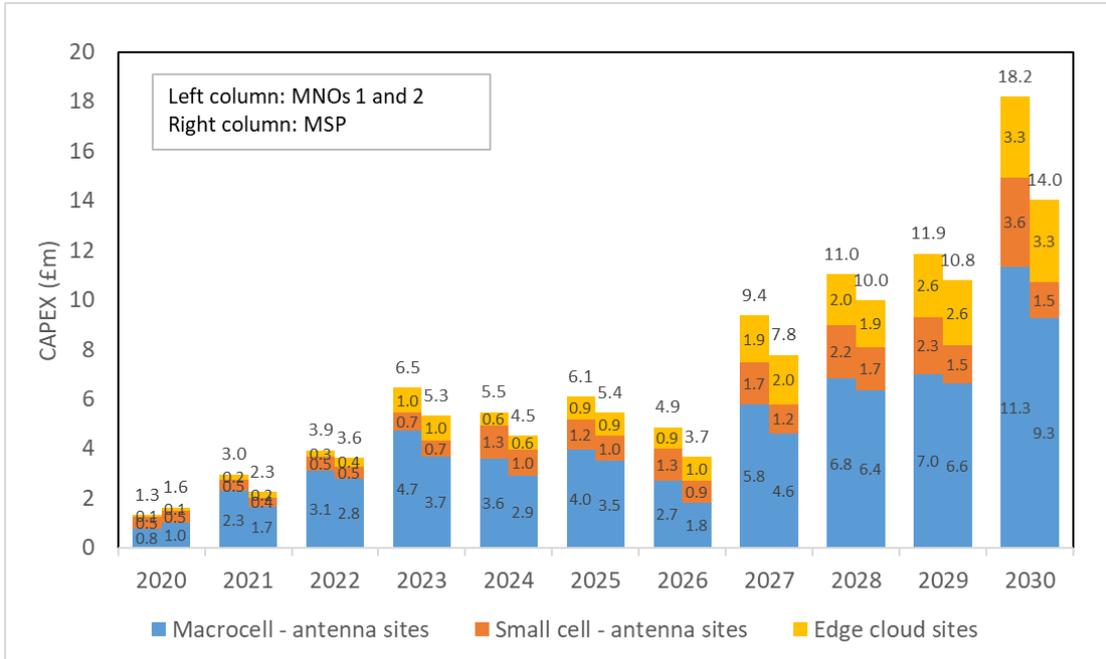
Fig. 5a shows the cost comparison for CAPEX. For all years, there is a cost reduction, and the cost reduction for the period 2020-2030 is 15.3%. The introduction of sharing in 2019 means that some of the demand of one service provider can be served by the other's infrastructure. This eliminates notspots (blackspots) of coverage by better utilising the existing site locations in the shared infrastructure sets rather than having to add new sites to the individual infrastructure sets. This is translated into less CAPEX spent in the first few years in the multi-tenant case. There is a reduction in CAPEX in almost all years due to the:

- Reduction in macrocell count, because of the advantage of more bandwidth and higher potential for closer propagation paths with two site portfolios of locations to choose from.
- Reduction in small cell count and edge cloud site processing required because of better utilisation of resources.

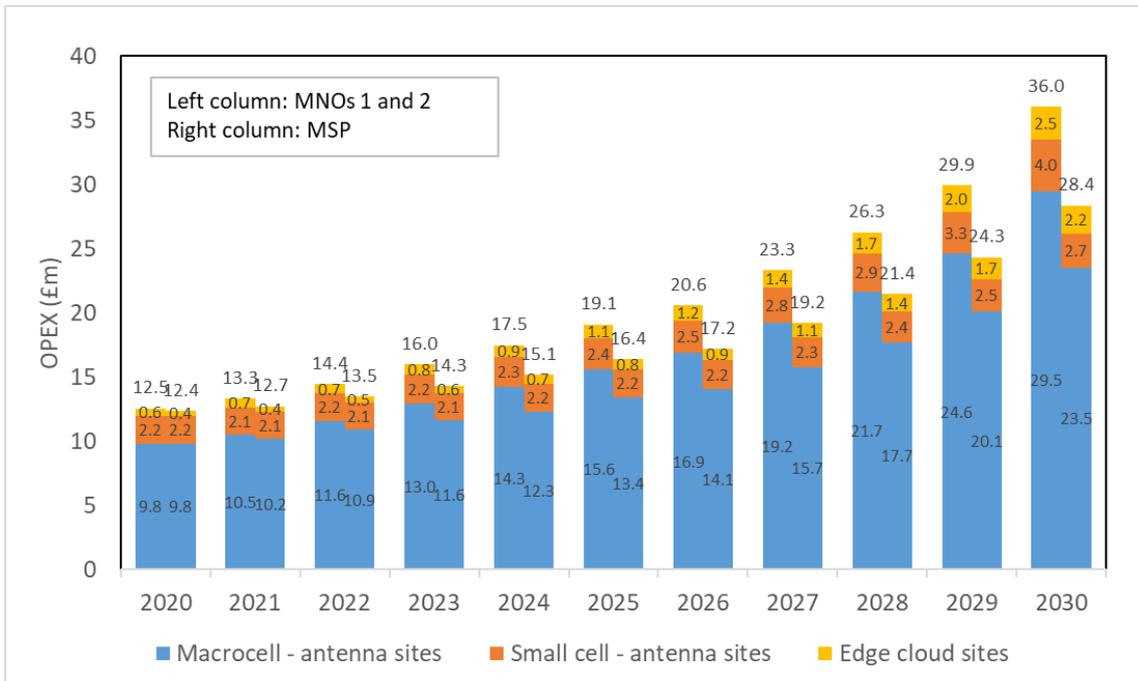
In Fig. 5b the comparison of OPEX is shown. For all years there is a cost reduction and the cost reduction for the period 2020-2030 is 14.8%. OPEX reductions each year are more apparent for macrocell antenna sites than for edge cloud sites. This is because the OPEX of edge cloud sites are more closely related to site utilisation. However, for antenna sites there are large OPEX components which remain largely fixed regardless of site utilisation or capability each year, such as site rental, which can be shared amongst the tenants being served.

Fig 5. Cost evolution over time: a) CAPEX; b) OPEX.

a)



b)



5 Conclusions

In this article we have analysed the cost of a multi-tenancy scheme for a 5G RAN network, and compared against the cost of two single-tenant networks. The analysis was performed within 3 boroughs of central London, United Kingdom, over the period 2020-2030. We considered C-RAN architecture and the costs arising from new and upgrades of antenna sites (macrocells, and small cells) and of their transport towards the central cloud, from upgrades in edge cloud sites and of their transport towards the central cloud.

The results show that with each year the multi-tenancy scheme leads to a cost of ownership reduction compared to a scheme where two operators deploy their networks independently. The total cost reduction over the period 2020-2030 for CAPEX and OPEX is 14.9%. The cost reductions achieved for CAPEX and OPEX are 15.3% and 14.8%, respectively. The savings in cost of ownership compound with each additional year, because multi-tenancy leads to postponement of new antenna site deployment and to reductions in running costs. The former, CAPEX reduction, is owed to opportunities arising to MSPs service providers from sharing pooled bandwidth resources and closer proximity to demand hotspots which may be spatially-independent to each provider. Coordinated resource management and reduced propagation paths lead to more efficient network utilisation. The latter, OPEX reduction, is a consequence of the lower site volumes in the multi-tenant case and the ability to share fixed site costs such as site rental for the infrastructure which is deployed.

Future research work will include investigating multi-service network cost savings in the proposed 5G NORMA architecture. There are indications that without multi-tenancy the cost of supporting services that require high coverage confidence and reliability may not be cost effective to be delivered over a single-tenant infrastructure which was designed for mobile broadband. Future work will also consider sensitivity of multi-service and -tenancy results to factors such as demand growth assumptions.

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