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Resource Analysis and Cost Modeling for End-to-End 5G Mobile Networks

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Abstract. 5G network demands massive infrastructure deployment to meet its requirements. The most cost-effective deployment solution is now a challenge. This paper identifies a cost implementation strategy for 5G by reformulating existing cost models. It analyses three geo-type scenarios and calculates the total cost of ownership (TCO) after estimating the Capex and Opex. The calculations are narrowed to specific cities for clearer understanding instead of the usual generic estimates. An end-to-end 5G network resource analysis is performed. Our result shows that by the end of first year Capex constitutes over 90% of TCO for urban scenarios. Also uniform capacity deployment across geo-types impose severe investment challenges.

Keywords: 5G, Capex, Opex, TCO, End-to-End, Fiber, Microwave, CRAN, Backhaul, and Core Network.

1 Introduction

The growth of mobile communications since inception in the 1980s indicates that capacity is increasing along with rising demands for higher data rates. This trend has now witnessed four generations of mobile networks. Current research anticipates the next generation of mobile networks (NGMN) around 2020 [1]. The rate of revenue growth from wireless networks has not been proportional to the exponential increase in the networks over the years. Telecommunication companies in the UK suffered revenue fall in 2017 [2] despite raising demand. The impact of continuous traffic upsurge on network infrastructure has been a challenge for Mobile Network Operators (MNOs) [3]. Balancing the capacity needs of the networks with profitability is now a growing source of concern for MNOs.

MNOs must devise innovative ways to bring down cost while providing enhanced services to customers [4]. The crucial challenge of realizing 5G is becoming more economic than technological [5].

It is important that suitable cost models are devised and applied to ensure an efficient use of resources to optimize Capital expenditure (Capex) and Operational expenditure (Opex). A detailed discussion on the TCO model for backhaul deployment was done by [6]. The study identified critical cost factors in order to achieve a cost-efficient strategy after considering two technology options: fiber and microwave. Our study shares some similarities with this work as it relates to cost models for wireless network. We extended the analysis to cover an end-to-end of the network and narrowed our discussion to three geo-type scenarios.

The idea of Centralized or Cloud Radio Access Network (CRAN) has been proposed by many studies. [7] shows that centralized Baseband Unit (BBU) is a viable option to save cost. Their considerations comprise cost comparisons in relation to baseband pooling and virtualization gains. This method is important for cost reduction towards TCO. But our analysis extend beyond the CRAN to encompass the entire mobile network end-to-end. We explored the deployment of 5G network by analyzing the key performance indicators. The number of small cells and macro cells were calculated for our case study cities - Lucca, Bristol and London.

Our paper reformulated earlier models to estimate the Capex, Opex, and TCO for the different geo-type scenarios. Some assumptions were considered in applying our model. Based on the results we recommend a 5G deployment strategy that would improve network cost efficiency.

The rest of the paper is structured as follows. Section 2 describes 5G Networks in detail. In Section 3, we present our cost model with analysis on the different aspects of the formulations. In Section 4 our case study is discussed with results while Section 5 concludes the paper and presents our future work.

Table 1. 5G Disruptive Capabilities [3, 8]

KPI	Requirement	Description
Peak data rate	≥ 10 Gbps	Low mobility
Peak data rate	≥ 1 Gbps	High mobility
Availability	99.999%	Reliability
Data traffic density	≥ 10 Tbps/km ²	Network throughput per km ²
Device density	≥ 1 Million/km ²	Connected devices per km ²
Energy consumption	$\leq 10\%$ of 4G	Total energy consumption
Latency	< 1 ms	10x reduction in 4G latency
Mobility	Up to 500 km/h	Speed between Rx and Tx
Network Opex	$\leq 20\%$ of 4G	Total network management Opex

2 5G Network Architecture

To achieve the target of 1000x capacity, 5G networks will adopt ultra-dense small cell, millimeter wave (mm-wave), and massive MIMO [9]. The NGMN would converge diverse technology types to deliver the key performance indicators (KPIs) as shown in Table 1. It describes 5G disruptive potentials and the superior KPIs.

2.1 Wireless Access Networks in 5G

5G will consist of 3 spectrum layers namely - Lower, Middle and Upper frequency bands, corresponding to 700MHz, 3.5GHz and 26GHz respectively. The use of higher frequency for future mobile networks has become imperative for small cells. The mm-wave spectrum range of 30GHz to 300GHz is attractive for 5G cost reduction strategy because it opens more room for spectrum and permits higher data rates [10]. However, mm-wave suffers increased path loss beyond 200m [3]. Experimental results show that the compression of higher order antenna elements against the shorter wavelength of the mm-wave bands compensates for the path loss. Massive antenna elements are projected to be as much as 10x the number of streams in service to all terminals, compared to present MIMO [9].

2.2 Cloud Radio Access Networks

The concept of Cloud or Virtualized RAN is one that basically divides the functions of the gNodeB (gNB) and centrally positions it at greater distance (up to kilometers) from the Remote Radio Head (RRH), to a shared pool of virtualized BBU [4]. This increases spectral efficiency, throughput and reduces equipment and power cost at cell sites. In 5G New Radio (NR) transport architecture, BBU is split into RRH, Distributed Unit (DU) and Central Unit (CU). CRAN is viewed as an enabler for 5G dense networks. It benefits the ultra-dense cell structure by the avoidance of inter-cell interference through centralized management and distribution of intelligent resource [11].

5G Fronthaul and Midhaul have evolved with the concept of CRAN. The portion of wireless architecture referred to as fronthaul is the link between DU or radio controller and the RRHs. The DU interfaces with the RRH through an optical fiber connection called enhanced Common Public Radio Interface (eCPRI). The eCPRI link forms the fronthaul of the Network as Fig. 1 shows. This imposes strict latency and synchronization requirements [12][13]. Different options of functional splits are now being proposed [14].

According to [4], BBU centralization can provide as much savings as 50% Opex and 15% Capex. Also, MNOs expend as much as 80% Capex on RAN. This implies that gNB infrastructure constitute significant cost component for RAN [3], which could reduce considerably with the use of CRAN and substantially decrease TCO.

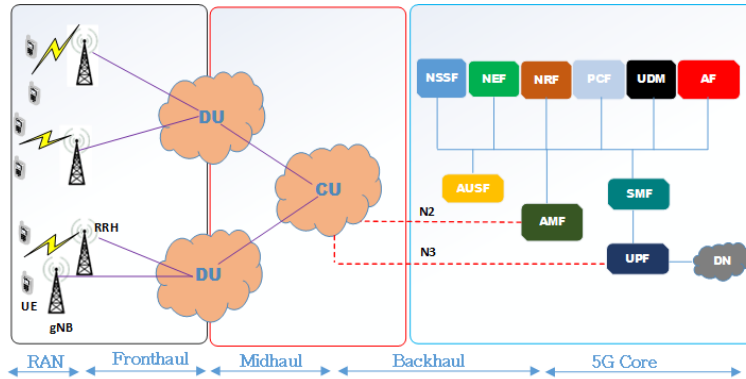


Fig. 1. End-to-End 5G Mobile Network Architecture

2.3 Multi-access Edge Computing

Multi-access Edge Computing (MEC) is an innovative concept that converges telecom and information technology applications by orchestrating cloud-based services at the edge of computing networks [15]. MEC run applications nearer the edge of the network. It brings the system closer to the end users and hence reduces latency, network congestion and creates an efficient backhaul and core networks. 5G latency dependent applications and services would benefit from this strategy, when distributed around the network edge. MEC is a promising innovation for 5G success and would reduce the cost of its implementation.

2.4 Backhaul for 5G Network

Backhaul or transport network, is the connection that transports data between the CU and 5G Core based on the N2 and N3 interfaces. The backhaul link is dimensioned to meet the required peak data rates and high-speed applications. This connection can be either wired or wireless. Different backhaul solutions include microwave, fiber optics, meshed wireless, copper cable and Free Space Optical communication (FSO). Contemporary 4G networks mostly use either fiber or Line of Sight (LOS) solutions.

The topology of fiber backhaul deployment has a structure of either in a tree or point-to-point (PtP) topology. In PtP the central office (CO) connects one optical line terminal (OLT) through a devoted fiber to an optical network unit (ONU) in the user/client premises. These devices perform signal conversions from electrical to optical and vice versa.

In a tree-based approach, such as Passive Optical Network (PON) or Active Optical Network (AON), one OLT is linked to multiple ONUs through splitting and switching devices located in street cabinets [6]. Fiber optics are transmitted across long distances starting from the transponder and existing the node at designated port. Amplifiers are installed about every 80 km to amplify fiber links that suffers attenuation over those distances.

The expected huge data traffic from 5G ultra-dense small cells that would be connected via the backhaul to the core network imposes extreme requirements in terms of capacity, energy, latency, and cost [12]. It becomes important to devise innovative backhaul provisioning to cater for these extreme requirements.

2.5 Core Network

The Core Network is the control hub of a telecom network infrastructure. Mainly it performs aggregation, authentication, charging, switching, service invocation and gateway functions. This involves the control plane such as the Access and Mobility Management Function (AMF), Session Management Function (SMF) or Authentication Server Function (AUSF) and the data plane involving User Plane Function (UPF).

Two key innovations are being proposed that are timely for 5G network architecture. These are software defined networking (SDN) and network function virtualization (NFV) [3]. SDN basically separates the forwarding of data function from the control using software. This makes a dynamic architecture that is much easier to adapt, manage and cost-effective to implement [12]. New developments are likely to come about due to SDN capabilities, one of which is the possibility of a reduced core network infrastructure [3].

NFV technology enables key network functions to be executed in software environment by enabling scalability and flexibility in programmable network slices. NFV creates the possibility of shorter deployment time and the use of commercial off the shelf (COTS) based solutions instead of proprietary hardware that are usually vendor specific [3]. The availability of COTS solutions will lead to reduce deployment cost.

2.6 5G Use Cases

The NGMN will witness much higher bandwidth with lower latency and massive interconnection of devices. The use cases can be classified into three main categories -

massive Machine Type Communication (mMTC), enhance Mobile Broadband (eMBB) and Ultra-Low Latency Communications (URLLC). Most of these 5G use cases depend on computing intelligence requiring sensor networks and driven by virtual reality and tactile internet. The capabilities of these uses cases are described in Table 1. Their implementation would pave the way for diverse business concepts at various levels of connectivity [8]. This will enrich the prospects of commercial involvement in the deployment of the NGMN.

3 Cost Model

The 5G objective calls for considerable planning. The usual resource over-provisioning strategy often result in network resource under utilization and high energy consumption [5]. We devised our model based on the following assumptions:

Table 2. Demographic, cell site and traffic capacity calculations

	Lucca	Bristol	London
Population	92,155	452,790	8,850,000
Area (km ²)	185.5	110.0	1,572.0
Population Density (per km ²)	496	4116	5629
User Density (per km ²)	50	412	563
Traffic Capacity (Gbps per km ²)	25	206	282
Mean Traffic Capacity (Mbps)	510	500	501
Number of Users per Cell	4.9	41.2	56.3
Small Cell (SC)	1850	1100	15720
Macro Cell (MC)	71	42	605

- 5% of subscribers simultaneous usage of network;
- 50:50 wired to wireless backhaul deployment ratio;
- 2.5% annual inflation rate;
- Fiber deployment option: cascaded splitter;
- Cost of Core network upgrade is 10% of RAN deployment cost [3];
- Small and Macro cell radius 200 m and 2 km.

3.1 Capacity Planning Estimation

The network coverage and capacity analysis will include the following, type of information, coverage area available spectrum, subscriber forecast and traffic density. The demographics for the three cities in our case study from where other calculations such as cell range, number of cells, users per cell arise are presented in Table 2.

3.2 Coverage, Cell Site and Traffic Capacity (TC) Calculation

Area of the hexagonal shape is given by the following equation:

$$\left[\left(3\sqrt{3} \right) / 2 \right] \cdot d^2 \quad (1)$$

TC = Pop. density x 10% subscription x 5% usage x data rate Hence number of small and macro cells for coverage, traffic capacity and mean traffic capacity are shown in Table 2.

The mean traffic capacity per user (MTC) equals to the cell capacity divided by the number of users. MTC is approximately 500 Mbps.

3.3 Total Cost of Ownership

Our research calculates the total cost of 5G deployment to equal the summation of the total cost of Capex and Opex. A cost model summary of non-sharing

infrastructure is presented

$$TCO_{5G} = \sum_{i=1}^{N_c} Capex_{5G} + \left(\sum_{i=1}^{N_o} Opex_{5G}_{[yr/infl]} \right) N_{yrs} \quad (2)$$

TCO_{5G} = Total cost of 5G network deployment

$Capex_{5G}$ = Sum of capital expenditures

$Opex_{5G}$ = Sum of operational expenditures plus inflation

N_{yrs} = Number of years used for Opex calculation

The Total Cost of Ownership for 5G network consist of Capex and Opex for the end-to-end stretch of wireless network. Reflecting the network portions in the TCO is given as follows

$$TCO = Capex_{[Acc+BH+CN]} + Opex_{[Acc+BH+CN]} \quad (3)$$

Where Acc, BH and CN denotes the Access, Backhaul and Core portions in the wireless network. Our model performs joint calculations for the Access and Backhaul segments of the network, particularly for some Opex cost factors such as energy consumption, maintenance and reparation cost. This is an error avoidance strategy. At points of convergence, such as cabinets, the distinction between Access and Backhaul for the purpose of Opex calculation diminishes greatly. In calculating the cost of Core network upgrade, we followed [3], which assumes 10% of RAN deployment cost as the cost of Core network upgrade.

3.4 Capex calculations

Capex is the capital expenditure which refers to a one-off-investment cost used to acquire or upgrade physical assets or infrastructure. Our formulation comprises the summation of equipment, infrastructure and installation cost plus spectrum licence fee.

$$Capex = \sum_{i=1}^{N_{Eq}} Cost_{Eq} + \sum_{i=1}^{N_{Infra}} Cost_{Infra} + \sum_{i=1}^{N_{Insta}} Cost_{Insta} + \sum_{i=1}^{N_L} Cost_{Lfee} \quad (4)$$

Equipment cost This refers to all cost connected to the acquisition of equipment both for fiber and microwave cost components. Fiber and microwave equipment cost are modelled as follows

$$Cost_{Eq}^F = \sum_{i=1}^{N_{OLT}} Cost_{OLT} + \sum_{i=1}^{N_{ONT}} Cost_{ONT} + \sum_{i=1}^{N_s} Cost_s \quad (5)$$

$$Cost_{Eq}^{Mw} = 2N_{Mwlink} \cdot Pr_{ant} + N_{sw} \cdot Pr_{sw} \quad (6)$$

Equation 4 follows that of [6]. Where $Cost_{OLT}$, $Cost_{ONT}$ and $Cost_s$ denotes cost of OLTs, ONTs and Splitters. Also, N_{Mwlink} , Pr_{ant} , N_{sw} and Pr_{sw} represents the number of links used for microwave, antenna price, number of switches and unit price of switches.

Infrastructure cost This refers to the total cost needed to deploy or lease communication infrastructure. We have associated fiber cost to the infrastructure component because the fiber length determines the duct and trenching length. It works better when these components are factored in common. On the part of microwave, the infrastructure cost include cost associated with microwave hubs, masts and antennas.

$$Cost_{Infra}^F = L.(Cost_F + Cost_{CW}) \quad (7)$$

Where L denotes length of trenches, whereas $Cost_F$ and $Cost_{CW}$ represents cost of fiber and civil works. The formulation for microwave is as follows

$$Cost_{Infra}^{Mw} = \sum_{i=1}^{N_{hub}} (N_{Mwhub} \cdot Pr_{hub}) \quad (8)$$

Where N_{Mwhub} denotes number of microwave hubs and Pr_{hub} its unit price.

Installation cost The installation component captures man-hours required to perform the necessary installations, wiring, preparation of sites, technician salary and travel time to and from site locations. The formulation is given by [5].

$$Cost_{Insta} = \left[\sum_{i=1}^{N_{link}} (IT_i + 2T_i) \cdot TS \right] NT_i \quad (9)$$

Where IT_i and T_i , denotes installation and travel time, TS and NT_i represents technician salary and number of technicians respectively.

3.5 Opex calculations

Opex translates to operational expenditure, which means the recurring cost needed to continuously operate the business daily. One of the key cost components for network operators is power consumption. We have formulated our Opex cost by remodelling that given by [16]. The major Opex cost components are energy consumption, maintenance and fault management or reparation cost. Our model for the Opex calculation is given as follows

$$Opex = 365 \left[\sum_{i=1}^N (24P_h \cdot C_E) \cdot N_C \right] + \sum_{i=1}^{N_m} C_M \cdot C_{F_c} \quad (10)$$

Energy consumption Electricity consumption is an important Opex cost driver. Between 70% - 80% of energy requirement of the network is projected to be consumed by the access network [8]. In view of the expected ultra-dense network, innovative energy management schemes are needed to cut operating cost of 5G network. We have derived the energy cost by adding the consumption cost of every electrical equipment in the different locations within the network such as those in the central office, cell sites and street cabinets.

$$Cost_{En} = 365 \left(\sum_{i=1}^N 24P_h \cdot C_E \cdot N_C \right) \quad (11)$$

Where P_h , C_E and N_C represents electric power needed per hour, cost of one kWh of energy and number of cabinets, which in this case could mean, Central Office, cell sites or street cabinet.

Maintenance expenses are regularly incurred to keep the network running at optimal performance. This may consist of routine system upgrade, equipment testing, and software licence renewal among others. Our maintenance cost model is given by [6].

Maintenance cost

$$Cost_M = \sum_{i=1}^N (C_{om} + C_{ab_m} + M_{Mw} + S_{wlic}) \quad (12)$$

Where C_{om} , C_{ab_m} and M_{Mw} denotes the cost incurred from maintaining central offices, street cabinets and microwave links. S_{wlic} reflects licence fee for periodic software upgrade. Details of this formulation can be obtained in [6].

Fault management/repairation cost Repairation of system failures such as fiber cut, and other natural or man-made faults incur cost. We have remodelled this cost component to reflect the probability of failure employing the Weibull distribution which is mainly applied in reliability engineering from [5].

Table 3. Values used for cost calculations

Components / parameters	Price (Euros)	Source
OLT core shell	5000	[17]
OLT cross connect	8000	[17]
OLT service shell	5000	[17]
ONT	150	[17]
Technician salary (hour)	52	[6]
Small / large microwave antenna	200 / 2000	[6]
Power splitter (1:16 / 1:32)	170 / 340	[6]
Fiber (km)	80	[6]
Trenching (km)	45000	[6]
Microwave link	400	[13]
Yearly cell site rent	8000	[13]
Microwave hub	800	[13]
Electricity cost	0.2 per kWh	[16]
Energy consumption per hour	1.4 kW	[16]

$$Cost_{F_m} = \left[\sum_{i=1}^N (FR + Pen) \right] P_f \quad (13)$$

Where FR and Pen denotes failure reparation and penalty cost respectively. P_f represents probability of failure following Weibull's distribution.

$$FR = \left[\sum_{i=1}^{N_f} (MTTR_f + 2T_i) . TS \right] NTR_f \quad (14)$$

Where $MTTR_f$ reflects mean time to repair failure and NTR_f denotes number of people to repair failure. Further details can be obtained in [5].

4 Case Study

Table 3 presents cost values used.

Our result in Fig. 2 (a) shows that fiber is consistently the most capital intensive cost factor in all scenarios. The result reveals significant cost difference between fiber and microwave for Lucca than Bristol and London.

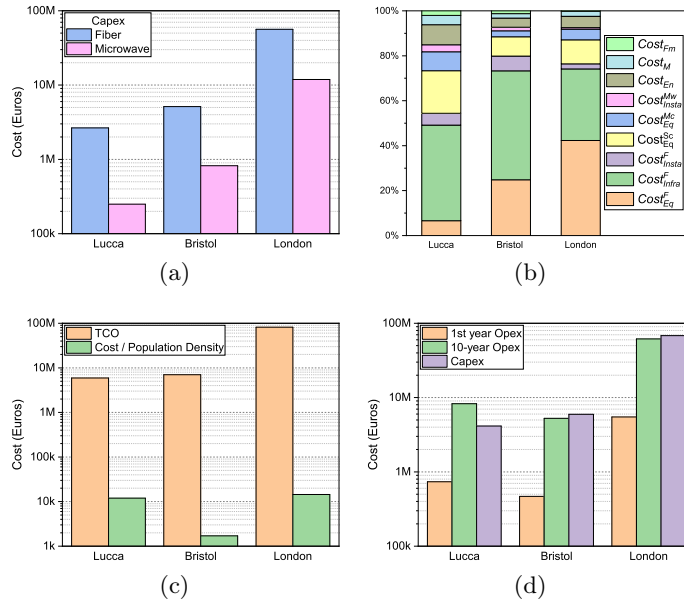


Fig. 2. (a) Capex comparison for fiber and microwave. (b) TCO breakdown across all scenarios. (c) TCO and cost per population density comparison showing Bristol with a higher TCO but much lower cost per population density than Lucca. (d) Capex, 1st year Opex, and 10 years cumulative Opex comparison.

Whereas the later two cities have 16% and 21% difference respectively, Lucca has as much as 56%. It is relatively more expensive to deploy fiber in Lucca than in the other two cities. This identifies the most cost-effective backhaul deployment for the NGMN.

The cost breakdown in Fig. 2 (b) presents infrastructure as the most dominant cost component constituting at least 30% of TCO in all scenarios.

The TCO as in Fig. 2 (c) shows that London has the highest deployment cost and Lucca the lowest. Bristol has the lowest cost per user, which validates the result that Lucca is relatively more expensive in comparison. Also Lucca with approximately 1% of London's population requires as much as 12% of London's TCO. This is due to the role of area and population density in the economies of scale.

Fig. 2 (d) shows the result of three comparisons. The ten years Opex has been calculated with compounding inflation rate. It shows that capital expenditure constitutes over 90% of TCO for Bristol and London by the end of first year, while Lucca's operational expenditure was as much as 15% for the same period. But after ten years, while Opex was still below Capex by 12% for Bristol and 10% for London, Lucca's Opex exceeds Capex by 50%. This trend depicts increasing operational expenditure cost as population density of the scenario decreases.

5 Conclusion and Future Work

We conducted an end-to-end analysis of 5G architecture. Given the 5G KPI's, we also calculated capacity requirements for three selected cities, including the number of small cells, macro cells and traffic capacities. We reformulated existing cost models to estimate the total cost of ownership by calculating Capex and Opex for the different segments of the wireless network.

Based on the results, we conclude that investment consideration should be a function of the geo-type scenarios. As a result, 5G system capacity should be adjusted in less densely populated areas to allow for profitable deployment. In such areas wireless backhaul option becomes a compelling economic choice. Consideration should be given to a capacity trade-off in favour of coverage. However, the benefits accruable to a network when ubiquitous services are rendered should not be overlooked.

As future work, we intend to investigate the impact of infrastructure sharing in under neutral host concept. We also aim at revenue estimation for a projected number of years and make similar comparisons between the different scenarios. Finally, we aim to investigate the effects of application related cost on cost savings and revenue forecast for the NGMN.

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