Applicable Cost Modeling of LTE-Advanced and IEEE 802.11ac based Heterogeneous Wireless Access Networks

Vladimir Nikolikj
Vip operator -
Member of Telekom Austria Group
Skopje, Macedonia
E-mail: v.nikolikj@vipoperator.mk

Toni Janevski
Ss. Cyril and Methodius University
Faculty of Electrical Engineering and Information Technologies, Skopje, Macedonia
E-mail: tonij@feit.ukim.edu.mk

***Abstract*—In this paper, we propose applicable and comparative cost-capacity analysis of the heterogeneous wireless networks in order to determine the most cost effective radio network deployment strategies as a function of an extreme demand levels of even more than 100 GB per user and month. We perform the modeling by considering of the unit cost drivers relevant for the various base station classes which provide different coverage and high capacity performance, coming with the Long Term Evolution Release 10 (LTE-Advanced) radio access technology or IEEE 802.11ac Wi-Fi standard. Considering different amounts of available bandwidth in the 800 MHz and 2.6 GHz bands, the key finding is that the small cell solutions like femto cells and Wi-Fi are more cost efficient when new macro base station sites need to be deployed or when very high demand levels need to be satisfied. In all other evaluated cases, the importance of the spectrum size comes to the highest level together with the introduction of the LTE-Advanced carrier aggregation functionality. Also, we evaluate the economic gains of a joint deployment of femto/Wi-Fi sites from one side and macrocells from other side. We determine that instead of investing in additional spectrum or deploying denser macro network, mobile operators could compensate the indoor wall penetration losses by deploying different number of femto sites per floor or user per femto site, for still satisfactory level of QoS.**

Keywords-Wireless Heterogeneous Networks; Cost modeling; LTE-Advanced; IEEE 802.11ac.

I. Introduction

The rapid increase of mobile broadband services has resulted in a marvel of decoupling the traffic load from operator revenues. Flat service subscriptions nowadays, even further increases the challenge of the Mobile Network Operators (MNOs) to monetize on the data traffic. Hence, it is from the highest importance of the MNOs to deploy more cost effective networks that will respond to the increasing user demand. The forthcoming wireless network architectures become more heterogeneous, with hierarchically ranged Base stations (BS) sites/cells, as follows: macro (MaBS) to cover wider areas, and micro (MiBS), pico (PBS) and femto (FBS) complemented with particular wireless local area network (WLAN/Wi-Fi) to cover smaller areas. A number of papers have been published on modeling the cost-effectiveness by comparing the MaBS cell deployment with the small-cell deployment and suggesting utilization of joint or heterogeneous and even cooperative networks. Analysis of MaBS, MiBS and PBS HSPA cells capacity-cost comparisons including IEEE 802.11a, are provided in [1][2][3]. Cost comparisons of LTE with HSPA deployed MaBS networks and FBS solutions are extensively covered in [3][4]. Additionally, the evaluation of the economic gain provided by various deployments of FBS and MaBS for LTE mobile broadband services is outlined in [5].

In this article, we originally introduce the comparative cost modeling of MaBS, MiBS, PBS and FBS utilizing LTE-Advanced (LTE-A) RAT [6][7], alongside with Wi-Fi standard IEEE 802.11ac [8]. Considering the "up to date" initial and running cost drivers, together with the coverage and capacity specific parameters, we deliver results helping more easily to assess the most cost efficient manner to deploy the heavily-loaded, wireless heterogeneous networks. The special focus is put on the comparison between MaBS and various small cell deployments. As according to Analysis Mason [9], more than 80% of the mobile traffic is generated in indoors, we create long-term investment case study related to indoor office users. In order to determine more realistic cost-capacity performance modeling, besides already discussed wall attenuation and indoor coverage strategies in [3][4], additionally, we consider the performance of the carrier aggregation functionality of LTE-A RAT. For all deployment scenarios, we analyze the deployment of new sites and reusing the existing sites.

Still having in mind that each cellular network in reality consists of a mix of BSs, we conduct the joint heterogeneous network cost-capacity analysis as well. The assessment of the economic gains of joint deployments is done for the period of 10 years by using the discounted cost model in order to take into account the "time value of investment and running costs".

The paper is organized as follows. Sections II and III describe the analysis approach through elaboration of RAN specific coverage, capacity and unit cost estimates for various BS classes. In the next section, we perform investment modeling of various wireless network deployment strategies through the case study. Based on the results from Section IV, in Section V, we discuss the findings and analyze the most and less cost-effective scenarios separately deployed. In Section VI, we demonstrate the combined cost-capacity modeling of different wireless heterogeneous network solutions to satisfy high demand levels. A conclusion is drawn in Section VII.

 ISBN: 978-1-61208-360-5

II. Radio Access Network Coverage and Capacity Modeling

Consisted of numerous BS sites and Radio Network Controllers (RNCs), the Radio Access Network (RAN) of the MNO is deployed to provide services within the entire system coverage area denoted as A_{syst}. According to Johansson et al. [10], a BS of class i is characterised by a maximum average throughput or capacity T_{maxi} and cell range r_i related to coverage. Based on the purpose of use, a BS of class i could be equipped with radio equipment supporting up to three sectors and up to three different frequency carriers. The number of cells $N_{cel,}$ within the particular BS site i, is obtained as multiple of the number of supported sectors and frequency carriers. We model the coverage A_{cell} of a particular cell area of BS site i as follows:

$$A_{cell} = \pi \cdot {r_i}^2 \qquad (1)$$

The maximum path loss allows the maximum cell range to be estimated with a suitable propagation model, such as Okumura-Hata [12]. Based on [11], the calculation shows that urban cell range varies from 0.6 km at 2.6GHz to 1.4 km at 900 MHz. Since in this paper we focus on the urban dense area, according to Markendahl and Mäkitalo [3] and Markendahl [4], we consider 0.57 km range for MaBS. Based on the elaborations in [1][2], we estimate 0.27 for MiBS and 0.1 km range for PBS. FBS cell range in [3] is assumed at 0.050 km and in [13] in range of 0.01 – 0.030 km. According to Mölleryd et al. [14], we model the aggregated capacity of the system, T_{syst}, as follows:

$$T_{syst} = W \cdot N_{site} \cdot N_{cell} \cdot S_{eff} \qquad (2)$$

where W is allocated bandwidth in MHz, N_{site} is the total number of BS sites within the system coverage area A_{syst} and S_{eff} is the cell average cell spectral efficiency in bps/Hz/cell. Based on [6] [7] the average spectral efficiency for LTE-A varies from 6.6, 4.2 and 3.8 bit/s/Hz/cell for the indoor, microcellular and base coverage urban environments, respectively (environments are determined in line with [15]). With regard to the FBS deployment, interference problems to non-FBS cell occur with the creation of the so called "Closed User Group" deployment FBS model [16]. As proposed by [17], in adjacent-channel deployments (the FBS is deployed on a dedicated carrier), the coverage holes are considerably easier to minimize and control than when the FBS is deployed on the same carrier as the macro layer (co-channel deployment - sharing the channel with the MaBS network). Hence, in this article we consider FBS deployment in a different frequency band than MaBS. Currently, the LTE FBS are developed with 5, 10 and 15 MHz bandwidth (achieving up to 37, 75 and 112 Mbps in downlink, respectively) and available from 8 to 16 users simultaneously [18]. Choi in [13], indicates that 4G FBS will utilize the bandwidth of 20 MHz per carrier. We use the indoor average spectral efficiency of 6.6 bps/Hz and 20 MHz of spectrum for FBS with 50m coverage range. According to Xiao [19], it is very difficult to exceed 50-60% of the nominal bit rate of the underlying physical layer of Wi-Fi. Frame aggregations techniques are used to improve the Medium Access Control (MAC) layer efficiency [20].

TABLE I. RADIO ACCESS NETWORK - COVERAGE AND CAPACITY PARAMETERS.

BS Parameter/ LTE-A and IEEE 802.11ac	MaBS	MiBs	PBS	FBS	Wi-Fi
Range (km)	0.57	0.25	0.10	0.05	0.03
Coverage (km²)	1.02	0.19	0.03	0.008	0.003
Sectors	3	1	1	1	1
Carriers	1 – 3	1 – 2	1	1	1
Cells	3 – 9	1 – 2	1	1	1
Bandwidth (MHz)	20	20	20	20	80
Av. Cell SE (bps/Hz)	3.8	3.8	6.6	6.6	16.25
Av. Cell Capac.(Mbps)	76	76	132	132	1300
Av. Site Capac. (Mbps)	228	76	132	132	1300

According to Cisco [21], we consider the first-wave IEEE 802.11ac products operating in the 5 GHz band with 80 MHz and delivering up to 1300 Mbps (high end) at the physical layer up to 30 m coverage range. Based on the all above coverage and capacity estimates, we summarize in Table I, RAN coverage and capacity parameters related to different RAT as used in this paper.

III. Heterogeneous Radio Access Network Cost Modeling

We base our cost structure modelling to the methodology developed in [1] [5] by limiting to the capital investment to acquire and deploy the RAN (CAPEX), and the costs to operate the RAN (OPEX). We consider the BS equipment, BS site installation & buildout, backhaul transmission equipment and Radio Network Controller equipment as BS related CAPEX items and electric power, operation & maintenance, site lease and backhaul transmission lease as BS related OPEX items. Also, we evaluate the CAPEX and OPEX of system spectrum. Regardless that CAPEX consists of one-time expenditures, usually for practical reasons these expenditures are spread over several years, i.e., annualized. Still, according to METIS [22] an even more accurate model could be obtained by using present values instead of annualizing the CAPEX. In order to calculate the cost per item of type i in present value, according to Johansson et al. [2], we use the standard economical method for cumulated discounted cash flows yield by summing up the total discounted annual expenditures for the whole network life cycle (K years) as follows:

$$\mathcal{E}_i = \sum_{k=0}^{K-1} \frac{\alpha_{k,i}}{(1+\beta)^k} \qquad (3)$$

where $\alpha_{k,i}$ is the sum of expenditures, in terms of CAPEX and OPEX, occurred within year k of an item of type i and β is the discount rate. In all analyzed scenarios in this paper, we assume network life cycle of K = 10 years and that all BSs are installed during the first year of deployment. Additionally, according to Frias and Pérez [5], we use the discounted rate equalized to the cost of capital (a WACC - weighted average cost of capital) of $\beta = 12$ %. Consequently, the total discounted cost, C_{TOT}, of a wireless heterogeneous access network comprising of macro sites and small sites normalized per unit of area, can be approximated as follows:

$$C_{TOT} = \mathcal{E}_M \cdot N_M + \mathcal{E}_S \cdot N_S + \frac{\mathcal{E}_{SPECTRUM}}{A_{syst}} \quad [cost/area] \qquad (4)$$

where $\mathcal{E}_M$ *is the* total discounted cost of MaBS, $\mathcal{E}_S$ *the* total discounted cost of small BS (or Wi-FI BS), $\mathcal{E}_{SPECTRUM}$ is the total discounted cost for spectrum licenses, A_{syst} is the coverage area of entire operator's network and N_M and N_S is the average number of MaBSs and small BSs, respectively (in this paper, we will not consider the costs that are not related to the technical solution, such as customer care and marketing, as well as the average customer retention or subsidy costs). The cost estimates related to different RATs and BS classes will be derived in the next subsections.

A. Base Stations Unit Cost Estimates

The cost per BS is significantly different based on the BS type considered in this paper. For example, BSs providing bigger coverage imply a higher cost for equipment, site leases and installation whereas a small cells BS sites costs much less in those aspects. Nevertheless, according to Johansson et al. [2], fixed costs not directly related to the capacity of the BS are divided between many users in a MaBS so the cost per user may still be lower in many scenarios.

According to Markendahl and Mäkitalo [3], the estimates for year 2010 show that cost for deploying a new MaBS site in the urban area is 110 k€ including transmission and that the cost for radio equipment supporting three sectors and 5–20 MHz to 10 k€, yielding to total CAPEX of 120 k€. According to Johansson [1], CAPEX for 2-carrier and single carrier MaBS deployment is 20% and 40% lower than 3-carrier MaBS, respectively. Notice though that the costs for an LTE-A cellular network are hypothetical since the system is now being released to the market. Out of Johansson [1], we consider the price of a MiBS and PBS station equals 50% and 15%, respectively, of a single-carrier MaBS equipment, with a note that PBS needs 2 k€ for transmission, and MiBS and PBS requires 10 k€ and 2 k€ for the site deployment, respectively. According to Markendahl [4], on average the deployment of one FBS is around 1 k€.

Even prior the full standardization, some manufactures start to offer IEEE 802.11ac products. WLAN Access points (AP) for consumers are currently available at prices of around €160 [24]. Nevertheless, for the enterprise solutions there should be used WLAN carrier grade access [25] [26]. Johansson in [1], outlines that the carrier grade AP is 10 time more expensive than WLAN AP for consumers, and that cost for router and access getaway is 20 k€. Consequently, we assume that carrier grade access point supporting IEEE 802.11ac will cost around 1.5 k€, and additional 1k€ should be added per AP, assuming that the control equipment is divided between 20 APs.

Regarding the OPEX, Markendahl and Mäkitalo in [3] assume 30 k€ annual cost for the new MaBS site and Johansson in [1] considers 13.4 k€ for the single carrier MaBS by outlining an appropriate ratios of 1.15, 1.29, 0.67, 0.21 and 0.10 related to this cost for the 2-carrier MaBS, 3-carrier MaBS, MiBS, PBS and Wi-Fi BS. Consequently in this paper, we assume 20 k€ OPEX for the new 3-carrier MaBS site.

TABLE II. CAPEX, OPEX AND RESULTING DISCOUNTED COST ESTIMATES PER BASE STATION CLASS FOR GREENFIELD DEPLOYMENT (ALL AMOUNTS IN [K€]).

BS Class/ LTE-A and IEEE 802.11ac	Initial CAPEX (Investment)	Annual OPEX	Total discounted cost in period of 10 years
Macro (1 carrier)	72.9	15.5	152.67
Macro (2 carriers)	96.2	17.8	186.47
Macro (3 carriers)	120.0	20.0	220.15
Micro	35.8	10.4	90.73
Pico	13.5	3.4	31.26
Femto	1.0	0.5	3.72
Wi- Fi	2.5	1.6	12.17

According to Markendahl and Mäkitalo [3], we assume 10 k€ for the existing site. For the FBS, Markendahl and Mäkitalo in [3] estimates the annual operational cost to be 0.5 k€ per BS. To summarize the discussion on cost estimates, Table II outlines the resulting discounted cost per the considered newly deployed BS class as calculated according to (3).

B. Spectrum Cost Analysis

Alternatively, and if possible, MNOs could increase the number of carriers by adding additional spectrum, which could replace the deployment of new sites. This brings spectrum to an essential asset as it could be a substitute for new sites.

The more bandwidth that can be used at one site the higher the capacity. Currently, across Europe MNOs have licensed spectrum at different bands and the carriers in between are set at 800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz bands. All parts from the available bandwidth provide different performance for coverage and capacity.

MNOs are annualizing the CAPEX related to the spectrum licenses for the period of their validity, which is mostly 10 years and usually no more than 20 years. Additionally MNOs have OPEX per MHz related to the annual frequency charges.

From today's perspective and according to the ongoing developments in the European telecommunication markets, most of the used spectrum is amortized, excluding the part of the spectrum from 790 MHz to 862 MHz (so called Digital Dividend - DD) that was acquired by the MNOs in the past few years in most of the European countries. Based on the benchmark analysis of the data collected from the European National Regulatory Authorities websites [26], the average annual frequency fee per MHz is below 1 EUR/MHz and population and maximum 10 EUR/MHz and km². Furthermore, according to BEREC [26], the Figure 1 depicts the invested price in DD band per MHz and per km² (Note that, for Netherlands and United Kingdom the price is 1525 and 736 EUR/MHz/km².

According to PWC [27], the invested price in DD band per MHz and per population moves from 0.2 EUR in Croatia up to 0.8 EUR in Italy.

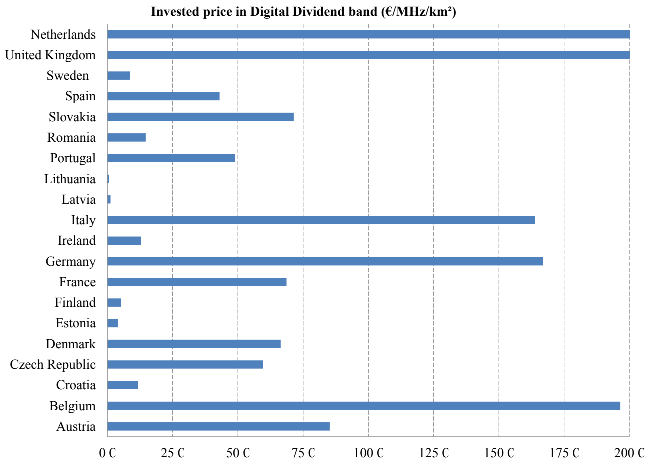

Fig. 1. Benchmark of the mean price (in €/paired MHz/km²) paid by the MNOs of the European Union Member States in the Digital Dividend (792-862 MHz) spectrum auctions.

IV. Investment Case Study

A. Case Study Description

According to Johansson et al. [2], the different BSs will minimize cost for different scenarios. Nevertheless, for the sake of simplicity, first we will perform cost modeling through case study of different base stations separately. Based on the results of separate analysis, than we will dimension the network of the analyzed service area as a combination of a of a macro layer solution, using existing sites and as much available spectrum as possible, with a supporting small cells network. Accordingly, based on the per unit cost estimates from Table I and Table II in this section, we will assess how the total investment cost (initial CAPEX) of the wireless network deployed within the particular area, varies as a function of the user demand. Furthermore, we will apply different deployment scenario combining the amount of the bandwidth and BS classes. In particular, we consider building of the new office center in the 1 km² urban indoor area through construction of ten 5 floor buildings hosting 10.000 workers. Consequently, we will not analyze the MiBS and PBS options out of the small cell deployments, but only the strict indoor solution of small cells represented by FBS alongside with the Wi-Fi. For the macro layer, we will consider the CAPEX needed for deployment of three-sector MaBS supporting three frequency carriers. Nevertheless, for the capacity estimates, we will consider that only single carrier is in use, to make the comparison between BS types simple.

In line with Figure 1, the cost of 1 MHz per the system area of 1 km² is negligible compared to the cost of even single carrier MaBS. Consequently, we will ignore the CAPEX inputs for the spectrum within the estimation of the total investment costs calculated according to (4).

TABLE III. Conversion of Load/User/Month to the User Data Rates (Mbps) and Capacity per Area Unit (Gbps/km²).

Demand	GB/user/month	Mbps/user	Gbps/km²
Moderate	44.0	0.407	4.0
High	110.0	1.019	10.0

B. Traffic Demand

Based on [28], in 2013 around 95% of the total global mobile traffic was generated by smartphones (62%), laptops (24.5%) and tablets (8.5%) with around 0.5 GB/month from smartphone user and 2.6 times more from the laptop users and 4.6 times more from tablets (only 3% of the users generated more than 5 GB/month and 24% more than 2 GB/month). The same source predicts that the average usage per month of smartphones will rise x 5 times (up to 2.7 GB) by 2018 having 66% from the total traffic and that tablet share will be more than 18%. Following the same ratios, we could draw conclusion that the average usage per month in 2018 will be around 12.2 GB and 6.9 GB for tablets and laptops respectively. Furthermore, [29] predicts an average N. American mobile user to consume 6 GB/month in 2017.

Consequently, in order to ensure future-proof network (e.g., beyond 2020), we will perform the dimensioning of the network from our case study with the following two demand levels: moderate demand or in average 44 GB/user/month and high demand of 110 GB/user/month.

We consider that the usage will be spread out over 8 hours per day, translating into a busy hour rate of 12.5%, in line with the industry standard [30]. Conversion of the load/user/month to the user data rates (Mbps) and capacity per area unit for 10 000 users (Gbps/km²) is given in Table III, for the 8 busy hours. In this paper, we consider uniform traffic distribution within the considered area.

C. Macro cellular Deployments

Assuming the spectral efficiency of 3.8 bit/s/Hz/cell of outdoor LTE-A RAT, the achieved capacity with a single carrier three-sector MaBS site is 114.0 Mbps, 228.0 Mbps and 342.0 Mbps with 10 MHz, 20 MHz and 30 MHz of spectrum, respectively (calculated in line with (2)).

1) Initial Scenario

Since a cell area of 1 km² corresponds to a cell radius of 0.57 km (according to (1)), our requirements on average user data rates during busy hours would be met even at the cell borders with the high broadband demand (~ 1.0 Mbps what is in line with the data rate of 1.0 Mbps as assumed in [11]).

Within the initial scenario, we perform the cost-capacity analysis using 20 MHz for the macro-layer in the 2.6 GHz band with the average spectral efficiency of LTE-A RAT. In accordance with [3], for the MaBS site re-use scenario, we estimate the total CAPEX of 20 k€ for existing site (the cost needed to upgrade an existing site is estimated to 10 k€ and the cost for radio equipment supporting three sectors and 5–20 MHz to 10 k€). Based on Tables I and II, Table IV summarizes the total invested costs for the moderate and high demand estimates. It is noticeable that the investment to satisfy the high demand with the implementation of the existing MaBS is almost half than the cost needed to ensure 2.5 times less capacity with new MaBS sites.

2) Wall Penetration Losses Compensation Scenario

When trying to compensate for the wall penetration losses, two options are possible according to Markendahl and Mäkitalo [3] and Markendahl [4]: building a denser 2.6 GHz network and deployment using 10 MHz within the 800 MHz band, i.e., better indoor coverage.

TABLE IV. INVESTMENTS AND CAPACITY (MACRO SITES INITIAL DEPLOYMENT - CASE 1).

Macro Initial Scenario (2.6 GHz)		Number of sites	Total CAPEX M€	Capacity (Gbps)
Site	*Demand*			
New	Moderate	18	2.16	4.1
New	High	44	5.3	10.03
Reuse	Moderate	18	0.36	4.1
Reuse	High	44	0.88	10.03

Markendahl and Mäkitalo in [3] calculated that in order to compensate the additional 12 dB of attenuation (the difference between operation in the 800 MHz and the 2.6 GHz band), 5 time denser network should build at 2.6 GHz band. Consequently, Table V summarizes the cost-capacity outcomes of this scenario. We can see that in order to compensate the wall penetration losses with the MaBS solution, the deployment of a large number of new sites is very costly. Again, the re-use of existing sites leads to less costly deployment even when many sites need to be equipped with new radio transceivers for the high demand. Still, due to the high coverage performance, the most cost-efficient option in case of high demand is the reuse of the existing sites with 10 MHz in 800 MHz band.

3) Carrier Aggregation Scenario

According to Qualcomm [31], carrier aggregation as characteristic of LTE-A RAT, allows combining lower and higher bands — leveraging better coverage of the former with higher availability of the latter (up to 5 carriers and up to 100 MHz supported in standards). In order to fully assess the cost-efficiency possibilities, we create one more deployment scenario assuming the aggregation of the both frequency carriers at 800 MHz and 2.6 GHz bands. By this the bandwidth available will be increased to 30 MHz, and exactly this is going to be the solution how to increase the capacity (even for 3 times) compared to the use of only 10 MHz bandwidth in 800 MHz band, but without increase the number of sites due to coverage reasons as in the case with 2.6 GHz deployment. From the cost perspective, this will mean that we need to install two type of different radio equipment per BS. Consequently, the CAPEX will increase for additional 10 k €, and the total CAPEX per site will be 130 k€ for the new sites and 30k € for the existing sites. According to pervious estimations, we will assume OPEX of 20 k€ for new and 10 k€ for the existing MaBSs.

The number of needed BS sites using carrier aggregation functionality and the relevant costs-capacity outcomes are summarized in Table VI.

TABLE V. INVESTMENTS AND CAPACITY (MACRO SITES WALL LOSSES COMPENSATION DEPLOYMENT - CASE 2).

Macro Wall Losses Compensat. (0.8 or 2.6 GHz)		Number of sites	Total CAPEX M€	Capac. (Gbps)
Site	*Demand*			
New 0.8 GHz	Mod.	36	4.32	4.1
New 0.8 GHz	High.	88	10.56	10.03
Reuse 0.8 GHz	Mod.	36	0.72	4.1
Reuse 0.8 GHz	High.	88	1.76	10.03
New 5 x 2.6 GHz	Mod.	90	10.8	20.5
New 5 x 2.6 GHz	High.	220	26.4	50.16
Reuse 5 x 2.6 GHz	Mod.	90	1.8	20.5
Reuse 5 x 2.6 GHz	High.	220	4.4	50.16

TABLE VI. INVESTMENTS AND CAPACITY (MACRO SITES WITH CARRIER AGGREGATION - CASE 3).

Macro Carr. Aggr. (0.8 & 2.6 GHz)		Number of sites	Total CAPEX M€	Capacity (Gbps)
Site	*Demand*			
New	Moderate	12	1.56	4.1
New	High	30	3.9	10.26
Reuse	Moderate	12	0.36	4.1
Reuse	High	30	0.9	10.26

Findings show that for around 0.9 M€ needed to upgrade the existing sites, the high user demand will be ensured. Further, with 1.56 M€ of investment and construction of new sites the high demands can be satisfied, too.

D. Femto Cell and Wi-Fi Deployments

In line with [3], and explanations for the maximum numbers of users per access point for FBS and Wi-Fi given in Section II above, we consider different options of the user oriented and coverage oriented approaches. Since the construction of the new office center is green-field, we will assume that previously there were no small cell installations within the considered area of 1 km². Consequently, the Table VII summarizes the cost-capacity figures for the FBS and Wi-Fi deployments. As expected with any of the considered scenarios of FBS and Wi-Fi, the provisioning of the demanded capacity will be achieved. The coverage is main cost driver for these two scenarios and high density indicates high network costs.

V. COMPARATIVE DISCUSSION RELATED TO THE SEPARATE NETWORK DEPLOYMENTS

Assuming the total investment budget of 3.0 Million € (M €), we compare in Figure 2 the investment costs in M € for separate network deployment scenarios as function of user demand in Gbps. It is noticeable that LTE-A MaBS deployment with site re-use and carrier aggregation in place, has the lowest cost for the capacities below 2.0 Gbps. Even LTE-A MaBS deployment with new sites and carrier aggregation in place is more cost effective option compared to the Macro 5xtime denser deployment and site reuse at 2.6 GHz band. Hence, the LTE-A RAT and carrier aggregation functionality from cost perspective could be acceptable MaBS deployment scenario for the new market entrant as well, since with it the new comer will be able to achieve comparable profitability with the existing operators for relatively high demand levels.

TABLE VII. INVESTMENTS AND CAPACITY (FBS LTE-A BASED AND WI-FI IEEE 802.11AC DEPLOYMENTS).

Femto Cells and Wi-Fi	No. of sites		CAPEX M€		Capac. (Gbps)	
	FBS	Wi-Fi	FBS	Wi-Fi	FBS	Wi-Fi
4 users / BS	2500	2500	2.5	6.25	330	3250
8 users / BS	1250	1250	1.25	3.13	165	1625
16 users / BS	625	625	0.63	1.56	82.5	812.5
32 users / BS	313	313	0.32	0.78	41.3	406.9
4 BS / floor	200	200	0.2	0.5	26.4	260
8 BS / floor	400	400	0.4	1.0	52.8	520
16 BS / floor	800	800	0.8	2.0	105.6	1040
32 BS / floor	1600	1600	1.6	4.00	211.2	2080

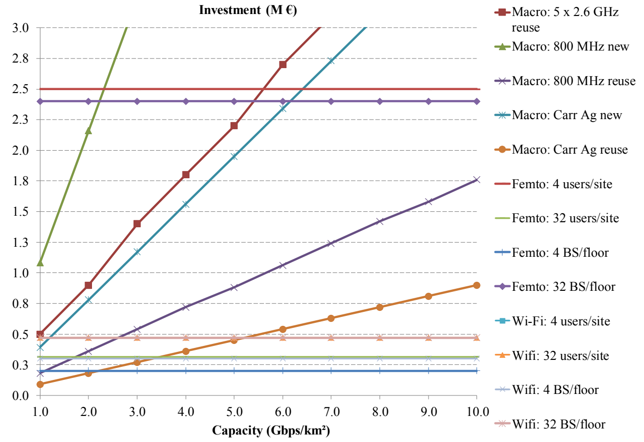

Fig. 2. Comparison of macro and small cell deployment costs as function of the user demand, with the LTE-A and IEEE 802.11ac, respectively.

From other side, deployment with the reuse of the existing MaBS with 10 MHz spectrum in the 800 MHz band causes achieving high demand with tolerable investment of 1,75 M€ due to the superb coverage and penetration performance of the 800 MHz carrier frequency. For the existing mobile operator missing spectrum in the 800 MHz, an option will be to reuse existing sites with 5 time higher density, what is more cost-effective solution than MaBs deployment with new sites in the 800 MHz band what in fact is the less cost efficient option. Thus, we can draw a conclusion that it is very important if new MaBS sites need to be deployed or not. In general, for the MaBS deployments it could be noticed that the slope of the lines depends on the number of sites that are needed and especially if new sites need to be deployed. The performances of FBS and Wi-Fi are different. As we already considered those types of indoor deployments are coverage, rather than capacity limited. Their cost depend form the density of BS used. As shown in Figure 2, for dense network deployments 4 users per FBS/Wi-Fi or 32 FBS/Wi-Fi sites per floor, is less cost-effective option comparing to most of the MaBS deployments unless the user demand is extremely high (above 6.5 Gbps). FBS/Wi-Fi deployments are cost-efficient when single site can support higher number of users (e.g., 32 per site or 4 sites per floor).

Thus, for the capacities above 2.0 Gbps, the most cost-effective deployment option is the utilization of 4 FBS per floor. A comparison of FBS and Wi-Fi shows that the FBS solution is more cost effective than Wi-Fi deployment, but from the capacity long-term perspective the better option should be IEEE 802.11ac Wi-Fi deployment due to its superb capacity performance.

VI. Demonstration of the Combined Cost-Capacity Modeling

In the previous section, we have conducted the cost-capacity modeling through case study of different BSs separately and focusing only at the investment performed within the first year. Following the findings of the separate solutions, here, we will demonstrate the network dimensioning of the analyzed service area as a combination of most cost-effective macro and small cell or Wi-Fi solutions.

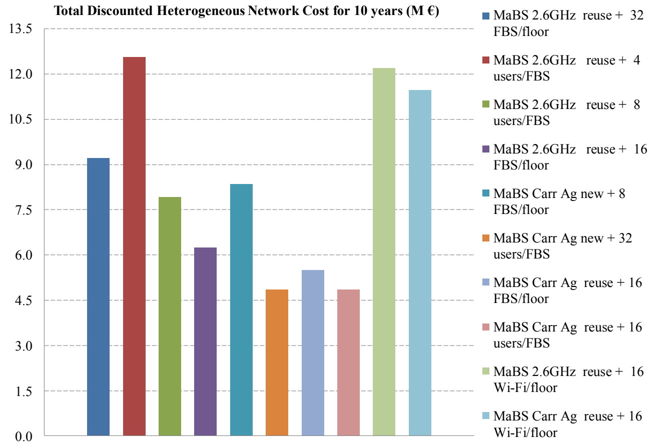

Fig. 3. Wireless heterogeneous network total discounted cost for the period of 10 years, jointly deployed by categories to satisfy high demand level of 10 Gbps/km ^{2} with the LTE-A and IEEE 802.11ac.

This could be as of particular interest of MNO having existing network deployment within the analyzed area. Thus, in the spotlight once again comes the initial scenario with the usage of 20 MHz in the 2.6 GHz band for the macro layer, identified as insufficient to compensate the wall penetration losses arising with the construction of the office center.

The graphical representation of the total discounted cost for various heterogeneous network deployments in 10 years period is shown in Figure 3. The results are yield in accordance with (3) and (4), the total discounted cost estimates per different BS classes (CAPEX + OPEX in present value for the period of 10 years and WACC = 12%) and findings for the number of BS (as per Tables IV – VII) needed to satisfy the high demand level of 10 Gbps/km ^{2}.

As some of the FBS and Wi-Fi options produce capacity overprovisioning (e.g., 4-8 user per BS or 16-32 BS per floor), we combine some of those deployments only with the initial MaBS scenario. The rest of the FBS and W-Fi solutions are combined with the MaBS scenarios which ensure wall penetration losses compensation, too.

It could be noticed that MNO having deployed macro network with 20 MHz in the 2.6 GHz network, instead of investing in additional spectrum or deploying denser network, it could compensate the indoor wall penetration losses by deploying 16 FBS sites per floor. That total discounted cost-efficient level of around 6.0 M€ is comparable for instance with deployment of new MaBS sites with carrier aggregation and 32 users per FBS indoor deployment what in fact is the most cost efficient combined macro/small cell deployment for still acceptable QoS from capacity perspective.

VII. Conclusion

We introduced a model for evaluation of the total deployment costs of heterogeneous wireless access networks. The model uses up to date inputs of the unit cost of particular base station class which is characterized with specific coverage and capacity parameters. For the cellular deployments, we use the forthcoming LTE-A RAT and for the WLAN networks, we consider the future-proof IEEE 802.11ac standard.

Through the investment case study, which considers construction of large office center, we have compared the cost-capacity performance for macro and small cell deployments as a function of moderate to very high user demand levels. The study analyzed deployments in both the 800 MHz and 2.6 GHz bands as well as the scenario of aggregated carriers in these bands. Findings show that the macro cell deployment scenarios show linear increase with demand. In order to satisfy moderate demand levels, it can be concluded that the re-use of sites, have a large impact also when a “denser” macro network is deployed in order to compensate for wall attenuation. The re-use of the existing macro sites with the low-end frequency carriers at 800 MHz, represents moderate cost-efficiency compared to other solutions.

Still, the solution to deploy the denser network at 2.6 GHz band with re-use of the existing sites is more cost-efficient than the solution to construct new sites with 800 MHz carrier, what shows the importance of the spectrum available, too. Hence, the key finding is that use of carrier aggregation functionality of LTE-A will significantly increase the cost-effectiveness of the macrocellular deployment. Thus, with enabling aggregation of the carriers in the band of 800 MHz and of 2.6 GHz on the existing sites, we create the most cost-efficient deployment for moderate demand levels.

On the other side, the indoor deployed femto cell and Wi-Fi solutions (being only coverage limited) are most cost efficient only for the higher to extreme user demands. Results indicate that FBS/Wi-Fi significantly become cost-efficient when single site can support higher number of users, basically due to the very low unit cost compared to the equipment cost of the higher order cellular deployments. With regard to the joint heterogeneous deployment, we determine that for operator holding less spectrum and in the upper bands, instead of investing in additional spectrum or deploying denser network, it could compensate the indoor wall penetration losses by deploying the acceptable number of FBS sites per floor from perspective of high demand levels and taking into account the “time value of money”.

Further studies in this field could investigate the cooperative layouts of macro with femto cells or Wi-Fi by consideration of the beyond 2020 mobile and wireless system targets [22].

REFERENCES

[1] K. Johansson, “Cost Effective Deployment Strategies for Heterogeneous Wireless Networks”, PhD Dissertation. The Royal Institute of Technology, Stockholm, 2007.

[2] K. Johansson, A. Furuskar, P. Karlsson, and J. Zander, “Relation between base station characteristics and cost structure in cellular systems In Personal, Indoor and Mobile Radio Communications," PIMRC 2004. 15th IEEE International Symposium on, volume 4, May 2004, pp. 2627– 2631, doi: 10.1109/PIMRC.2004.1368795.

[3] J. Markendahl and Ö. Mäkitalo, "A comparative study of deployment options, capacity and cost structure for macrocellular and femtocell networks Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), 2010 IEEE 21st International Symposium, Istanbul, Sep. 2010, pp. 145-150, doi: 10.1109/PIMRCW.2010.5670351.

[4] J. Markendahl, “Mobile Network Operators and Cooperation”, PhD Dissertation. The Royal Institute of Technology, Stockholm, 2011.

[5] Z. Frias and J. Pérez, “Techno-economic analysis of femtocell deployment in long-term evolution networks,” EURASIP Journal on Wireless Communications and Networking, volume: 2012, 2012, issue: 1 pp. 288-302.

[6] ETSI TR 136 913 V10.0.0 (2011-04) LTE: ETSI, 2011.

[7] ETSI TR 136 912 V11.0.0 (2012-10): ETSI(2012).

[8] IEEE 802.11acTM-2013. IEEE Standards Association 2014.

[9] Analysis Mason,”Wireless network traffic 2010–2015”, 2010.

[10] K. Johansson, J. Zander, and A. Furuskär, “Modelling the cost of heterogeneous wireless access networks”. Int. J. Mobile Network Design and Innovation, Special Issue on Planning and Optimisation of Wireless Networks, vol. 2, no. 1, 2007, May 2007.

[11] H. Holma and A. Toskala, (ed), LTE for UMTS – OFDMA and SC-FDMA Based Radio Access. John Wiley & Sons, 2009.

[12] K. Johansson and A. Furuskär, “Cost efficient capacity expansion strategies using multi-access networks,” Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st, Volume 5, Jun. 2005, pp. 2989 – 2993, doi: 10.1109/VETECS.2005.1543895.

[13] S. Choi, “Femtocell vs. WiFi”. The 22nd High-Speed Network Workshop. Multimedia & Wireless Networking Lab, 2012.

[14] B. G. Mölleryd, J. Markendahl, and Ö. Mäkitalo, “Spectrum valuation derived from network deployment and strategic positioning with different levels of spectrum in 800 MHz,” In Proceedings of 8th Biennial and Silver Anniversary ITS Conference, Tokyo, Jun. 2010.

[15] REPORT ITU-R M.2134, Requirements related to technical performance for IMT-Advanced radio interface(s), 2008.

[16] R4-071231, Open and Closed Access for Home NodeBs. "Nortel, Vodafone", 3GPP TSG RAN Working Group 4 meeting #44, 2007.

[17] Femto Forum, Interference Management in UMTS Femtocells, Feb. 2010, Retrived: May 30, 2014 from http://www.smallcellforum.org/.

[18] M. Gast, 802.11 Wireless Networks – The Definitive Guide. 2nd ed. O’Reilly, 2005.

[19] Y. Xiao, “IEEE 802.11n: Enhancements for higher throughput in wireless LANs,” Wireless Communications, IEEE (Volume: 12, Issue: 6), Dec. 2005, pp. 82 - 91, doi: 10.1109/MWC.2005.1561948.

[20] C. Wang and H. Wei, “IEEE 802.11n MAC Enhancement and Performance Evaluation,” Mobile Networks and Applications volume 14, 6, 2009, pp. 760-771.

[21] White Paper. 802.11ac: The 5th Generation of Wi-Fi. Cisco, 2014.

[22] METIS (Mobile and wireless communications Enablers for the Twenty-twenty Information Society) Project, “Scenarios, requirements and KPIs for 5G mobile and wireless system”, Document Number: ICT-317669-METIS/D1.1, 2013.

[23] Asus, RT-AC68U AC1900 Wi-Fi Router specs. PS WORLD, Retrived: May 30, 2014 from http://www.pcworld.com.

[24] White Paper. Proven-Carier Grade Wi-Fi Solutions. Motorola, 2011.

[25] White Paper. Carrier Class – The Esential Ingridient for Succesfull Metro Wi-Fi. Zhone, 2008.

[26] BEREC, Member and Observer National Regulatory Authorities, Retrived: May 30, 2014 from http://berec.europa.eu/eng/links/.

[27] PWC, “Digital dividend in Southeast Europe”, November 2012.

[28] Cisco, “Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2013–2018”, Feb. 2014.

[29] Cisco. Average N. American mobile user to consume 6 GB/month in 2017. Fierce Wireless, Feb. 2013, Retrived: May 30, 2014 from http://www.fiercewireless.com/story/cisco-average-n-american-mobile-user-consume-6-gbmonth-2017/2013-02-05.

[30] A. Furuskär, M. Almgren, and K. Johansson, “An Infrastructure Cost Evaluation of Single- and Multi-Access Networks with Heterogeneous Traffic Density,” IEEE Vehicular Technology Conference, Vol. 5, Jun. 2005, pp. 3166 – 3170, doi: 10.1109/MWC.2005.1561948.

[31] Qualcomm, LTE Advanced—Leading in chipsets and evolution, Aug. 2013, Retrived: May 30, 2014 from http://www.4gmast.nl/Upload/wireless-networks-lte_advanced-leading_in_chipsets_and_evolution.v6.20130827.pdf