Modelling the cost of heterogeneous wireless access networks

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Abstract: Heterogeneous wireless access networks are today considered to be a key enabler for affordable wireless access to the internet. Thanks to the diverse usage patterns and quality of service requirements for mobile and wireless data services, operators may reduce their costs significantly by exploiting different radio access technologies. These are then accessed via 'multiradio' terminals that automatically select between available systems. As a means to identify efficient combinations of radio access technologies, we propose a methodology to estimate the total infrastructure cost for non-uniform traffic distributions. With a few numerical examples including the packet data optimised evolutions of third generation mobile systems (3G) as well as Wireless Local Area Network (WLAN) technology, the model is used to quantify the average total cost of different system configurations. The methodology should prove useful as a basis for more specific analysis of the economics of heterogeneous wireless access networks.

Keywords: wireless infrastructure cost model; tele-economics; heterogeneous wireless networks; spatial traffic distribution; multiaccess networks; deployment strategies.

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1 Introduction

Future wireless access networks are likely to consist of multiple radio access standards and base station technologies forming what is called as *heterogeneous networks* (Gustafsson and Jonsson, 2003; Niebert et al., 2004). This is because the use of successive generations of radio access standards tend to overlap considerably, and no single technology has proven to be suitable and affordable for all services and deployment scenarios. More specifically, heterogeneous networks in this context refer to both *multiaccess networks*, where multiple radio access technologies based on different standards are accessed with a multiradio capable terminal and *hierarchical cell structures* constituted of a single radio access standard with different base station classes (e.g. macro, micro and pico).

At present we can observe two main evolution tracks of wireless access technology originating from the telecom and datacom industry, respectively (cf. the standards developed by 3GPP and IEEE, respectively). While mobile systems offer good coverage and reliability for low and moderate data rates, Wireless Local Area Network (WLAN) technologies complement fixed broadband connectivity with local area coverage for higher data rates. A mobile network operator could then reach a similar increase in network capacity in different ways. For example, they could choose to:

- improve the air interfaces in cellular systems
- deploy denser (heterogenous) networks
- lease capacity from specialised (WLAN) network providers
- share (radio access) infrastructure with other operators.

To what extent these options are exploited in practice will of course be case specific and ultimately depend on a number of technical, financial, marketing and regulatory factors.

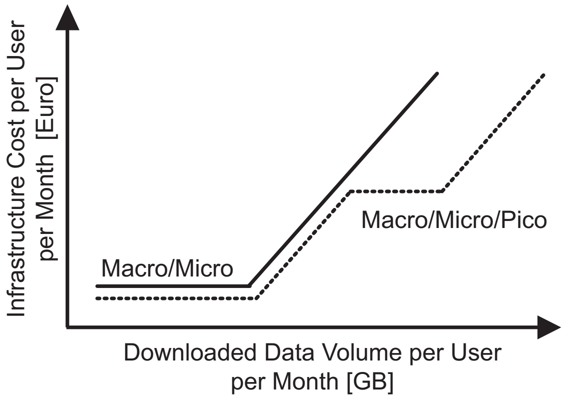
Hence, identifying general requirements for future systems is a difficult task which is of great importance not only for the operators, but also for equipment vendors and telecom regulators. In any case, as the industry matures, it will become even more important for operators to minimise their cost of infrastructure for the targeted service offering and this is the point of departure for this paper.

For mobile telephony systems the dominating deployment strategy in this aspect has been to minimise the number of base station sites and reuse existing infrastructure as far as possible. This is quite logical since the cost of homogeneous wireless access networks is approximately proportional to the number of access points deployed (see, e.g. Loizillon et al., 2002; Zander, 1997). In a heterogeneous scenario, however, that strategy would not necessarily minimise the total cost of a network since equipment, installation and operational costs all are less expensive for 'small' base stations (Johansson et al., 2004; Stanley, 1998). Moreover, the demand for area coverage, mobility and peak data rates may differ greatly between services. Thus, substantial cost savings could be achieved by matching the network deployment – including choice of radio access technologies and base station capabilities – to the actual, most often heterogeneous, traffic demand.

In this paper, we will introduce the techno-economic problem of estimating the cost of such heterogeneous wireless access networks. General dimensioning principles are discussed and, as an initial solution, a simple methodology is proposed for dimensioning the network. Base stations are characterised by their average cost, maximum range and total throughput and the traffic demand is modelled as a spatially correlated, non-uniform, stochastic variable. In this way it is possible to estimate the average total cost of a heterogeneous network, including both investments and running costs.

As schematically shown in Figure 1, the cost per user per month is evaluated for different system concepts as a function of downloaded data volume (per user per month). In this, quite typical deployment example, macrocellular base stations are uniformly placed over a service area with a given cell radius and complementary micro and pico base stations are added in traffic hot spots until the targeted traffic level is supported.

Figure 1 An example of numerical results illustrating the average total infrastructure cost as a function of downloaded data volume per user per month



This paper is outlined as follows: in Section 2 an overview of previous work on cost modelling of wireless networks is provided. Basic deployment principles for heterogeneous networks are described in Section 3. Thereafter, in Section 4, the proposed infrastructure cost model is described. In Section 5 a few numerical examples, including both cellular and WLAN technologies, are presented to illustrate how the methodology can be used in practice to compare the cost-efficiency of different heterogeneous system concepts. The validity of the model is discussed in Section 6 and this paper is concluded in Section 7.

2 State-of-the-art

Research on the cost structure of wireless access networks was initiated during the development of second and third generation mobile telephony systems, with a significant work carried out as part of a series of larger research programmes organised by the European Union. In particular, a methodology for techno-economic evaluation of access networks for telecommunication services was developed during the period 1992–1996 in the project Tool for Introduction Scenario and Techno-economic Evaluation of Access Network (TITAN) (Stordahl and Murphy, 1995). This was later on refined under the acronym TERA (see, e.g. Harno et al., 2006; Loizillon et al., 2000). These references (and references therein) are valuable sources for the cost structure of wireless systems and various techno-economic issues.

Network planning with respect to spatially varying traffic load has been addressed in a number of studies (Amaldi et al., 2003; Graf et al., 1997; Hao et al., 1997; Hurley, 2002; Lee and Kang, 2000; Sarnecki et al., 1993; Sherali et al., 1996; Stanley, 1998; Velez and Correia, 2003; Yuan et al., 1998). It was also acknowledged in Hao et al. (1997) that both economic and technic factors needed to be considered in the design of a cellular network and that many parameters need to be tuned. For this purpose, a hierarchical optimisation-based planning method was proposed and the resulting combinatorial optimisation problem was solved using simulated annealing techniques. Similar approaches have later been proposed by Amaldi et al. (2003), Hurley (2002), Sherali et al. (1996) and Lee and Kang (2000) for power-controlled systems, hierarchical cell structures and incremental network deployment.

The financial benefits with a few capacity enhancement techniques were analysed by Avidor et al. (2003) and Graf et al. (1997). For instance, a net present value analysis was presented for the case of introducing advanced antenna concepts in 3G systems (Avidor et al., 2003). Methods to lower base station site costs (in total) were also discussed by Sarnecki et al. (1993), and it was noted that pedestrian users do not need as advanced base stations as vehicular ones do. Moreover, cost reductions of 60–70% per subscriber were estimated by introducing a microcell layer for the case of second generation mobile systems.

The problem of optimising base station range and aggregate throughput versus cost was addressed by Gavish and Sridhar (1995), Johansson et al. (2004), Stanley (1998) and Velez and Correia (2003). It was, for example, observed by Johansson et al. (2004) and Stanley (1998) that the cost structure shifts from base stations and physical infrastructure to 'last mile'-transmission as the range of the base station decreases. Thus, cutting costs for the base station equipment does not necessarily lead to, in total, significantly lower infrastructure costs. An interesting observation is that the fixed part of the 'last mile'-transmission stand for a significant portion of the overall wireless infrastructure costs – in the order of 5–15% (Loizillon et al., 2002; Yuan et al., 1998).

National telecom regulators, such as the Office of Communications (OFCOM) in the UK, have further developed cost models for the sake of regulating interconnection charges and spectrum assignments. A thorough cost analysis was also presented by Reed, as part of a quite extensive study for the Federal Communications Commission (FCC) in the USA, 1992, assessing the spectrum required for 'personal communication services' (Reed, 1993).

3 Deployment principles

Heterogeneous wireless access infrastructures could, as indicated above, be beneficial for a number of reasons, such as for example, to meet an increased traffic demand, improve coverage for higher data rates in specific places or to support legacy systems. We can also observe that introducing unlicensed or licence exempt technologies, such as WLAN, potentially could decrease the need for operators to acquire licensed frequency spectrum. The chief advantage with hierarchical cell structures, on the other hand, is that handsets, central systems, etc., only need to support one access method and that the licensed spectrum enables an increaced reliability.

With respect to the ability to serve some given aggregate traffic load (throughput), which is the focus of the sequel of this paper, heterogenous networks are expected to be beneficial mainly in scenarios with a non-uniform spatial traffic distribution (Johansson et al., 2004). The key idea is to utilise cheaper base stations with a shorter range and, potentially, more spectrum bandwidth in areas with high traffic density (hot spots). By doing so, the total network cost can be lowered.

However, this requires that the traffic covered per base station is sufficiently high. If traffic peaks are small, as compared to the base station range, these will most likely be underutilised and unnecessarily expensive. This reasoning is further explained by the following example in which micro and picobase stations are deployed in hot spots to complement the base-line capacity provided with macrobase stations.

Example: Assume that a macrocell layer is deployed for basic coverage; (see Figure 2). The capacity of this network is sufficient as long as the aggregate traffic demand within the cell range is lower than the maximum capacity per base station. Otherwise the operator of interest can choose to either deploy micro or picobase stations. Which option brings the cost down to the lowest will then depend on both the geographical distribution of traffic and the capacity, range and cost for the respective type of base station.

In the first case (left) in Figure 2 there is one large hot spot which could be served either by a single microbase station or by three picobase stations. Assuming that a picobase station costs 50% less than a microbase station, the micro cellular solution is still cheaper, 33%. In the second example we have two smaller, geographically separated, hot spots that could be served either by two microbase stations or by two picobase stations. In this case, adding the picobase stations would instead be 50% cheaper.

An infrastructure cost model showing these effects is presented next. Thereafter a few numerical examples will be presented for an urban scenario.

4 Infrastructure cost model

In this section, we describe the proposed cost model, including a model for non-uniform traffic density, a network dimensioning algorithm and cost metrics. Figure 3 illustrates the parts of a typical wireless network architecture included in the model, which was first introduced in Furuskär et al. (2005). The model is a simple one and emphasis has been laid in covering both technical and economic factors at a similar level of accuracy. Later on, for more detailed analysis, the methodology would be refined, in various aspects.

4.1 Cost modelling and performance measures

A base station of class i is associated with a cost c_i. The total network cost c^{tot} is then simply calculated as

$$c^{\text{tot}} = \sum_i c_i n_i$$

This is then normalised per month per subscriber. For simplicity reasons, an average cost per base station is assumed. Local variations in site rent, transmission, etc. are not modelled.

Moreover, only the radio access network has been considered. Thus, common costs for core network nodes,

Figure 2 Two simple examples of different traffic distributions that are best served by a macro base station in combination with either microbase stations (case 1) or picobase stations (case 2)

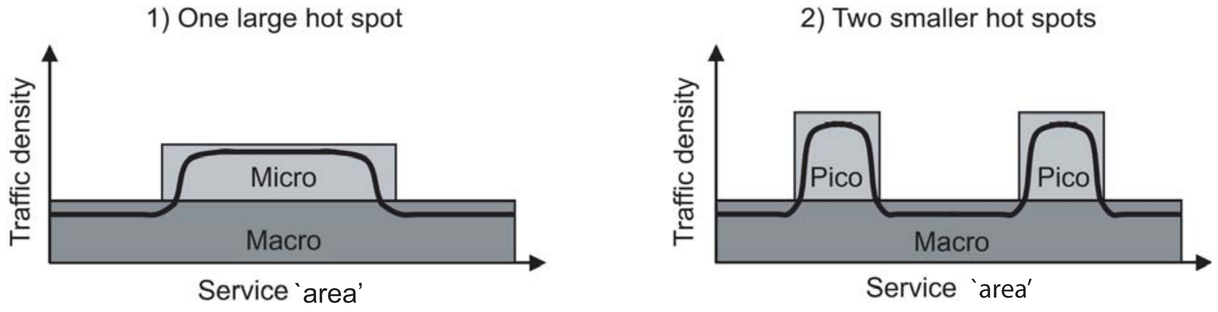
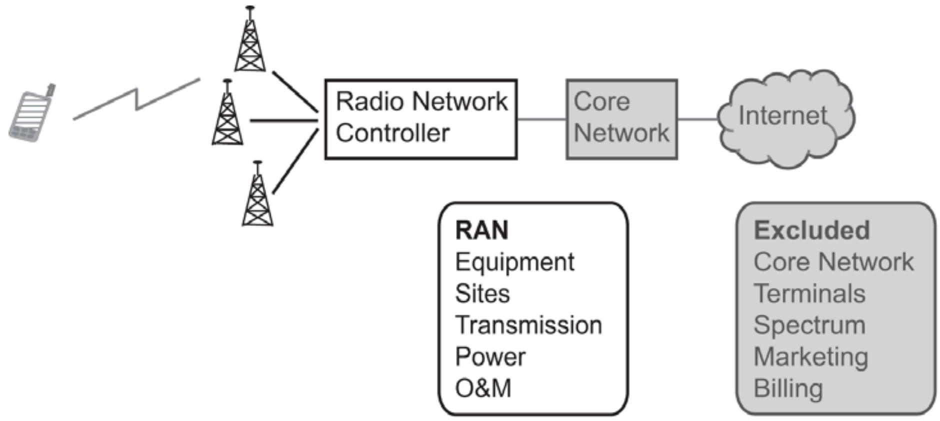


Figure 3 Overview of the components included in the proposed wireless network cost model



billing systems and service platforms are excluded. We assume that these costs are relatively small as compared to the radio access network (Avidor et al., 2003; Loizillon et al., 2002; Reed, 1993; Stanley, 1998; Zander, 1997). It is straightforward, however, to add a fixed cost if this is considered relevant for a specific case.

Spectrum licence fees are also excluded, partly for the reason that a mobile network operator typically needs a licence anyway; thereby it is a sunk cost. But also due to that, a generally applicable spectrum cost model is very difficult to be defined because of regional differences in regulation (Cave et al., 2002).

4.2 *Network dimensioning*

With the model, a network of multiple base station classes, having different characteristics, is *dimensioned* to serve a certain traffic demand defined in terms of the average throughput per area unit. We only account for the traffic that the interested operator has to serve with own base stations. Hence, access points deployed by users themselves and network capacity leased from other network providers are excluded.

A base station of class i is characterised by a maximum average throughput $s_i^{\max}$ and range r_i. These two attributes implicitly determine the supported Quality of Service requirements, such as outage, blocking, data rate and delay, as well as radio aspects such as path loss and cochannel interference, which thus are exogenous to the model. For a fair and relevant comparison all considered services, therefore, need to be feasible to provide with the assumed base station throughput and range.

A simple heuristic method is used to dimension the network according to a given traffic map. If we denote the average offered throughput per user during busy hour as s [kbps], the aggregate offered area throughput s_j^a [kbps] in an area sample j of size a [km^2] is given by

$$s_j^a = s\lambda_u(x, y)a$$

where $\lambda_u(x, y)$ [users/km^2] is a random variable that describes the user density at coordinate (x, y). The total number of base stations deployed for each kind is denoted as n_i and this is determined iteratively in a ‘greedy’ fashion in the sense that traffic served by a base station class is removed from the traffic map.

The base stations to be deployed are sorted in a decreasing order of range per base station r_i for each base station class:

1 each area sample j is associated with the respective closest (with respect to the Euclidean distance) candidate base station site (k) so that the area samples in the set $\mathcal{A}_k$ are associated with site k

2 the total offered throughput per candidate site k is calculated as

$$s_k^{\text{tot}} = \sum_{j \in \mathcal{A}_k} s_j^a$$

3 the number of carriers n_k^i deployed at the site k is then given by

$$n_k^i = \min\left\{\left\lceil \frac{s_k^{\text{tot}}}{s_i^{\max}} \right\rceil, n_i^{\max}\right\}$$

where $n_i^{\max}$ denotes the maximum number of carriers for base station class i.

4 In case $s_k^{\text{tot}} > s_{\max}^i n_i^{\max}$, which corresponds to that not all traffic associated with that base station site could be supported, traffic elements are allocated to the site k in an increasing order of the offered traffic per area sample s_j^a until the maximum number of carriers are deployed at that site.

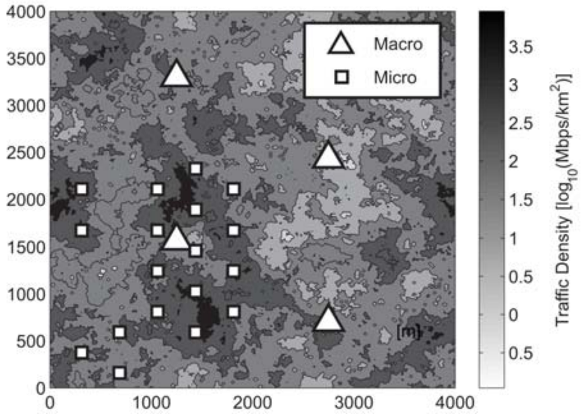
This way, residual traffic that has to be served with the remaining base station classes (having shorter range) will primarily belong to the traffic elements with the highest traffic density. If no traffic element remains to be served after the last base station class is deployed, 100% of the offered traffic can be supported with the considered system concept. To obtain the cost of systems with fractional traffic coverage, the base stations are deployed in an ascending order of the aggregate throughput served per base station divided by the cost per base station (until the desired level of traffic coverage is reached).

4.3 *Traffic density map*

Knowing the spatial characteristics of traffic demand is one of the key elements to achieve a cost-efficient network deployment. This includes both where users are and which type of services they consume (depending on the location, mobility, etc.). Since this is a new and complex problem, not many empirical studies are available on the subject. However, we can observe that both population density (US Census Bureau, 2000) and mobile telephony traffic load (Gotzner et al., 1998) are approximately log-normal distributed on different aggregation levels. Hence, we propose to model the user density over some service area ($\lambda_u(x, y)$) by a log-normal random variable with a spatial correlation to model the effect of traffic hot spots.

The gray scale contour in Figure 4 depicts a realisation of a traffic density map. In the same figure, the triangles and squares show example of deployment of macro and microbase stations, respectively.

Figure 4 Example of a generated traffic density map with site locations depicted for macro and microcells, respectively



5 Example of a cost analysis

Having introduced the model, we will now illustrate how it can be used in practice to quantify the infrastructure cost of heterogeneous wireless access networks, including both hierarchical cell structures and multiaccess networks. With this example, we will investigate:

1 whether or not the lower cost of WLAN, as compared to picocells, has any significant impact on the average total infrastructure cost

2 at what traffic levels such 'hot spot'-solutions are needed as complement to macro and microcells

3 to what extent microcells are useful if picocells or WLAN have to be deployed anyway (due to the high traffic volumes).

We will focus on an urban scenario which should be the most interesting case since macrocellular systems alone typically yield the lowest cost in less populated regions due to the low average traffic density (Johansson et al., 2004). Moreover, aggregate throughput figures will be determined by downlink communications whereas uplink sets the maximum feasible range per base station, which is a standard assumption for cellular systems (Holma and Toskala, 2004).

The studied radio access technologies include the 3G evolution, High-Speed Downlink Packet Access (HSDPA), the currently standardised Long-Term 3G Evolution (LTE) and IEEE 802.11a WLAN. As a base-line for the applied cost and performance assumptions it is assumed that the network is deployed by a greenfield mobile network operator in a western European city. However, the model can readily be applied also for incumbent operators.

5.1 *Traffic demand*

In this example, we emulate a low-rise urban environment with an assumed population density of 10,000 people/km^2, with 95% overall service penetration and a market share equal to one third for the operator of interest (corresponding to 3000 subscribers/km^2). Based on US Census Bureau (2000) and Gotzner et al. (1998), we have further identified that a standard deviation equal to 5 and 500 m correlation distance (yielding a correlation of e^{-1}) should be a reasonable default assumption for the user distribution. This was obtained by first adopting the standard deviation for the given correlation distance so that an assumed peak population density of 10^5 people/km^2 is reached with a reasonable probability. Then, the correlation distance was such that the standard deviation per macrocell matched the statistics reported for GSM networks in Gotzner et al. (1998). Notice that this corresponds to a quite skew distribution and that the resulting traffic hot spots will be in the order of a few hundred metres.

The throughput per subscriber during busy hour is assumed to be linearly proportional to the total traffic volume downloaded per month. For this mapping, we use the standard assumption that around 0.6% of the monthly traffic in a mobile network is transmitted during busy hour (Holma and Toskala, 2004). As a benchmark, the voice traffic of a typical mobile telephony subscriber today corresponds to approximately 1–10 MB per month. This holds for a

10 kbps application data rate, with 50% activity factor and 30–300 monthly minutes of call per user and will be used as a reference level in the following discussion. Since the model does not include the supportable data rate, we will for simplicity assume that the guaranteed data rate required with full coverage is moderate and in the order of a few hundred kbps. The network is so dimensioned that 95% of the offered traffic load is supported.

Given that the traffic density can be served with a certain system concept, the feasible traffic volume will ultimately be determined by the users' willingness to pay. As a reference level we assume that on an average €3 per user per month can be spent on the radio access network. This can be motivated by that the average revenue per user of mobile operators today is in the order of €30 per month, with a margin for taxes, profit, marketing, central systems and other non-infrastructure related costs. Moreover, the anticipated subscriber base will not be reached instantaneously.

5.2 Base station characteristics

Performance and cost parameters for all considered base stations are summarised in Table 1. Notice that these parameters depend on a large number of factors and may, in a real case, deviate from the example figures given here. Yet, we believe that the relative differences are reasonable.

5.2.1 Range and capacity

For HSDPA (Release 5), it is assumed that the operator of interest has 15 MHz in total for downlink transmission and that the cell throughput is 2.5 Mbps. LTE, instead, is assumed to have a 20 MHz spectrum allocation. In conjunction with an assumed spectral efficiency of 1.5 bps/Hz/cell (three times higher than in HSDPA, which is enabled mainly by introduction of advanced antenna systems) this results in a capacity of 30 Mbps per cell. The cell radius of a given base station type (macro, micro and pico) is assumed to be the same for both HSDPA and LTE. Furthermore, the micro and picocell capacities are assumed to be the same as the macrocell capacities. WLAN figures assume non-interfered access points.

5.2.2 Cost coefficients

The base station cost coefficients are normalised with the average total cost for a single-carrier, 3-sector, macrobase station (which is assumed to be €1500 per month). The resulting cost structure of each base station type is further illustrated in Figure 5. The estimates are based on the estimates from 2006 and include all major costs associated with a base station. This includes Capital Expenditures (CAPEX) for equipment and sites and Operational Expenditures (OPEX) essentially stemming from operation and maintenance, 'last-mile'-transmission, electric power and site rental.

The network life span is assumed to be ten years for all radio access technologies and, in order to account for both capital and operational expenditures, the costs are discounted to present value at 10% rate. Motivated by fierce competition, 'Last-mile'-transmission and base station equipment are assumed to be subject to a yearly price erosion of 10%. The cost of electric power is, instead, assumed to increase at 10% per year. To model a roll-out phase, one-third of the base stations of each kind are deployed per year during the first three years.

Empirical data on the cost of cellular base station equipment were provided by the Gartner Group. The other costs are based on Loizillon et al. (2002), Harno et al. (2006), Barbaresi et al. (2006) and our own assumptions. The cost estimates have further been verified with representatives from telecom operators, equipment vendors and financial analysts. Notice though, that the costs for LTE are hypothetical since the system is not yet available on the market. It should be a reasonable assumption that the cost of physical infrastructure, such as sites and transmission lines, will be similar to those for HSDPA. In addition, although price levels of electronics are constantly falling, new generation of radio access technologies with increased performance tend to have the same price level (per unit) as those in the previous systems.

5.3 Numerical results

In Figure 6, the monthly infrastructure cost per user is plotted as a function of downloaded traffic volume (per month). For HSDPA and LTE, respectively, the following mixes of cellular base stations and WLAN access points have been simulated:

1 macro and microcells

2 macro and picocells

Table 1 Base station performance parameters and cost coefficients

Base station class	*Bandwidth [MHz]*	*Range [m]*	*Throughput [Mbps]*	*Cost coefficient [Rel. to macro]*
HSDPA Macro (3-sector)	5–15	250	[1–3] x 7.5	1.0 + 0.15 per carrier
HSDPA Micro	5–10	100	[1–2] x 2.5	0.33 + 0.033 per carrier
HSDPA pico	5–15	50	[1–3] x 2.5	0.20 + 0.017 per carrier
LTE	20	As HSDPA	90 (macro), 30 (micro, pico)	As HSDPA
IEEE 802.11a hot spot	20–60	25	22	0.10

Figure 5 Base station cost structure including both CAPEX and OPEX for the considered base station classes (macro, micro, pico and WLAN) grouped by radio related, site and transmission costs

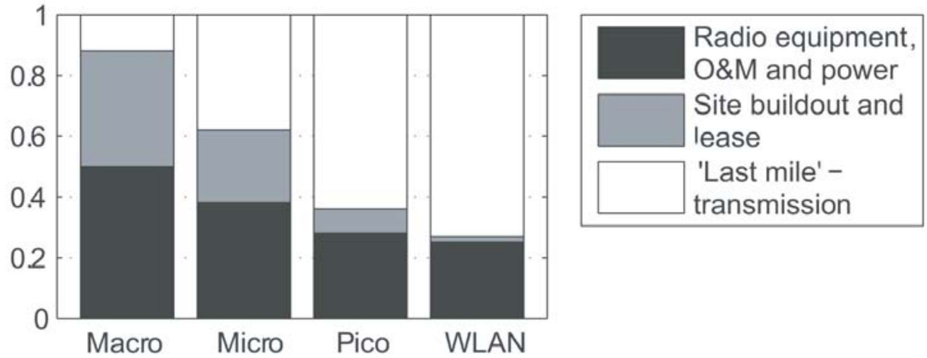
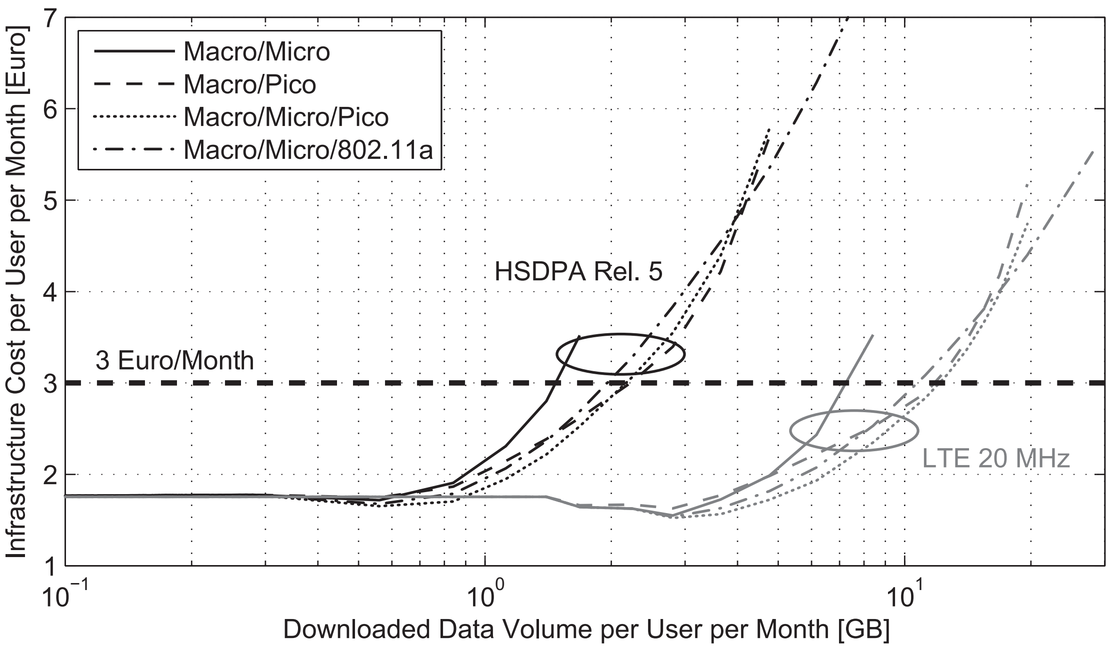


Figure 6 Examples of the infrastructure cost per user per month as a function of downloaded data volume depicted for different combinations of cellular base stations and IEEE 802.11a access points. The parameters are chosen to model an urban area with 3000 subscribers/km^2 and the black lines depict HSDPA as cellular radio access technology, whereas the grey lines represent LTE. Notice that the scale of the horizontal axis is logarithmic



3 macro, micro and picocells

4 macrocells, microcells and IEEE 802.11a access points.

Thus the macro base stations have reached the capacity limit for HSDPA and LTE when approximately 1 and 3 GB, respectively is downloaded on average per user per month. This corresponds to around 100 and 300 times the typical traffic generated by voice users. Thereafter the cost per user increases as a function of traffic volume. The monthly infrastructure cost per user can be kept below €3 up to approximately 2 GB per month with HSDPA and 10 GB with LTE. Furthermore, LTE macrocells alone have a lower cost than all systems based on HSDPA.

For both HSDPA and LTE the systems, including either pico cells or IEEE 802.11a, have the lowest costs. There is, however, no significant difference between these system concepts (i.e. 2, 3 and 4). It should be stressed though, that the feasible Quality of Service level (which is not evaluated here) may differ significantly between these network configurations.

Yet, these results indicate that the cost of a heterogeneous network would be less sensitive than expected to the choice of complementary base station technology. Another interesting observation is that the microcells, as an intermediate capacity expansion, potentially could be avoided. An attractive migration strategy would be to first install HSDPA macro base stations for rudimentary coverage and capacity together with IEEE 802.11a access points in local traffic hot spots. Then, if average traffic demand increases significantly, the macrocellular system should be upgraded with LTE while keeping the WLAN access points.

6 Discussion of model validity

The numerical results presented are naturally subject to the assumptions and modelling applied. Because of difficulties in determining the cost and average performance estimates of the respective technology, these parameters and the resulting cost estimates should be seen as indicative only. For a real investment analysis, the neglected common costs, availability of technology and spectrum, competitive strategy and marketing issues, etc., also have to be accounted for.

Furthermore, the traffic model was based on measurements from GSM networks and may thus underestimate the spatial variability in traffic demand for mobile data services; user-behaviour could be quite different as compared to voice. This is owing to the type of terminal and application, and also because the session duration can be expected to be dependent on the radio conditions. For example, users with poor coverage could stay longer in the system for some applications (such as file transfers), whereas for other services the usage may increase at higher data rates. However, the parameters of the model can naturally be altered for the sake of analysing the sensitivity of the resulting infrastructure cost in respect of this factor.

Even though costs are averaged over the whole network life span, the network is dimensioned for one level of traffic density. Later on, as more empirical studies on demand for mobile data services become available, gradual deployment according to a time evolving traffic demand will be an interesting extension to the model.

It should also be noted that the proposed network deployment algorithm is based on heuristics and does not optimise the network deployment. For example, we have limited access point positions to regular grids and only one cell radius is allowed per base station type. This was, to some extent, done to keep the model tractable. But due to that the real networks cannot be planned with a sufficient granularity to fully optimise the network in respect of local traffic peaks. Instead, the objective is to have been a straightforward method that is reasonably cost-efficient and facilitates a fair comparison between system concepts. Nevertheless, we have verified through simulations that the deployment algorithm performs as intended, that is the network deployment is in accordance with the traffic map and the average capacity utilisation per base station is reasonable. Moreover, the effect of different cell radii and throughput can, thanks to the low computational complexity, readily be investigated with this model (as illustrated in Johansson and Furuskär (2005)).

7 Conclusions

A cost model has been proposed as a means to analyse mobile network deployment strategies involving different radio access technologies. With the average cost, range and throughput per base station as main input parameters, the network is dimensioned to serve a spatially non-uniform traffic demand generated with a stochastic model. With the model, it is possible to evaluate the combination of base stations that yields the lowest cost as a function of transmitted data volume (per user). Moreover, it is straightforward to assess the effects of improvements in, for example, base station range or capacity on total system cost.

We furthermore illustrated how the model can be utilised in practice with a few examples, including both cellular and WLAN systems. Based on our assumptions and modelling of a typical Western European mobile operators' network deployed in an urban scenario, it was shown that introducing multiaccess networks is equally cost-efficient as single-access hierarchical cell structures. However, if traffic volumes surge significantly, the cellular system also needs to be improved to maintain a reasonable infrastructure cost per user (or, alternatively, the total cost per high capacity access point need to be lowered substantially). In this way, the model can be used to compare systems with different cost and performance characteristics.

In particular, the model should be useful as input for more detailed investment analysis of heterogeneous wireless infrastructures, taking into account also the business and marketing related factors we have excluded in this paper. Of all these, perhaps the most important determinants for an operators deployment strategy would be the competition, time-evolving demand for traffic, differentiated area coverage and pricing strategies for different services and the availability of base station site locations and frequency spectrum. Having these aspects in mind, which often are determined by local conditions, it is not necessary that the solution with the lowest cost per transmitted data volume in practice would be deployed by a mobile network operator. Yet, we believe that the cost of infrastructure is a key parameter in the technology strategy and that the present model should be useful to analyse.

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