RELATION BETWEEN BASE STATION CHARACTERISTICS AND COST STRUCTURE IN CELLULAR SYSTEMS

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Abstract - A simple method for estimating the costs of building and operating a cellular mobile network is proposed. Using empirical data from a third generation mobile system (WCDMA) it is shown that the cost is driven by different factors depending on the characteristics of the base stations deployed. When site density increase, operational and transmission costs tend to dominate rather than radio equipment and site costs. The results also show how, for different capacity requirements, the costs can be minimized by a proper selection of for example macro, micro and pico base stations. In many scenarios the macro base stations yield the lowest cost, indicating that coverage (cell range) is an important parameter when designing wireless systems.

Keywords - Tele-economics, cost model, infrastructure cost, base station cost

I. INTRODUCTION

The costs of providing wide-area coverage for high data rate wireless access have been discussed widely in the telecom industry over the last couple of years. While mobile operators have struggled with high license fees and roll-out costs due to regulatory requirements for third generation networks, technologies such as Wireless LAN have evolved as complementing and in specific scenarios even competitive alternatives [2]. This has evidently contributed to an increased cost awareness among both mobile operators and equipment vendors [4].

Mobile infrastructure cost was under study already during the development of GSM and other 2G systems, however it has been more focused only recently for 3G and beyond. In [6] the costs of providing mobile data services was analyzed in terms of economies of scale and scope. Furthermore, cost effective ways of configuring cellular networks was addressed in [1] and an empirically based cost model for cellular systems was proposed in [7].

It is commonly known that the capacity is proportionally to the base station density for a given cellular system. Unfortunately, also the infrastructure costs seems to increase almost linearly with the capacity required (indicating a low degree of economies of scale). This was discussed in [9], where the cost structure of wireless access infrastructure was analyzed. It was concluded that the network cost rises linearly with the data rate per user. This should hold for a given frequency allocation provided that the same coverage is required, and was identified in [10] as a key problem for providing wideband data services in wireless systems.

A simple infrastructure cost model was also presented in [9] (and developed further in [10]), in which the total infrastructure cost of a wireless system is modeled as linearly proportional to the number of base stations:

\[ C_{\text{system}} = cN_{\text{bs}} \]

where \( N_{\text{bs}} \) is the number of base stations and \( c \) is a constant corresponding to the cost per base station. Note that in [9] \( c \) is assumed to be the same for all base stations and it is independent of the base station characteristics.

However, in a practical system, a number of different base station types could be used for different deployment scenarios and the requirements on, e.g., cell range and reliability greatly affects the total cost per base station (including capital and operational expenditures). As a consequence the cost structure of a radio access network is dependent of the system configuration, i.e. the quantities and types of different access points employed to achieve various total network capacities and coverage.

This topic will be treated further in the sequel of this paper, which is outlined as follows. The overall distribution of costs in current mobile networks is presented in Section II. This discussion justifies a simple infrastructure cost model which is described in Section III. Using this, the total cost and cost structure is calculated in Section IV for different demands and potential solutions for delivering affordable wireless services with high data rates is discussed briefly. The paper is concluded in Section V.

II. OVERALL COST STRUCTURE FOR MOBILE OPERATORS

Before going into a more detailed analysis, let us first look briefly at the overall cost structure of a mobile operator as of today. Typically, their investments relate to radio and transmission equipment, license fees, site build-outs and installation of equipment. The running costs, in turn, consider mainly transmission, site rentals, marketing, terminal subsidies, and operation and maintenance (O&M).

The exact breakdown of those costs is of course case specific, and it may vary significantly between different...
countries and operators. An attempt to model the costs and revenues for western European operators was done within the TONIC project [5]. The cost structure was estimated for operators providing UMTS services in (i) a small and sparsely populated country and (ii) a large country with denser population.

From these results it is clear that cumulated running costs dominate the total cost structure of a mobile operator and, according to [5], they correspond to roughly 75% of the total costs for a large country. More specifically, the running costs are dominated by non-technical costs, such as marketing, terminal subsidies and wages which can be seen in Table 1. Note also that transmission constitutes a significantly higher portion of the running costs in the small country. This since 'last mile'-transmission is priced per kilometer in the model in [5] and the distance between base stations is higher in the small country example, due to its lower population density.

A. Infrastructure cost model

In principle there is an infinite number of possible configurations of base stations (including different alternatives for sites, transmission, etc.). A rough division, though, could be to stick to three main categories based on the cell range; namely macro, micro and pico cell base stations. The cost per base station $c$ should also be significantly different for those base stations. For example, a small micro or pico base station implies a low cost for equipment, site leases and installation whereas a large macro base station costs much more in those aspects. On the other hand, fixed costs not directly related to the capacity of the base station are divided between many users in a macro base station so the cost per user may still be lower in many scenarios.

The total infrastructure cost for a mobile operator could then be modeled as

$$C_{\text{system}} = c_1 N_{\text{macro}} + c_2 N_{\text{micro}} + c_3 N_{\text{pico}},$$

(2)

where $c_1$, $c_2$, and $c_3$ are the total costs for macro, micro and pico base station respectively. Typically $c_1 > c_2 > c_3$ and, if we in the same way define the maximum cell radius $R$ per base station, $R_1 > R_2 > R_3$. Hence, different base stations will minimize cost for different scenarios. However, for the sake of simplicity, we will study the different base stations separately but keep in mind that each cellular network in reality consist of a mix of base stations.

B. Network dimensioning

The number of base stations required, $N_{bs}$, is calculated as a function of the demand specified by the:

- Service area to be covered, $A_{\text{service}}$.
- Average capacity per user during busy hour, $W_{\text{user}}$.
- Number of subscribers within the coverage area, $N_{\text{user}}$.

Furthermore, the dimensioning will be done for downlink only. This should be reasonable since the downlink generally limits the aggregate capacity in a WCDMA system, while the uplink limits the data rate per link and coverage when the traffic load is low [3].

Only a single carrier is assumed, to make the comparison between base station types simple (more carriers would reduce the number of sites in a capacity limited scenario). Each base station has a given maximum cell range ($R_{\text{max}}$), minimum cell range ($R_{\text{min}}$) and supported capacity ($W_{\text{max}}$). For simplicity the capacity is kept constant, and does not vary as a function of the actual cell range ($R_{bs}$). Each cell has circular coverage area, which according to [7] is a reasonable assumption.

The network can either be coverage or capacity (interference) limited and the number of base stations required is dimensioned according to the following model:

$$N_{bs} = \max \left\{ \frac{A_{\text{service}}}{\pi R_{\text{max}}^2}, \frac{N_{\text{user}}W_{\text{user}}}{W_{\text{max}}} \right\},$$

(3)
assuming a continuous service area and that users are uniformly distributed (as in e.g. [9]). Note also that the network is dimensioned in an average sense, and that the wanted blocking and outage probability has to be possible to achieve at the assumed cell range $R_{\text{max}}$ and base station capacity $W_{\text{max}}$ for each considered service. Now, given that the resulting cell range

$$R_{bs} = \sqrt{\frac{A_{\text{service}}}{\pi N_{bs}}} \geq R_{\text{min}},$$

(4)

the capacity requirements can be met with the selected type of base station.

C. Empirical cost and performance data

The performance and cost data related to the base stations are given in Table 3. All values are approximate, but should be representative in a relative sense for a typical WCDMA system deployed during 2003. For simplicity only an urban scenario is considered and typical cell ranges and capacities are based on general estimates provided in [3] and do not represent the performance of any specific product. We assume that the capacity per cell is higher for micro and pico cell base stations. This since it is possible to minimize inter-cell interference by a proper placement of the antennas (below roof-top or indoors).

The equipment costs estimates have been provided by the Gartner Group and the other cost parameters are based on [5]. The macro base station is naturally much more expensive than the smaller base stations, because of its higher output power and capacity, but also due to that it has to be more reliable since more users are served per base station. This clearly affects the costs for sites, installation and O&M.

<table>
<thead>
<tr>
<th>Performance [3]:</th>
<th>Macro BS</th>
<th>Micro BS</th>
<th>Pico BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sectors</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Carriers 2*5MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum cell range ($R_{\text{max}}$)</td>
<td>1km</td>
<td>0.25km</td>
<td>0.1km</td>
</tr>
<tr>
<td>Minimum cell range ($R_{\text{min}}$)</td>
<td>0.25km</td>
<td>0.1km</td>
<td>0.025km</td>
</tr>
<tr>
<td>Capacity ($W_{\text{max}}$)</td>
<td>2.25Mbps</td>
<td>1.25Mbps</td>
<td>1.75Mbps</td>
</tr>
<tr>
<td>Initial costs:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment (Source: Gartner)</td>
<td>50k€</td>
<td>20k€</td>
<td>5k€</td>
</tr>
<tr>
<td>Site buildout [5]</td>
<td>70k€</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Site installation [5]</td>
<td>30k€</td>
<td>15k€</td>
<td>3k€</td>
</tr>
<tr>
<td>Annual costs [5]:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual O&amp;M</td>
<td>3k€</td>
<td>1k€</td>
<td>1k€</td>
</tr>
<tr>
<td>Site lease</td>
<td>10k€</td>
<td>3k€</td>
<td>1k€</td>
</tr>
<tr>
<td>Transmission</td>
<td>5k€</td>
<td>5k€</td>
<td>5k€</td>
</tr>
</tbody>
</table>

‘Last mile’-transmission costs are also included in the model, and for this purpose we use a simplified modeling of leased lines. Each base station is assumed to have the same cost for transmission of 5k€ per year. The transmission prices are subject to a yearly price erosion of 5%. The other annual costs are assumed to be constant.

D. Discounted cash flow model

The total cost per base station $c$ is calculated in present value using a standard economical method for cumulated discounted cash flows. By doing so, we can account for both investments and running cost in the comparison and analyze the total cost structure of different base stations. This is simply done by summing up the discounted annual cash flows (in this case yearly expenditures) for the whole network life cycle ($K$ years) according to

$$c = \sum_{k=0}^{K-1} \frac{c_k}{(1+d)^k},$$

(5)

where $d$ is a discount rate which is assumed to be equal to 10%. The network is in all examples in the sequel assumed to be used during $K = 10$ years and the cost for equipment and site buildouts are accounted for in the first year ($k = 0$). That is, the whole network is deployed during the first year.

E. Discussion on the model’s applicability

Although this is a very simplified model, we believe this approach can be useful to understand the fundamental characteristics of different technical solutions. E.g., when different base stations are applicable and what the bottlenecks are in today’s system. Yet, a few important things that distinguish the model from a real network could be worth to point out. Firstly, neither base stations, nor users, are uniformly distributed as we assume in the simple model. Second, a network typically consists of a variety of base stations, transmission and antenna system designs.

The latter is partly due to that an operator naturally optimizes the choice of technology depending on the specific deployment case as discussed above. But also because networks evolve over time, and existing infrastructure can quite often be reused when new technology is rolled out. Hence, the previous investments in, e.g., sites and cabling are treated as long term investments and do not add to the incremental cost of adding more capacity. Note also that the empirical cost and performance data only should be considered as estimates, and the statistical significance of those is not known. However, we believe that the figures used reflects the costs for a typical mobile network fairly well and the conclusions should therefore hold also for other cellular technologies, such as GSM or CDMA2000.

IV. Results

In this section we will illustrate how the total system cost varies as a function of demand, given by the user density and demanded busy hour throughput per user $W_{\text{user}}$, and the base station type (macro, micro and pico). This is followed by an analysis of the cost structure of the base stations under study, and a brief discussion on technical improvements required to provide high data rates with wide area coverage.
A. Infrastructure cost

Fig. 1 illustrates the total infrastructure cost $C_{\text{system}}$ for different base stations with a data rate $W_{\text{user}} = 1\text{ kbps}$. This could, e.g., correspond to a speech service of 10kbps at 0.1Erlang traffic load (typical corporate user). According to (3) the infrastructure cost is constant as long as the system is coverage limited. Then, as more base stations are needed to meet the capacity requirements the total cost increase linearly according to the cost per base station $c$.

From this picture it is possible to find the base station type that minimize infrastructure cost for different user densities. In this specific case, with $W_{\text{user}} = 1\text{ kbps}$, the macro cell base stations should be used until demand exceed 4000 users/km$^2$, thereafter micro cell base stations could be worthwhile to introduce up to a very high user density (approximately 20 000 users/km$^2$) when pico cells are cheapest.

We can also see when demand increase significantly so that a denser deployment is needed, the cost per user is lowered and there is a certain degree of scale economics as depicted in Fig. 2. Here we have plotted the cost per user as function of user density for $W_{\text{user}}$ equal to
- 0.2kbps (typical private speech user at 20mErl),
- 1kbps (typical corporate speech user at 100mErl), and
- 10kbps (data user downloading appr. 5MB/hour) respectively. Note also that the cost per user diminishes stepwise because of the limited number of base station types used in this example and that each base station is coverage limited within some region.

B. Cost structure

The cost structure of different solutions is here divided in three parts:
- Radio: Base station equipment and discounted O&M costs.
- Sites: Site buildout & installation and discounted site leases.
- Transmission: discounted lease line costs.

The total cost per base station $c$ and the respective cost structure are given in Table 4. The values are based on the assumptions given in Section III.

<table>
<thead>
<tr>
<th>Base station</th>
<th>Radio</th>
<th>Sites</th>
<th>Transmission</th>
<th>Cost per BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>70k€</td>
<td>168k€</td>
<td>28k€</td>
<td>366k€</td>
</tr>
<tr>
<td>Micro</td>
<td>27k€</td>
<td>36k€</td>
<td>28k€</td>
<td>90k€</td>
</tr>
<tr>
<td>Pico</td>
<td>12k€</td>
<td>10k€</td>
<td>28k€</td>
<td>50k€</td>
</tr>
</tbody>
</table>

In this example micro base stations are 66% cheaper than macro base stations, whereas the cost for a pico base station is only 44% lower than a micro base station. This has a rather intuitive explanation: the equipment cost is lower and site costs can be reduced significantly as the required cell range decreases. However, the transmission costs are the same for all base stations in this example. Hence, as the base station range decrease the cost is driven by transmission, rather than by radio and site costs.

C. Potential development paths towards higher data rates at a low cost

A key problem for delivering data services in wireless systems is the cost per bit, which does not decrease in the same pace as demand increases with today’s cellular technology. As discussed in [9] we can not assume that the users’ total willingness to pay for wireless services increase significantly in the future (at least not in the same order as data traffic is expected to grow). Therefore, novel solutions seem to be needed in order to achieve greater economics of

Fig. 1. Infrastructure cost for different base stations.

Fig. 2. Minimum cost per user for different capacity.
scale in wireless networks. But how can this be achieved in practice?

There are mainly two possible development tracks. One is to re-use existing sites, or even reduce the number of sites, by extending the capacity of existing solutions. This can in principle be done by either

1) allocating more spectrum for third generation networks,
2) increase spectral efficiency, e.g. by utilizing adaptive antennas,
3) introduce multi-hop technology in the cellular networks,
or using a combination of those.

Another way would be to actually allow for denser deployment by decreasing the cost per base station. Using the cost structure analysis above as a starting point, there is a potential in lowering transmission and O&M costs for pico cell base stations. Instead of the expensive leased lines (E1/T1) or microwave radio links cheaper transmission technologies could be introduced, e.g., wireless fixed broadband or xDSL.

The costs for O&M and sites could be reduced by allowing for privately owned and deployed base stations, possibly connected to existing fixed broadband or local area networks. Similar to Wireless LAN access points, one could imagine small 3G base stations owned by individuals or enterprises. However, for such solutions to be economically feasible, some significant modifications are required also in the core network equipment (simply to handle a large increase in the number of base stations). It also requires slightly modified business models and value chain constellations for the mobile operators.

V. Conclusion

A simple model for estimating the infrastructure costs of cellular systems was proposed. The model is based on average cost and performance data from third generation mobile networks and includes both investments and running costs. With this model, it is possible to analyze the infrastructure cost as a function of demand for different base station configurations.

The cost drivers were shown to be a function of the characteristics of the base stations. With macro base stations the costs mainly considers base station equipment, O&M and sites, whereas for pico-cell deployment the 'last mile' transmission dominates with the present technology. Results also show that the macro base stations yield the lowest cost in many scenarios. This indicates that coverage (cell range) is an important parameter when designing future wireless access systems.

Further studies in this area could include improved modeling and methods for evaluating the economical gain of new technical features, e.g. by means of elasticity analysis. Also the potential economical benefits and suitable business models for a wide deployment of pico base stations, or other types of local access points, could be interesting to study in more detail.

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