# OPTIMAL CAPACITY EXPANSION OF NEXT-GENERATION WIRELESS BASE STATION SUBSYSTEMS

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## Abstract

*With an increasing mobility of today's workforce, organizations have a growing need for information and transactions anytime and anywhere. Mobile network operators (MNO) must therefore meet this need by deploying wireless networks capable of offering advanced voice and data services. While wireless network planning and design has been studied extensively in the literature, most work has focused on voice demand only. As MNO transition to next-generation wireless networks, however, voice and data traffic combined will have to be considered in these capacity expansion and allocation decisions. In this paper, we examine the wireless base station subsystem and propose a multi-demand type optimization model that solves the capacity expansion problem of current to next-generation wireless networks. We provide an integer programming formulation for the optimal design of next-generation wireless BSS with the objective of minimizing the costs associated with the installation, connection, replacement, and capacity upgrade of infrastructure equipment. Our problem is similar to the well-known hierarchical concentrator location problem, which is shown to be NP-complete. A Lagrangian relaxation is used to obtain lower bounds for this problem. Computational results will be presented for a set of real-world and randomly generated test problems.*

## 1. Introduction

The increasing demand for mobile voice and data communications has raised customer expectations and increased pressure on mobile network operators (MNO) to provide broad service coverage, high capacity networks, and advanced mobile services while ensuring a flexible, high-quality and cost effective network (Hjelm and Long 2001). With the potential of higher mobile usage and revenues luring, MNO have been looking to expand their current networks and replace existing infrastructure with next-generation technologies. One of the many goals for next-generation mobile communications systems is to seamlessly provide a wide variety of services to anybody – anywhere, anytime (Commworks 2001). This includes services such as the transmission of high speed data, video and multimedia as well as traditional voice signals. The technologies needed to provide these advanced services are popularly known as third generation (3G) cellular systems. 3G cellular systems are being designed to support wideband wireless services like high speed Internet access, video and high quality image transmission with the same quality as fixed-line networks.

The wireless network infrastructure consists of equipment required by MNO to enable mobile telephony calls or to connect fixed subscribers by radio technology. A generic architecture of a wireless network is shown in Figure 1. These concepts apply to all digital mobile telephony standards, such as GSM 900/1800, PCS 1900 or CDMA (Garg 2001). The PSTN-cloud covers all network elements to make a standard telephone call, while the data network cloud includes the Internet, Intranets, and other IP based networks. The architectural building blocks enabling mobile telephony are (i) the core network, comprised of the mobile switching centers (MSC), the packet data serving nodes (PDSN), and home agents (HA), and (ii) the base station subsystem (BSS), also known as the radio access network, consisting of base station controllers (BSC) and base transceiver stations (BS) (Lee and Kang 2000).

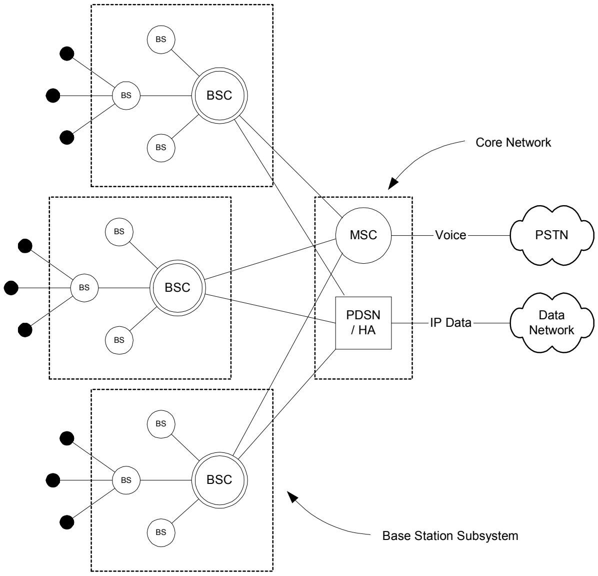

**Figure 1**. Generic Wireless Network Infrastructure

The MSC is a modified central office switch, with extensions for mobile subscriber databases and intelligent network links, which enable the MSC to decide where to route an incoming call. If the requested subscriber for example is registered to be located in the MSCs area, the call will be routed to the respective base station controller (BSC). The BSC is part of the link between the BS and the MSC and is responsible for allocating and releasing radio channels to the mobile stations by way of the BS. In addition to managing channels on a radio interface, the BSC is also responsible for managing mobile station handovers to other radio channels. Other BSC functions include routing calls to the MSC, handling call control processes, and maintaining a database of subscribers and records of calls for billing (Fente et al. 1997). The BSC is directly connected to the MSC and the PDSN. The PDSN is the point of entry into the wireless packet data network for mobile subscribers. The PDSN performs two basic functions (Commworks 2001), which are (1) exchanging packets with the mobile station over the radio network and (2) exchanging packets with other IP networks. The PDSN is generally coupled with HA, which is a router on a mobile node's home network that maintains information about the device's current location, as identified in its care-of address (IETF 2002). Corresponding to the architectural building blocks of a wireless network, are three types of interconnects (Siemens Mobile 2001). These are (1) mobile device to BS interconnect, which includes both forward and reverse radio links, (2) the BS to BSC interconnect, which is called the backhaul, and (3) BSC to MSC interconnect. Both the BS to BSC and BSC to MSC interconnects are generally linked via E1 and T1 lines.

While a complete rollout of next-generation networks is desirable, it is often very time-consuming, expensive and sometimes not feasible from an operational perspective (Qualcomm 2001). MNO therefore look to alternate network deployment strategies. In the network design and capacity planning literature, conventional approaches to meeting demand growth include location and installation of additional network elements (Balakrishnan et al. 1991, Tutschku 1998). However, this approach ignores two important aspects of upgrading to next-generation wireless networks, namely, (i) the importance of backward compatibility with pre-existing networks (Hjelm and Long 2001), and (ii) the cost and operational benefit of gradually enhancing networks, by replacing, upgrading and installing new wireless network infrastructure elements that can accommodate both voice and data demand (Siemens Mobile 2001). In this paper, we focus on the wireless BSS and present a multi-demand type optimization model that captures capacity expansion of current to next-generation wireless networks. In particular, we consider the objective of minimizing the costs associated with the installation, connection, replacement and capacity upgrade of wireless BSS infrastructure equipment. The decision variables are (1) which type of existing BS to operate, upgrade or shut down, (2) where to install new BS, (3) which BSC to operate or shut down, (4) where to install new BSC, (5) which BS to connect to a BSC, and (6) how to allocate mobile users to BS.

## 2. Relevant Literature

The wireless telecommunications literature is replete with work on network design and capacity expansion (see Hurley 2002, Liu and Worrall 2002, Tutschku et al. 1996, and Hjelm 2001 for reviews). Wireless network design is concerned with the architecture and layout of network resources while capacity expansion is concerned with additional capacity to be installed on the network so as to meet increased customer demand while minimizing total costs incurred (Kubat et al. 2000, Lee and Kang 2000, Mathar 2000). Whitaker et al. (2002), Lister et al. (2000), and Fente et al. (1997) provide an overview to the issues in the optimization of 3G wireless network planning and design. Wireless network planning models can be broadly classified into two categories, namely coverage location and cell planning problems.

Tutschku (1996) studied the maximal coverage location problem using a greedy heuristic which takes RF design objectives as well as capacity and network deployment constraints into account. Calegari et al. (1997) examine the cell planning problem using a genetic algorithm approach. The selection of base stations is represented in a bit string and is based on fitness value, crossover and mutation operators. Two main objectives are captured by the fitness value: maximizing the coverage area and minimizing the number of transmitters. Yu et al. (1998) solve the cell planning in a CDMA network by maximizing the cell coverage for given traffic and finding optimal location configurations.

Mathar and Schmeink (2002) study the optimal cell site selection in CDMA networks using a greedy type strategy. A related problem is the one identified by Eisenblaetter et al. (2002), in which the authors study the configuration of base stations in an UMTS network. Here, the authors focus on the location of base stations and the optimal configuration of cells taking stochastic components such as bandwidth restrictions at the base stations and service dependent traffic profiles into account. Similarly, Winter (2002) proposes a planning process for UMTS radio access networks and incorporates aspects of co-location with existing infrastructure and equipment sharing between operators.

An alternate approach to capacity planning and expansion is introduced by Giuliano et al. (2002) who examine upgrade of 3G network system capacity without an increase in base stations using a cell splitting approach. Specifically, they propose techniques of cell sectorization using smart antennas that through rotation and resizing can adapt to varying traffic conditions.

A tabu search algorithm approach to cellular capacity expansion is presented by Lee and Kang (2000). They consider existing base stations and determine the location and capacity of new base stations for given traffic demands. In contrast to our examination of the wireless base station subsystem, however, they solely solve the capacity expansion of base stations. More recently, Kalvenes et al. (2002) studied the base station location and service assignment problem in a W-CDMA network.

While a vast body of cell planning literature exists, most of the research in the optimization of coverage in wireless systems is restricted to the selection of base station locations, see e.g. Amaldi (2002), Galota (2001), Glasser et al. (2000) and Mathar and Niessen (2000). Only little research has been reported in the simultaneous selection of infrastructure locations, capacity expansion and service assignments. In our paper, we intend to fill this gap and propose a solution to optimally expand existing wireless base station subsystems and allocate customers in these networks. Specifically, we determine the optimal number and location of BS and BSC and allocate mobile users and BS among these infrastructure elements without exceeding the capacities of them. Related work has been done by Wu and Anandalingam (2002) in which the authors examine the positioning of base stations on possible locations sites with the aim to maximize the number of supplied demand nodes and minimize the number of stations that have to be built.

Our model differs from all of the previous work in that we focus on the wireless BSS rather than the entire wireless network, consider different base station capacity types, and allow for demand type diversity, i.e. voice and data demand, which is highly characteristic of demand in next-generation wireless networks (Garg 2001).

## 3. Model

The problem addressed in this paper can be formulated as a binary integer programming problem as follows, for which we introduce the following notation:

| | |
|---|---|
| $M$ | Index set of mobile user locations |
| $K1$ | Index set of existing BSC |
| $K2$ | Index set of potential BSC |
| $K$ | Index set of all BSC, $K1 \cup K2$ |
| $J1$ | Index set of existing BS |
| $J2$ | Index set of potential BS |
| $J_t$ | Index set of all BS of type $t$, $J1_t \cup J2_t$ |
| $T_j$ | Set of types available for BS $j$ |
| $S$ | Set of commodity types; |

$$s = \begin{cases} 1 & \text{if commodity type is voice} \\ 2 & \text{if commodity type is data} \end{cases}$$

| | |
|---|---|
| $D_m^s$ | Demand of commodity type $s$ for mobile user $m$, $m \in M$, $s \in S$ |
| $cap_{j_t}$ | Maximum capacity of BS $j$ of type $t$, $j \in J$, $t \in T_j$ |
| $cap_k$ | Maximum capacity of BSC $k$, $k \in K$ |
| $dist_{mj_t}$ | Distance of mobile user $m$ from BS $j$, $m \in M$, $j \in J$, $t \in T_j$ |
| $R_{j_t}$ | Maximum coverage range for BS $j$ of type $t$, $j \in J$, $t \in T_j$ |

| | |
|---|---|
| $c\_connect_{j_t k}$ | Cost of connecting BS $j$ of type $t$ to BSC $k$, $k \in K$ |
| $c\_install_k$ | Cost of installing BSC $k$, $k \in K2$ |
| $c\_upgrade_j$ | Per Channel Cost of upgrading BS $j$, $j \in J1$ |
| $c\_setup_{j_t}$ | Cost of constructing and connecting BS $j$ of type $t$, $j \in J2$ |

To capture the initial assignment of mobile users to BS and the connection of BS to BSC, we use the following indicator variables:

$$\alpha_{j_t k} = \begin{cases} 1 & \text{if BS } j \text{ of type } t \text{ is connected to BSC } k \\ 0 & \text{otherwise} \end{cases}$$

$$\beta_k = \begin{cases} 1 & \text{if BSC } k \text{ is operated in initial assignment} \\ 0 & \text{otherwise} \end{cases}$$

$$\delta_{j_t} = \begin{cases} 1 & \text{if BS } j \text{ of type } t \text{ is operated} \\ 0 & \text{otherwise} \end{cases}$$

The decision variables are:

$$U_{j_t k} = \begin{cases} 1 & \text{if BS } j \text{ of type } t \text{ is connected to BSC } k \\ 0 & \text{otherwise} \end{cases}$$

$$V_k = \begin{cases} 1 & \text{if BSC } k \text{ is operated} \\ 0 & \text{otherwise} \end{cases}$$

$$X_{mj_t} = \begin{cases} 1 & \text{if mobile user } m \text{ is connected to BS } j \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{j_t} = \begin{cases} 1 & \text{if BS } j \text{ of type } t \text{ is operated} \\ 0 & \text{otherwise} \end{cases}$$

Then the formulation [W-EXP] is:

$$\begin{aligned} \text{Min} \quad & \sum_{j \in J} \sum_{k \in K} \sum_{t \in T_j} c\_connect_{j_t k} \left( U_{j_t k} - \alpha_{j_t k} \right) \\ & + \sum_{k \in K2} c\_install_k \left( V_k - \beta_k \right) \\ & + \sum_{j \in J1} c\_upgrade_j \left( \sum_{t \in T_j} ( cap_{j_t} Z_{j_t} - cap_{j_t} \delta_{j_t} ) \right) \\ & + \sum_{j \in J2} \sum_{t \in T_j} c\_setup_{j_t} Z_{j_t} \end{aligned}$$

subject to

$$\sum_{j \in J} \sum_{t \in T_j} X_{mj_t} = 1 \qquad \forall \ m \in M \qquad (1)$$

$$dist_{mj} X_{mj_t} \le R_{j_t} Z_{j_t}$$

$$\forall \ m \in M, \ j \in J, \ t \in T_j \qquad (2)$$

$$\sum_{t \in T_j} Z_{j_t} \le 1 \qquad \forall \ j \in J \qquad (3)$$

$$Z_{j_t} \le \sum_{k \in K} U_{j_t k} \qquad \forall \; j \in J \,,\; t \in T_j \qquad (4)$$

$$U_{j_t k} \le V_k \qquad \forall \; j \in J \,,\; k \in K \,,\; t \in T_j \qquad (5)$$

$$\sum_{m \in M} \sum_{s \in S} D_m^s X_{mj_t} \le cap_{j_t} Z_{j_t} \qquad \forall \; j \in J \,,\; t \in T_j \qquad (6)$$

$$\sum_{j \in J} \sum_{t \in T_j} U_{j_t k} \le cap_k V_k \qquad \forall \; k \in K \qquad (7)$$

$$X_{mj_t} \,,\; Z_{j_t} \;\in\; \{0,\, 1\} \qquad \forall \; m \in M \,,\; j \in J \,,\; t \in T_j \qquad (8)$$

$$U_{j_t k} \,,\; V_k \;\in\; \{0,\, 1\} \qquad \forall \; j \in J \,,\; k \in K \,,\; t \in T_j \qquad (9)$$

The objective is to minimize the total cost of expanding an initial wireless BSS to accommodate increased traffic demand. The first term in the objective function is the cost of connecting a BS to a BSC, while the second term is the cost of installing a new BSC. The third term defines the cost of upgrading the capacity of existing BS, whereas the fourth term is the cost of constructing and installing new BS. These costs will include the total setup and operation, as well as the cost of personnel required to maintain the BS and BSC in the wireless BSS.

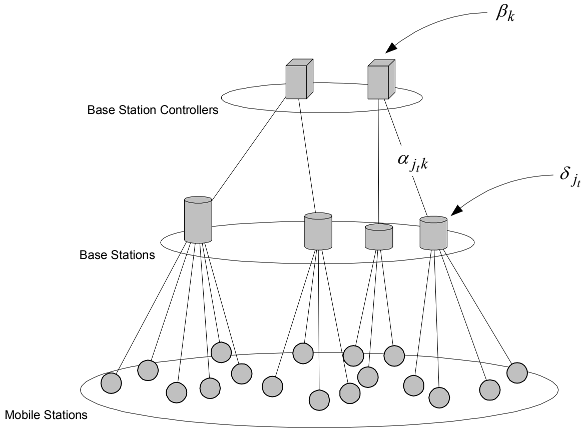

**Figure 2**. Initial Assignment

Each term in the objective function also captures existing infrastructure assignments through a set of indicator variables. An example of an existing initial assignment is shown in Figure 2. It highlights that each mobile user can be assigned to only one BS, while each BS has to be connected to a single BSC.

Figure 3 illustrates an assignment after capacity expansion and traffic increase, and indicates the respective decision variables. New wireless BSS infrastructure equipment, i.e. BS and BSC, are shown in darker shades.

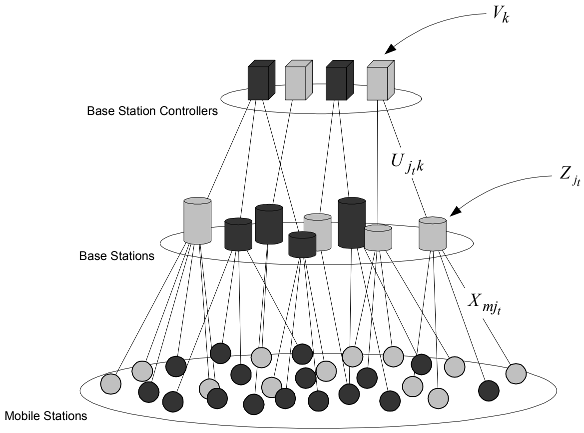

**Figure 3**. Assignment after Expansion and Traffic Increase

Constraint (1) specifies that each mobile user m will be assigned to exactly one base station j of type t, while constraint (2) ensures that mobile users are within that base stations' maximum range R. Constraint (3) specifies that at most one base station of type t can exist at location j. Constraints (4) and (5) specify that if a base station is operated, it has to be connected to a BSC and the BSC has to be active, respectively. Constraints (6) and (7) represent the capacity constraints of the model, in which we argue that base stations must have the necessary capacity to accommodate traffic demand of all demand types s for all mobile users assigned to it and the base station controller must have the necessary capacity to accommodate all base stations assigned to it, respectively.Our problem is similar to the more commonly known hierarchical capacitated concentrator location (HCCL) problem, which is an extension of the concentrator location (CL) problem to multiple levels and a classical research issue in the telecommunications literature (Narasimhan and Pirkul 1992, Gupta and Kalvenes 1999, Gavish 1989, Pirkul 1987, Lee 1993). The basic idea behind the CL problem is that given a number of sources which can be assigned to a set of possible concentrator sites, the goal is to find the optimal layout so that the sources to concentrators connectivity cost as well as the cost of locating concentrators is minimized given the requirement that a source needs to be connected to only a concentrator and a concentrator can have limits on how many sources it can handle. In our model, the CL problem is extended to two levels in which mobile users are sources, and both BSs and BSCs are concentrators. Since the HCCL problem is proven NP-complete (Mirzaian and Steiglitz 1981), an effective and efficient heuristic is required. We will employ a Langrangian relaxation to obtain lower bounds for this capacity expansion problem.

## 5. Conclusions

With a growing need for anywhere and anytime access to information and transactions, mobile networks operators are expanding their existing wireless networks and providing more capacity to accommodate next-generation wireless services. In this paper, we model the optimal capacity expansion of wireless base station subsystems with respect to multi-demand type and system capacity constraints. Our problem is similar to the well-known hierarchical concentrator location problem, which is shown to be NP-complete. A Langrangian relaxation will be used to obtain lower bounds for this capacity expansion problem. Computational results will be presented for a set of real-world and randomly generated test problems.

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