Radio Access Network Topology Planning for the 4G Networks

A. Krendzel, Y. Koucheryavy, J. Harju

Tampere University of Technology, Institute of Communication Engineering,
P.O. Box 553, FIN-33101, Tampere, Finland.
e-mail: {krendzel, yk, harju}@cs.tut.fi

Abstract: **Network physical links configuration is one of the most important problems of mobile communication network planning because it will determine the long-term performance and service quality of networks. In the 4G Radio Access Network (RAN) a new ring topology of physical links may be applied in contrast to RANs of current wireless systems. In this paper, the problem of the ring configuration of physical links from the viewpoint of minimum 4G RAN construction cost is considered. We formulate this problem as a combinatorial-optimization one and use dynamic programming principle for its solution. Software calculation results demonstrate the capability of our approach to determine the minimum-cost configuration.**

1. Introduction

There has been an evolution in wireless communications almost every ten years [1]. The first generation (1G) in 1980s and the second generation (2G) mobile systems in 1990s have been oriented mainly for providing circuit-switched services to users. The 2G subscribers have used the data rates of up to 14 kbp/s as a maximum. In 1996, European Telecommunications Standards Institute (ETSI) decided to enhance 2G GSM standard in the Phase 2+ release that incorporate the third generation (3G) features such as General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE). The data rates for users of the systems are limited to less than several hundreds of kbp/s.

Universal Mobile Telecommunications System (UMTS) as the 3G mobile system will be introduced during the first decade of new century. It is specified by ETSI and the world-wide 3G Partnership Project (3GPP) within the framework defined by the International Telecommunication Union (ITU) and known as International Mobile Telecommunications - 2000 (IMT-2000). The 3G systems can support 2 Mbp/s for indoor environments and at least 144 kb/s for vehicular environments.

The next step of wireless communications evolution is the fourth generation (4G) of mobile communication systems (the systems beyond IMT-2000). Now it is difficult to predict when the 3G evolution ends and the 4G really starts [2]. The 4G systems should be designed to offer higher bit rate channels than 2 Mb/s and accommodate a significantly larger amount of traffic than the 3G systems.

On the Core Network (CN) side of the 4G systems the main purpose is to minimize changes and utilize the 3G CN elements and the 3G CN functionality as much as possible. It is supposed that the CN of the 3G systems will be able to support the functionality of 4G system services. On the other hand, in the 4G systems the RAN will experience the major changes. It will make the 4G RAN different from current RANs. In particular, in 4G systems the Base Station (BS) radius cell is supposed to be shorter than that of 3G systems [3]. Therefore, the 4G RAN will comprise more BSs and more frequent handover will take place in the system. As a result of it, there will be a heavy load on the links between such elements of RAN as Remote Network Controller (RNC) and BSs, suggesting changes to the RAN architecture. It may lead to increasing significantly the expenses when the 4G RAN construction [4].

In [1,3,4] a new and innovative physical links topology for the 4G RAN has been proposed and analytically argued from the viewpoint of a load and routing capabilities. It is named the “cluster-cellular” or, in other words, it is known as a ring topology. An example of the 4G-RAN ring topology is shown in Figure 1.

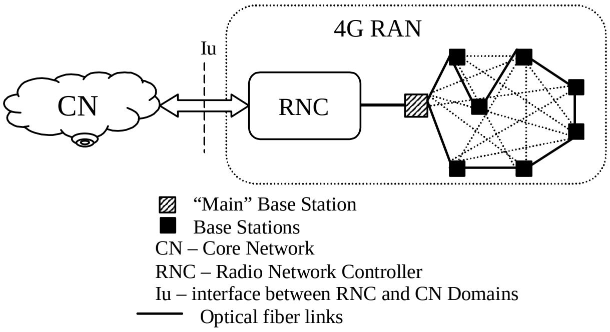

Figure 1: An example of the 4G-RAN ring topology

In such topology BSs are connected to each other and there is a “cluster-main” BS linked to the RNC. Note that in the 3G RAN, BSs can be connected to their dedicated RNC directly (tree or radial topology) or in cascade way only, because in the current 3G releases BSs do not have routing capabilities and traffic between them has to be forwarded through the dedicated RNC [12].

It has been proven that the ring topology may be preferable than other topologies not only the viewpoint of a load and routing capabilities, but from the cost and reliability viewpoint as well [5]. BSs in the ring topology may be connected to each other by optical fiber links that are preferred as the dominant links to construct the 4G RAN, first of all, from the viewpoint of link capacity [6]. Besides, there are some other reasons to apply optical fiber cables in 4G RAN [3]. Nevertheless, it should be emphasized that the infrastructure cost of optical fiber networks is very expensive because of high installation cost. Therefore, the problem of a configuration of optical fiber links with a minimum cost between such RAN elements as BSs in the 4G RAN ring topology is very topical.

In this paper the problem of the physical links ring configuration between BSs in the 4G RAN is considered. The purpose is to determine the minimum-cost ring configuration that satisfies the specified constraints. We pose this as a combinatorial-optimization problem of high complexity (NP-complete) and demonstrate the ability of dynamic programming principle to provide an acceptable solution for it.

2. Definition of the Problem of the Physical Links Configuration

The problem of the physical links ring configuration may be formulated as follows.

It is given: the set of BSs, $M \in \{1,2,\ldots\}$, the cost matrix of links connecting these 4G-RAN nodes with each other. It is assumed that BSs are connected to each other by optical fiber links.

It is necessary to find: the shortest path ***(on the cost optimum criterion)*** that satisfies to the following constraints:

1. It must pass over all BSs.
2. It must pass over each BS only once.
3. It must begin and to end in the same point corresponding to the "main" BS.
4. It must have no splits.

Let us number the nodes: $x \in \{1,2,\ldots,M\}$.

Then, the problem is to determine

$$\min \sum_{i=1}^{M} C(x_{i-1}, x_i) = \min_{\{x_2,\ldots,x_{M+1}\}} J_{M+1}(x_1, x_2, \ldots, x_M, x_{M+1}) \qquad (1)$$

taking into consideration the above-stated constraints. Here, x is the number of a node, $x \in \{1,2,\ldots,M\}$; the index i denotes the place of a node on the path, $i=1,2,\ldots,(M+1)$; $C(x_{i-1},x_i)$ is the cost of a link between x_{i-1} and x_i nodes correspondingly; $J_{M+1}(x_1,x_2,\ldots,x_M,x_{M+1})$ is the path cost equal to the total cost of the links in it.

The cost $C(x_{i-1},x_i)$ may comprise the following components

$$C(x_{i-1}, x_i) = \alpha\rho + \beta g + \gamma f + v \qquad (2)$$

where α is the cost of the link length unit; ρ is the distance between x_i and x_{i-1} nodes; β is the complexity coefficient of the cable-laying; g is the cost of the cable-laying; γ is the complexity coefficient of installation works dependent on methods of the cable-laying; f is the installation works cost of the cable-laying; v are the additional expenses depending on some specific local conditions. Note that in practice the cost $C(x_{i-1},x_i)$ may be assigned not only for fiber-optical cable but, taking into account real planning conditions, also for other types of cables, for microwave radio links, for existing cables.

3. Approach for the Problem Solution

Most of the known shortest-path algorithms cannot be applied for the problem solution because of the above-stated constraints [7]. For many of such problems optimal solutions cannot be guaranteed [7]. We present the approach using the dynamic programming principle to solve the problem [8]. The dynamic programming principle has been successfully used for network planning purposes [9,10].

Let's cut the ring, for example, in the node # 1, which corresponds to the "main" BS location. Then, it is necessary to find the shortest path beginning in the node $x_1=1$ and coming to its end in the node x_{M+1}, as shown in Figure 2. It is clear, that the node x_{M+1} coincides with the node x_1: $x_1=x_{M+1}=1$.

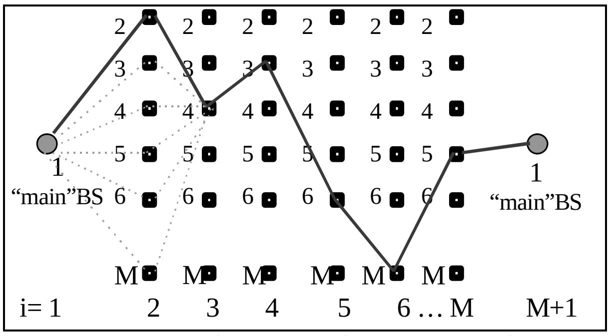

Figure 2: Illustration of the approach for determination of the ring configuration with the minimum cost

There are nodes from 2 to M on intervals $i=2,3,\ldots,M$.

The state of the system on i-step is $x_i \in \{2,3,\ldots,M;\ i=2,3,\ldots,M\}$.

The form of the objective function for the path with its length of i-links is given by

$$\underset{i=1,2,\ldots,(M+1)}{J_i}(x_1, x_2, \ldots, x_i) = J(x_i) = \\ = \begin{cases} \hat{J}(x_{i-1}) + C(x_i, x_{i-1}), & if \quad x_i \cap \{\hat{x}_i \ldots \hat{x}_{i-1}\} = 0 \\ \infty, \quad if \quad x_i \cap \{\hat{x}_i \ldots \hat{x}_{i-1}\} \neq 0, \end{cases} \qquad (3)$$

where $\hat{J}(x_{i-1})$ is the survive path cost equal to the sum of link costs from the node 1 to the node x_{i-1}.

Using the Bellman principle [6] we form the system of M functional equations (for each value x_i).

$$\hat{J}(x_i)=\begin{cases}\min\limits_{x_i\longrightarrow x_{i-1}}\hat{J}(x_{i-1})+C(x_i,x_{i-1}), & if \quad x_i\cap\{\hat{x}_i\ldots\hat{x}_{i-1}\}=0\\ \infty, & if \quad x_i\cap\{\hat{x}_i\ldots\hat{x}_{i-1}\}\neq 0 \qquad (*)\end{cases} \tag{4}$$

Solving (4) we get a variant of the physical links ring configuration that has the nearly optimal cost. The restriction (*) allows us to take into account the constraint (ii) according to which the path can pass only once over each node. Unfortunately, there is no guarantee that optimal solutions will be found in all cases. However, with help of the approach it is possible to achieve the following advantages:

- to get the variant of the ring configuration being close to the optimum;
- to reduce the huge amount of calculations taking place in such kind of problems up to ~M^3 (M - the number of nodes);
- to take into account all the above-stated constraints;
- to observe the non-ring configurations close to the optimum on intermediate stages of the search procedure.

These advantages make the approach different from other search algorithms [7].

It is unlikely, but the restriction (*) may lead to some incorrectness of the result, in particular, when the number of nodes is considerable [8]. It has been argued that the number of BSs in one ring does not have to exceed 6 or 7 [5]. Nevertheless, in cases when it is planned to connect more than 7 BSs in a ring then it is worthwhile, just in case, to repeat the above-stated procedure of the path quest by cutting the ring in other nodes:

$x_1 = x_{M+1} = 2,3,\ldots,M$.

The minimum-cost path should be chosen for the physical links configuration. These operations shall increase slightly the number of calculations (up to ~M^4) but it will make sure that the variant of configuration determined earlier is right, i.e. that we have the shortest ring path.

4. A Case Study

In this section we demonstrate the ability of our approach to find the minimum-cost configuration by the following example.

It is given:

1) the 7 BSs (M=7) in the 4G RAN (Figure 3),
2) the matrix of cost (conventional units) of the links connecting the nodes

$$\|C\|=\begin{Vmatrix}0 & 0.333 & 0.048 & 0.955 & 0.905 & 0.714 & 0.476\\ 0.333 & 0 & 0.381 & 1 & 0.857 & 0.286 & 0.429\\ 0.048 & 0.381 & 0 & 0.524 & 0.095 & 0.762 & 0.571\\ 0.952 & 1 & 0.524 & 0 & 0.809 & 0.238 & 0.190\\ 0.905 & 0.857 & 0.095 & 0.809 & 0 & 0.619 & 0.143\\ 0.714 & 0.286 & 0.762 & 0.238 & 0.619 & 0 & 0.666\\ 0.476 & 0.429 & 0.571 & 0.190 & 0.143 & 0.666 & 0\end{Vmatrix} \tag{5}$$

It is necessary: to find the shortest path passing over all BSs in a ring.

The approach described in Section 3 was used for software calculations, which gave the shortest path shown in Figure 3.

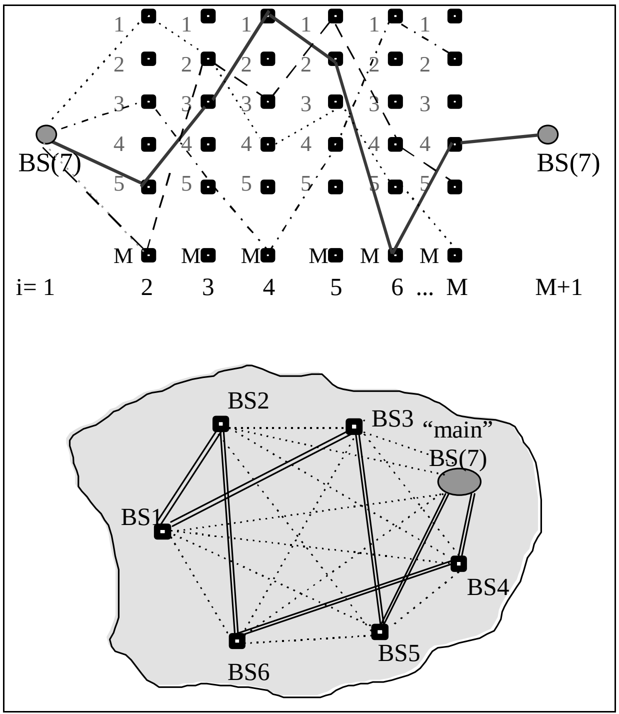

Figure 3: An example of the determination of the ring configuration with the minimum cost for 7 BSc in 4G RAN

If we cut the ring in other nodes that do not correspond to the "main" BS location and repeat all calculations, the minimum-cost path passes by the same route. Consequently, this variant of the ring configuration of physical links can be considered as optimal one from the cost viewpoint for the 4G RAN planning. The cost of the path equals 1.333. In contrast, the cost of the configuration of tree links from the "main" BS to other BSs is 2.475. It is of 86 % more than the cost of the ring route.

Let's consider the cost bottom boundary of the non-ring path that satisfies the constraints (i) and (ii) only. This parameter may be calculated as follows

$$C_{opt} \geq \sum_{i=1}^{M} \min_{j} C(x_i, x_j), \quad i \neq j, \quad j = \overline{1, M}, \tag{6}$$

where $C(x_i x_j)$ is the cost of the link between x_i and x_j nodes.

The value of the cost bottom boundary in this example comes to 1.047. The difference between this value and the value of optimal ring path cost (1.333) is less than 28%, whereas a ring topology is much more reliable than non-ring configurations.

Note that tree and treelike topologies optimizing is not a topic of the research. Different aspects of planning of the topologies in 3G RAN have been considered in [11,12].

Such software calculations were run for different number of BSs in the 4G RAN. The calculations have been able to produce minimum-cost results in all runs. The fact that all results had the optimum values in such a large fraction of the cases studied demonstrates the robustness of our approach, and allows suggesting that it may perform well in considerably larger examples as well.

5. Conclusion

In this paper, we have formulated a version of the configuration problem of physical links between BSs in the 4G RAN ring topology as a combinatorial-optimization problem, and used dynamic programming to solve it.

Our approach enables to get the ring configuration of optical fiber links between BSs in the RAN being close to optimum. The approach allows reducing the expenses on fiber-optic cable and its laying on deployment of a 4G RAN. It also allows to considerable reduce the amount of calculations up to ~M^3, where M is the number of BSs in the ring. One more advantage of the submitted approach from other algorithms, which can be used for similar problems, is visualization of the state of the system on each step of the search procedure. In other words, the non-ring configurations close to the bottom boundary of cost (6) can arise on intermediate stages. It enables considering different topologies of physical links when planning a 4G RAN.

Software calculation results demonstrate the effectiveness of the approach for the minimization of the ring configuration cost. Note, that the same approach may be easily adopted for similar configuration problems between such elements of the RAN as RNCs. It should be emphasized that at the final choice of a physical links configuration in the RAN, there is a need to take into account the reliability parameters and the complexity of the network management, as well.

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