Cost and Reliability Estimation of Radio Access Network Structures for 4G Systems

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Abstract – Topological configuration the physical links of a network (network structure) is an important problem of mobile communication network planning because it will determine the long-term performance and service quality of networks. In this paper, the architecture aspects of Radio Access Network (RAN) physical links configuration for the Fourth Generation (4G) of wireless networks are considered. In the 4G systems ring structures of a RAN configuration may be applied in contrast to RANs of current wireless systems. Therefore, the objective of our research is to estimate the RAN ring structure from the viewpoint of cost and reliability parameters and compare the obtained parameters with those of other structures. As a result of this study, we are able to give recommendations on using different configurations of physical links in the RAN for mobile communication systems beyond IMT-2000 (4G systems).

I. INTRODUCTION

Currently, there is an evolution in wireless communications from GSM Phase 2+ cellular systems towards the Fourth Generation (4G) wireless multimedia systems. Several important aspects of this global process have to be highlighted.

The 4G systems should offer significantly higher bit rates than 2 Mb/s, also should have higher capacity and lower bit cost then those of the Third Generation (3G) cellular systems and be able to support all types of new and future multimedia services. Certainly, these requirements will make the 4G Radio Access Network (RAN) different from current RANs and will innovate in its architecture [1].

In the 3G RAN Base Stations (BSs) can be connected to their dedicated Radio Network Controller (RNC) directly (tree or radial structure) or in a cascade way. In the current 3G releases BSs do not have routing capability, therefore, traffic between them has to be forwarded through the dedicated RNC [2].

It is expected that in the 4G systems a load on both the RNC signal processing equipment and the entrance links between the RNC and BSs will be heavier [3]. It may raise valuable funds for the RAN construction. In [1,3,4] a new and innovative RAN structure for the 4G systems from points of view of a load and routing capabilities has been proposed and analytical proved. This structure is called a cluster-type configuration or, in other words, it is known as a ring structure. In such structure BSs are grouped in a “cluster” and a “cluster-main” BS connected to the RNC is assigned. BSs in a cluster may be linked to each other by a kind of local area network [3].

In this paper, the ring structure of the RAN physical links with respect to its reliability and cost is considered. The objective is to make the quantitative estimation of reliability and cost parameters of the ring structure, to compare it with those of other structures and to give recommendations on applying different structures of a physical links configuration for the 4G RAN.

The paper is organised as follows. We start with estimating of the reliability parameters for structures consisting of one, two, three and more rings, and radial structure. Then we estimate the cost parameters of these structures. After that we compare the structures with each other taking into consideration both cost and reliability. Finally, we give a number of recommendations how to choose a RAN physical links structure depending on a number of BSs in a RAN.

II. RING STRUCTURE RELIABILITY ESTIMATION

A. Definition of The Ring Structure Reliability

4G systems should provide the capacity of 100 Mb/s as the maximum for the data communication channels [5]. In such systems, because there will be a need to deal with the enormous amount of traffic, the BS radius cell is supposed to be shorter than that of 3G systems. Therefore, the 4G RAN will comprise more BSs. Therefore, more frequent handover will occur resulting in a heavy load on the links between RNC and BSs. It is expected that the 4G RAN will transfer 23-fold more traffic than the current RANs [4].

Optical fiber links are preferred as the dominant links to construct the RAN, first of all, from the viewpoint of link capacity [5]. Besides, when employing radio entrance links, a higher frequency band will be used to transmit broadband signals. However, the higher frequency bands suffer from rain attenuation and the signal transmission range may be limited to less than a few kilometres [4]. Therefore, radio repeaters are necessary for BSs remote from the RNC that will cause a cost increase in the RAN.

It should be emphasised that the infrastructure cost of optical fiber networks is also quite expensive because of high installation cost. But, due to the dark fiber services, the cost of optical fiber networking is expected to decrease in the near future [5]. Besides, there is a new technology such as fiber and free-space hybrid optical (FFHO) networking that has a number of advantages with respect to the structure of broadband RANs compared to wireless links from network cost, flexibility and capacity points of view [5].

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Taking into account the above-mentioned explanation, let’s assume that BSs are connected to each other by optical fibers in the RAN. The model of a 4G RAN configuration is presented in Fig. 1. The ring structure is organised by type of “petals of flower”.

![Diagram of a 4G RAN configuration](image)

**Fig. 1. The model of a 4G RAN configuration**

Under the reliability we shall mean the ability of the RAN to perform its required functions under stated conditions for a given time interval at possible damages which can arise in it.

As a quantitative parameter of the structure reliability, the average number of knocked out BSs is calculated. Such BSs cannot serve its mobile terminals because of damages in the RAN physical links connecting BSs to each other. The BS is knocked out if there are damages in the ring on both side of this BS.

### Problem

**It is given:**

1. $z$ is a number of BSs in the RAN, $z \in \{1, 2, \ldots\}$.
2. $N$ is a number of rings in the RAN, $N \in \{1, 2, \ldots\}$.
3. $L$ is a number of damages in the RAN, $L \in \{0, 1, 2, \ldots\}$.
4. $M$ is a number of BSs in a ring, $M \in \{1, 2, \ldots\}$. The number of BSs in each ring is equal.

Let us assume that the probability of damages appearing in RAN physical links is defined as Poisson process:

$$p_L(T) = (\lambda T)^L \frac{e^{-\lambda T}}{L!},$$

where $p_L(T)$ is the probability of $L$ damages appearing in the RAN for a given time interval $T$, $\lambda$ is the flow parameter of damages.

**It is necessary:** to find an average number of knocked out BSs depending on the number of rings in the RAN, the number of BSs in the ring, the damages number in the RAN - $X(N, M, L) \in \{1, 2, \ldots, z\}$.

### B. Approach to The Problem Solution

The common expression for calculation of average number of knocked out BSs is

$$\hat{X}(N, M, L) = \sum_{l=1}^{L} \hat{X}(N, M \mid L)p_L = \hat{X}(N, M \mid L=1)p_1 + \hat{X}(N, M \mid L=2)p_2 + \hat{X}(N, M \mid L=3)p_3 + \ldots,$$

where $p_L$ is a probability of $L$ damages in the RAN, $L \in \{0, 1, 2, \ldots\}$; $\hat{X}(N, M \mid L=1)$, $\hat{X}(N, M \mid L=2)$, $\hat{X}(N, M \mid L=3)$ is an average number of knocked out BSs when there are one, two or three damages in the RAN accordingly.

Using (1), the probabilities $p_1, p_2, p_3$ can be expressed in terms of the probability $p_0$ ($p_0$ is the probability that there are no damages in the RAN) as follows

$$p_1 = (-\ln p_0)p_0, \quad p_2 = (-\ln p_0)^2 \frac{p_0}{2}, \quad p_3 = (-\ln p_0)^3 \frac{p_0}{6}, \ldots$$

By substituting probabilities (3) into (2) the following expression is obtained

$$\hat{X}(N, M \mid L) = \hat{X}(N, M \mid L=1)(-\ln p_0)p_0 + \hat{X}(N, M \mid L=2)(-\ln p_0)^2 \frac{p_0}{2} + \hat{X}(N, M \mid L=3)(-\ln p_0)^3 \frac{p_0}{6} + \ldots$$

Some preliminary calculations have been made. If the value $p_0$ is varied from 0 to 1 then the first, second and third members of series (4) exert the main influence on the value $\hat{X}(N, M \mid L)$. It is several orders more than the influence of the fourth and following members of (4) on the value $\hat{X}(N, M \mid L)$. This fact does not depend on values of coefficients $\hat{X}(N, M \mid L=1)$, $\hat{X}(N, M \mid L=2)$, $\hat{X}(N, M \mid L=3)$ and so on. Thus, there is no practical reason to perform the calculations for the damages number more than 3. On this basis, (4) takes the form

$$\hat{X}(N, M \mid L) = \hat{X}(N, M \mid L=1)(-\ln p_0)p_0 + \hat{X}(N, M \mid L=2)(-\ln p_0)^2 \frac{p_0}{2} + \hat{X}(N, M \mid L=3)(-\ln p_0)^3 \frac{p_0}{6}$$

It is obviously that if there is a single damage in the RAN then the average number of knocked out BSs $\hat{X}(N, M \mid L=1)$ equals 0.

The expressions for calculations $\hat{X}(N, M \mid L=2)$ and $\hat{X}(N, M \mid L=3)$ are given by:
\[ \hat{X}(N, M / L = 2) = \frac{2(M+2)}{3(N+1)} \]  

(6)

\[ \hat{X}(N, M / L = 3) = \frac{(M+2)(2N+1)}{(N+1)(N+2)} \]  

(7)

We use the probability theory principles to make a deduction of (6) and (7). The deduction of the expressions does not present here because of the enormous quantity of calculations. The expression (5) can be written taking into account of (6), (7) and that \( \hat{X}(N, M / L = 1) = 0 \) as

\[ \hat{X}(N, M, L) = \frac{(M+2)(-\ln p_0)^2 p_0}{3(N+1)} + \frac{(M+2)(2N+1)(-\ln p_0)^3 p_0}{6(N+1)(N+2)} \]  

(8)

The formula (8) is the final expression for calculations of the average number of BSs that are not able to serve mobile terminals as a result of damages in the RAN ring structure.

C. Results of The Problem Solution

The probability of zero damage (\( p_0 \)) corresponds to the availability in term of the reliability theory [6]. Under the availability we shall mean the probability that the RAN is able to be in a state to perform operating at a given instant of time. According to [7], an availability objective of 99.99% can be considered as acceptable in our case. Relationships of the average number of knocked out BSs from the rings number \( N \) and the number of BSs in each ring \( M \) when value \( p_0 \) equals 0.9999 is shown in Fig. 2.

![Fig. 2. Relationships of the average number of knocked out BSs from the rings number and the number of BSs in each ring when value \( p_0 = 0.9999 \)](image)

As may be seen from the diagrams, the ring structures are provided the high reliability for the RAN. So, value \( \hat{X}(N, M, L) \) is in order of magnitude of \( 10^{-8} \) when the availability equals 0.9999. For better visualization of this fact similar relationships are shown in Fig. 3 when the availability is very low, e.g. \( p_0 = 0.3 \).

It is seen that with increasing the ring number the RAN reliability is considerably raised up. In particular, for one ring in the RAN the average number of knocked out BSs is 1 if the number of BSs in the ring is 7. For two rings, \( \hat{X}(N, M, L) = 1 \) if the number of BSs in each ring is 10. For three rings, \( \hat{X}(N, M, L) = 1 \) if the number of BSs in each ring is 13.

![Fig. 3. Relationships of the average number of knocked out BSs from the rings number and the number of BSs in each ring when \( p_0 = 0.3 \)](image)

III. RADIAL STRUCTURE RELIABILITY ESTIMATION

Let us compare the ring structure reliability parameters with other structures. As an example, let us calculate the average number of knocked out BSs for a radial (or tree) structure taking into account that the structure is the basic configuration of the RAN physical links of 3G systems [3].

Definition of this problem is identical to that for section II. However, there are some modifications in it. In particular, it is supposed that each BS is connected to the RNC directly (radial structure), accordingly, the rings number equals 0. The damages number does not exceed 3. The BS is knocked out if there is a single damage of line link between this BS and the RNC. Two damages cannot take place in one line link.

The common formula for calculations of the average number of knocked out BSs is given by

\[ \hat{X}(M, L) = \hat{X}(M / L = 1)p_1 + \hat{X}(M / L = 2)p_2 + \hat{X}(M / L = 3)p_3 \]  

(9)

Expressions for calculations of probabilities \( p_1, p_2, p_3 \) are identical (3). It is clear that if there is a single damage in the RAN then the average number of knocked out BSs equals 1.
If there are two damages in the RAN then the average number of knocked out BSs is 2. If there are three damages in RAN then the average number of knocked out BSs is 3: 
\[ \hat{X}(M/L = 1) = 1, \quad \hat{X}(M/L = 2) = 2, \quad \hat{X}(M/L = 3) = 3. \] 
\[ (10) \]

Thus, the expression for the radial structure reliability parameter calculation is 
\[ \hat{X}(M,L) = (-\ln p_0)p_a + (-\ln p_0)^2 p_a + \frac{(-\ln p_0)^3 p_a}{2} \] 
\[ (11) \]
As can be seen from (11) this reliability parameter does not depend on the number of BSs in the RAN at given conditions. If \( p_0 = 0.9999 \) then the average number of knocked out BSs equals \( 10^{-4} \). This value is about four orders greater than one for ring structures or, in other words, a radial structure is considerably worse than ring structures from the viewpoint of reliability. Note that when the availability is very low then values of reliability parameters both ring structures and the radial structure may be comparable. So, if \( p_0 = 0.3 \) then the average number of knocked out BSs equals approximately 1. For comparison, for two rings in the RAN the average number of knocked out BSs is 1 when the number of BSs in each ring is 10 (\( p_0 = 0.3 \)).

IV. RING AND RADIAL STRUCTURES COST ESTIMATION

In order to give recommendations on selecting a RAN physical links structure it is necessary to analyse different structures from reliability and cost points of view simultaneously. In this section, we calculate ring and radial structures parameters and compare them with each other.

As it was mentioned in Section II, the optical fiber physical links cost may be very essential in the RAN total cost. For this reason, let us consider the normalised length of links connecting BSs to each other as a quantitative parameter of cost.

Problem

It is given: \( M \) is a number of BSs in the ring, \( M \in \{1,2,\ldots\}; \) \( N \) is a number of rings in the RAN, \( N \in \{1,2,\ldots\}; \) 
coordinates of BSs.

It is necessary: to find the normalised length of links connecting BSs to each other depending on the number of BSs and rings in the RAN - \( L(M,N) \).

As an example, tree rings structure linked 18 BSs are shown by dotted line in Fig 4.

The expression for calculation of the cost parameter \( L(M,N) \) of ring structures has the following view 
\[ L(M,N) = \frac{2r(M + N)}{M}, \] 
\[ (12) \]
where \( r \) is radius of the internal circle of cells.

For calculation of the cost parameter of a tree or a radial structure of the RAN (\( N = 0 \)) the following expression is obtained
\[ \left\{ \begin{array}{l}
L(M, N = 0) = 2r, \quad M = 16 \\
L(M, N = 0) = \frac{12r + 3.46r(M - 6)}{M}, \quad M = 7,12 \\
L(M, N = 0) = \frac{r(4M - 15)}{M}, \quad M = 12,18 \\
\end{array} \right. \] 
\[ (13) \]
Relationships of the normalised length of links from the number of BSs and the rings number in the RAN are presented in Fig 5.
It is seen that if the number of BSs in the RAN is from 1 to 7 then the cost parameter of the radial structure is more beneficial than the ring structures one. If the number of BSs is 7 and more then the ring structures are preferable to radial from the viewpoint of cost.

V. RECOMMENDATIONS ON USING DIFFERENT STRUCTURES IN THE 4G RAN

In order to make recommendations on applying a ring structure, multi-ring structure (two and more rings) or a radial structure in the 4G RAN, let us analyse both the reliability and cost relationships simultaneously. For this purpose the relationships presented in Fig. 3 and Fig. 5 are combined in Fig. 6.

Fig. 6. Relationships of the normalised length of links and the number of BSs and the ring number in the RAN (four upper curves) and relationships of the average number of knocked out BSs and the ring number and the number of BSs in each ring when $p_0 = 0.3$

Analysing the presented relationships the following conclusions may be formulated. If the number of BSs in the RAN is 1,2 or 3 then it is worthwhile to apply the radial structure of physical links configuration. However, taking into account very low reliability of the radial structure it may be reasonable to use one ring structure when there are 3 BSs in the RAN. One ring structure is also preferable when there are 4 and 5 BSs in the RAN. If the number of BSs is more than 5 then it is not recommended to apply one ring structure because it has reliability parameters worse then multi-rings structures. If BS number is from 6 to 10 it is worthwhile to arrange two rings in the RAN. If the number of BSs is from 11 to 16 then three rings structure may be applied. If very high reliability is necessary then two rings and three rings structures may be organized when there are 5 BSs and 10 BSs in the RAN accordingly.

VI. CONCLUSION

In this paper, a method of selecting 4G RAN physical links structures has been presented. The proposed approach allows making a quantitative estimation of reliability and cost parameters of different structures. In particular, the parameters of one ring structure, multi-ring structures (two and more rings) and a radial structure have been considered and compared with each other. The results of the research allow making a conclusion that multi-ring ring structures are more preferable from the viewpoint of cost and reliability for the 4G RAN than other structures. It should be emphasized that at the final decision about a RAN configuration it is necessary to take into account load parameters and complexity of the network management, as well.

REFERENCES