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Microwave-Links In Cellular Backhaul Networks: Statistical Studying And Modeling

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Abstract. While the effect of rainfall and other environmental phenomena on a link budget in microwave wireless communication has been well studied for networks design, it has usually been done for each link separately. Recently, attenuation in multiple microwave links is used for rainfall mapping in specific areas, so rain-induced attenuation fields can be constructed. The novel algorithms which relate attenuation and rain-fields are useful for both weather monitoring and networks design. As the topology of microwave links network is region-dependent, general theory can only be developed statistically. In this paper we study the statistical nature of Cellular Microwave Networks and lay the groundwork for such model based on empirical results.

Keywords: *Microwave links, rainfall mapping, rain-field estimation, network statistics.*

1. Introduction

In cellular backhaul networks, microwave-links are used as the wireless channels to connect two base-stations (BS). Each of the BSs is equipped with a transmitting-receiving antenna. Fig. 1 illustrates this configuration. Giuli et al. describe in their work [4,5] how such microwave channels can be used for rainfall mapping. Capitalizing on the use of microwave links in cellular communications, Messer et al. [7] suggested commercial backhauls network for environmental monitoring. They suggested utilizing the commercial network, already set-up and functional, thus offering a cheap and opportunistic approach to the problem of precipitation monitoring. In that framework, the precipitation-field is the signal to be reconstructed and the microwave-links are random line projections, sampling the signal. As the microwave propagates along the link, it accumulates attenuation that is attributed to the air's moisture, thus providing a kind of a sample of the precipitation field. This physical phenomenon is described in [9] and is elaborated on in [4]. In order to yield a reconstruction method for a given sampled field, one must characterize the

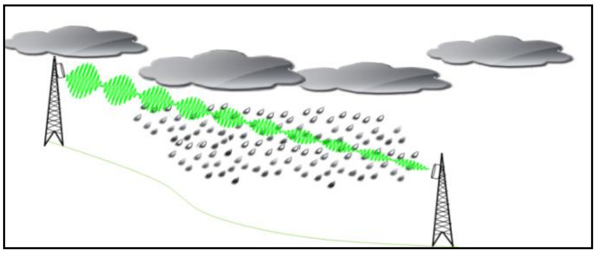

Figure 1 – A single microwave-link, taken from [3].

sampling scheme, i.e., the features of microwave-links [3]. The spread of network BSs, and thus microwave-links, is designed based on several considerations. When designing a topology of microwave-links, one can divide the factors to two, micro and macro.

Micro factors would be those that make a minor difference on the location of the BS. For instance, after deciding to position a BS on a specific street block, one would consider micro factors dictating positioning that BS on a specific building's roof-top rather than another's. The macro factors, on the other hand, will dictate to the cellular providers what would be the amount of microwave-links to deploy in an area, how to spatially distribute them, and how their lengths should vary. Insights regarding the design of backhaul networks can be found in [2]. We suggest that there is a random factor in the spread of microwave-links. This claim, which is the base to this paper, relies on both the micro and macro factors. In this paper, the macro factors are addressed, having that they affect the spatial distribution of links as a whole, and their density in particular. As will be demonstrated, this spatial distribution of links can be divided to subsets of distribution categories based on population density and topography.

Fig. 2 shows the distribution of microwave-links in Sweden and the Netherlands. By taking a look at the map one can get a feel for the volume and distribution of links. It is clear that the distribution is in the form of dense clusters. In each of the two maps, the dense clusters coincide with dense

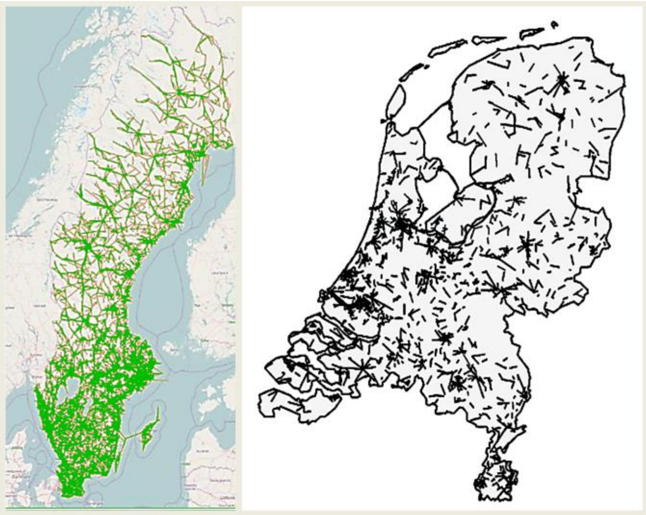

Figure 2 – Microwave links distributions in the Netherlands (right) [10], and Sweden (left) (source: Swedish Post and Telecom Authority, 2016).

populations, i.e. cities. The bigger the city, the bigger the cluster, and the denser the population, the denser the links. These links maps give us an intuition for the macro factors regarding distribution and volume.

The common categories relating to spatial distributions are urban (most dense), suburban, and rural (least dense) [12,13]. In [1] one may also find a connection between population density and perspective BS capacity. Meaning, how population volume may saturate BSs service capacity, thus calling for the allocation of additional BSs to share the load. Table 1 shows results of BS density studies. Note that these BS densities reflect microwave-links densities to the same extent. To witness this relationship, Fig. 2 presents the four common links topologies. One can see that for each of these, the number of edges is similar to the number of nodes, as they symbolize the links and BSs, respectively.

Fig. 2 and Table 1 suggest that statistics of the spatial distribution of microwave links is not, and cannot be homogenous. However, our study is based on the assumption that any given region can be partitioned to sub-regions, each homogeneous in the sense that all links' positions in such sub-region are drawn from

Table 1 – Statistical BS densities [13]. BS densities depend on population densities. Since links topologies are such that the number of links is nearly identical to the number of BSs, this table also reflects spatial densities of links.

Region	Area [Km^2]	BS Amount	BS (~Links) Density [$1/Km^2$]
Most Dense City	60×40	6,251	2.604
Second Densest City	30×50	1,911	1.274
Third Densest City	40×40	977	0.611
Rural	200×200	12,691	0.317

the same uniform distribution. Here and throughout this paper, when referring to a link's position, it is the

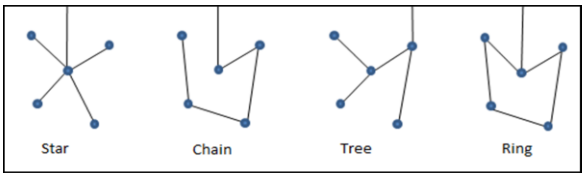

Figure 3- Typical links topologies. All four are such that the number of links is approximated by the number of BSs [8].

position of its midpoint that is considered. Based on [11], we suggest describing microwave-links distribution in any homogeneous region by three characteristics:

1. Spatial density of the links
2. Orientations of the links
3. Lengths of the links

The rest of the paper is organized as follows: in sections 2 and 3 we study the links' statistical characteristics as listed above and suggest statistical models. Section 2 tends to links spatial density, and section 3 tends to their orientations and lengths. Section 4 suggests a mathematical model for the relationship between links' lengths and their spatial density. Section 5 discusses the results. The geographical regions analyzed here are described in the appendix.

2. Spatial Distribution

We suggest partitioning a region to sub-regions, each with spatially-uniform links density. It is anticipated that such sub-regions correspond to the common environmental terms: urban, sub-urban, and rural. The results of this study, as will be shown, are concerned with the number of links in the region of interest. It is assumed that those links' centers are spread evenly, meaning, not clustered together. If such partition to homogeneous regions was not performed and the links were clustered together, their spatial distribution would need to be addressed more specifically in order to evaluate reconstruction potential.

Another guideline for partitioning a region is to maintain a nominal area appropriate for capturing relevant rain phenomena. Typical rain-clouds over Israel tend to reach an area of up to 10x10 [Km^2] [6]. It is recommended to maintain a minimum of such area. Accordingly, in this paper we examined regions that are 10x10 [Km^2].

3. Length and Orientation

In addition to the locations and volume of microwave-links, characteristics of individual links present a significant measurement factor as well. These characteristics are the orientation and length of the link. The understanding of all three factors allows for a 2-D modeling of microwave-links, as this paper is

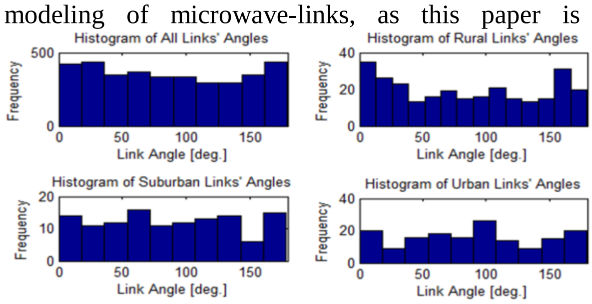

Figure 4 - The distribution of links angles. Top-left: All Israel, top-right: top northern Israel as rural, bottom-left: Hasharon as suburban, bottom-right: Tel-Aviv as urban.

concerned with. It should be mentioned that if one were to examine the 3-D modeling of microwave-links, the links' height variability would be a factor as well.

The study presented here addresses microwave-links in the state of Israel belonging to a single cellular provider, Cellcom (see appendix for farther details). Results show that in any type of region studied, links' orientation takes on any angle with equal probability. Meaning, the direction of microwave-links is distributed uniformly without relation to the type of population density. Fig. 4 portrays this conclusion. Moreover, the orientation is found to be statistically-independent of the other factors studied here, the link's length, and the links' density.

There is prior work that addressed the distribution of links orientations and lengths. In his master thesis, Sendik [11] divided Israel to four parts based on latitude (Israel stretches from latitude 29.5 to 33.29). These four parts were used as sub-regions for the study of links. These four regions are heterogeneous in their environmental types. By isolating sub-regions in Israel that are of homogeneous environment type and characterizing links statistics by such type, we suggest a contribution to Sendik's work for link's statistical modeling.

Lengths of microwave-link, unlike orientations, are distributed non-uniformly. Moreover, also unlike links' orientation, the lengths' statistical characteristics depend on the type of environment. Microwave-links' lengths are distributed exponentially. This claim is portrayed in Fig. 5.

The sample-means specified in the above figures correspond directly to the fitted exponential distribution. For an exponential random-variable, e.g. $T \sim Exp(1/\theta)$, the probability density function is:

$$f_T(t \mid \theta) = \begin{cases} \frac{1}{\theta} e^{-\frac{t}{\theta}} & t \geq 0 \\ 0 & t < 0 \end{cases} \quad (1)$$

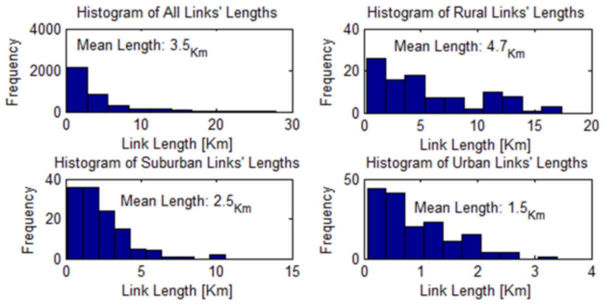

Figure 5 - Lengths distributions for various environments. Top-left: All Israel, top-right: top northern Israel as rural, bottom-left: Hasharon as suburban, bottom-right: Tel-Aviv as urban.

where $\theta = E[T]$. This presents a direct tie between the mean links' length and the exponential fitting. Table 2 concludes empirical results for microwave-links in Israel.

4. Modeling the Relationship between Links' Length and Density

The findings in table 2 suggest that there may be an underling relationship between the links' density and their mean length for a given region. Following that intuition, an experiment in a larger scale was performed. Given the set of links over Israel, a set of 3,626 sub-regions was generated. A moving window with varying dimensions scanned the area of Israel. For every iteration, meaning, every window of the 3,626 windows, the links' density and the links' mean length were captured. Thus, 3,626 pairs of {density, mean length} were observed. Fig. 6 presents the scatter plot of those observations.

A non-linear empirical relationship is hinted in the scatter plot. We suggest a model of the form:

$$\hat{d}(l) = \frac{1}{a_1(l - a_2)} \quad (2)$$

Table 2 - Empirical microwave-link distributions based on environment type. All sub-regions are described in the appendix. Note that the attributes of Tel-Aviv, for instance, don't regard the city of Tel-Aviv, but just the specific region named "Tel-Aviv".

	Region	Area [Km^2]	Links Amount	Links Density [1/Km^2]	Links Mean Length
-	All of Israel	22,770	3,624	0.16	3.54
Urban	Tel-Aviv	85.18	264	3.1	1.48
	Jerusalem	44.16	141	3.2	1.26
	Haifa	56.14	159	2.8	1.58
Sub-urban	Hasharon	235.54	124	0.53	2.5
	Caesarea Area	149.27	77	0.52	2.3
	Nazareth Area	182.78	89	0.49	2.4
Rural	Top North Israel	2,718.74	278	0.1	4.7
	Kseifa Area	1,474.73	69	0.05	8.07

Here d is the links' density (links/Km^2), and it is noted as an explicit function of l, the link's mean

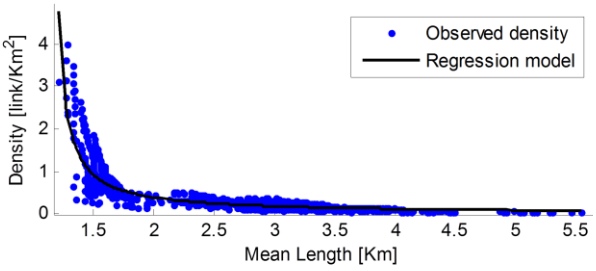

Figure 6 – The empirical relationship between link's density and mean length in a given region. The black curve was derived through non-linear regression.

length (Km). a_1 and a_2 are constant coefficients to be optimized via non-linear regression:

$$\min_{a_1,a_2}\{MSE\} = \min_{a_1,a_2}\left\{\frac{1}{I}\sum_{i=1}^{I}\left(d[i]-\frac{1}{a_1(l[i]-a_2)}\right)^2\right\}. \quad (3)$$

I is the number of observations, 3,626. Given the ratio between the model order (two coefficients) and sample size (3,626), we simply fitted the entire set, avoiding a train-test validation scheme. Optimization was performed using MATLAB (Natick, MA, USA) and the coefficients were derived to be, $a_1 = 3,\ a_2 = 1.14$, yielding and MSE=0.206. So,

$$\hat{d}(l) = \frac{1}{3(l-1.14)} \Leftrightarrow \hat{l}(d) = \frac{1+3.42d}{3d}. \quad (4)$$

The regressed model is plotted in Fig. 6 in black.

5. Conclusion and Discussion

Microwave-links possess three random features, spatial-distribution, orientation, and length. All three were addressed in this study and empirical conclusions were derived. The simplest of the three is the orientation, appearing to be statistically-independent of the other two features, and distributed uniformly across all angles [0^o,180^o]. The links' spatial distribution was found empirically to be dependent of the environment type in the sense of population density. The denser the population is in the observed region, the denser the links are. Such finding support prior studies regarding backhaul BSs densities [13]. The links' length was found to suit an exponential random variable. Moreover, links' mean length, l, which we claim corresponds to the distribution parameter θ (see equation (1)), was found to be dependent on the population density as well. The denser the population is, the shorter the links are. Thus, by association, dependence is suggested between the links' lengths and their spatial density. Such dependence was modeled using a non-linear model.

The ability to apply statistical models to microwave-links allows a much needed understanding for the study of microwave-links-based precipitation monitoring. Through these models one may design reconstruction algorithms engineered for the nature of these random projections. Moreover, these models allow one to compute simulated microwave-links and thus create unlimited synthetic links for the sake of simulations and larger scale experiments.

6. Appendix

This section provides descriptions for the regions analyzed to derive links statistics. All links belong to a single cellular provider, Cellcom, and are dated to January, 2013. Fig. 7 presents the distribution of these links. As table 2 specifies eight sub-regions, their coordinates are specified in tables 3-5.

Figure 7 – Israel's surrounding. The yellow lines show the distribution of Cellcom's microwave-links.

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Table 3 – The urban regions analyzed

	Tel-Aviv	Jerusalem	Haifa
Min. latitude coordinate	32.013	31.74	32.765
Max. latitude coordinate	32.096	31.81	32.825
Min. longitude coordinate	34.776	35.175	34.985
Max. longitude coordinate	34.8739	35.235	35.075

Table 4 – The suburban regions analyzed

	Hasharon	Caesarea	Nazareth
Min. latitude coordinate	32.15	32.41	32.615
Max. latitude coordinate	32.3	32.52	32.732
Min. longitude coordinate	34.83	34.91	35.224
Max. longitude coordinate	34.98	35.04	35.374

Table 5 - The rural regions analyzed

	Top North Area	Kseifa Area
Min. latitude coordinate	32.7	31.4
Max. latitude coordinate	33.09	31.008
Min. longitude coordinate	35.15	35.26
Max. longitude coordinate	35.82	34.905

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