Informed spectrum usage in cognitive radio networks: Interference cartography

(Invited paper)

Afef Ben Hadj Alaya-Feki, Sana Ben Jemaa, Berna Sayrac, Paul Houze
Orange Labs R&D
Issy les Moulineaux, France
{afef.benhadjalaya, sana.benjemaa, berna.sayrac,paul.houze}@orange-ftgroup.com

Eric Moulines
Telecom ParisTech
Paris, France
eric.moulines@enst.fr

Abstract—This paper introduces interference cartography, a simple and effective concept that helps detect, identify and use spectrum opportunities in a secondary spectrum usage context. Interference cartography combines measurements performed by different network entities (mobile terminals, base stations, access points) with the geo-location information and applies simple and effective spatial interpolation techniques to achieve a map which indicates the level of interference experienced at each mesh over the area of interest. Using this information, a secondary network can detect the presence of a primary network (or of other secondary networks) and can use spectrum opportunities without causing harmful interference to them. As an example, a reliable spatial interpolation technique, Kriging, is applied to interference data obtained from a radio network simulator. Obtained results demonstrate that interference cartography is a promising concept that can enhance the performance of secondary spectrum usage.

Keywords—Interference cartography, Opportunistic spectrum access, Kriging

I. INTRODUCTION

Recently, the radio communications community has witnessed definition of new concepts in order to meet the increasing consumer demands (new applications/services, more capacity etc.). Cognitive radio is one of these concepts, which requires mobile terminals to be aware of their environments in order to take intelligent decisions [1]. This awareness is ensured by radio measurements, thus increasing the importance of measurement exploitation in wireless networks in the cognitive radio context. Indeed, cognitive radio renders radio measurements as a crucial part of a mobile radio network for the supervision and control of proper functioning of the network.

Collection and utilization of measurement data in mobile radio networks is becoming more and more efficient, thanks to recent improvements in mobile terminal, network and measurement technologies. Besides, with the recent advances in the field of Data Mining, effective and efficient exploitation techniques are being developed. Such techniques make it possible to extract useful information from the measurement data and use it effectively to enhance network performance [2][3].

With all these driving forces behind, there is a considerable amount of increase in efforts to ameliorate the performance of radio measurement utilization and collection in mobile networks. For that purpose, the definition of more complex measurements (such as the medium sensing time histogram report in 802.11k standard [4][5]), and the use of radio measurements to define models [6] have been introduced in the wireless communications community. The latter case mainly aims to detect spectrum opportunities and to realize dynamic spectrum access in the context of secondary spectrum usage.

Secondary spectrum usage allows unlicensed users (secondary users) to operate in frequency bands allocated to licensed systems (primary users) by detecting the unused spectrum portions (spectrum holes) without causing any deterioration to primary users [6]. In order to detect, identify and use the spectrum opportunities, the secondary users need spatial information of the 'state' of the spectrum. This 'state' mainly involves interference information. Specifically, the secondary transmitter has to know whether there are primary/other secondary receivers (transmitters) in the vicinity of the secondary transmitter (receiver) and how much interference can these receivers (transmitters) tolerate. Dissemination of this interference information in the secondary network needs special signalization with the primary network/other secondary networks as well as special signalization within the secondary network, which may not always be practical to implement.

The goal of this article is to present an interesting solution to this dissemination problem by proposing an original concept called as the interference cartography. It corresponds to a geo-
localized combination and exploitation of radio measurements both at mobile terminal level and at network level. The concept of cartography in wireless networks is mainly used in radio network prediction where maps of coverage, capacity and quality are used for network layout, maintenance, evolution and optimization. It requires geo-localized information on attributes like signal attenuation, received level of signal-to-noise ratio, received total power, best server and received level of quality indicators (throughput etc.) over the area of interest. To the best of our knowledge, the idea of combining location information with radio measurements has appeared recently in the research community. In [14] and [15], first investigations dealt with general databases combining environmental information with location. These databases are called Available Resource Map (ARM) in [14] and Radio Environment Map in [15]. We remark that these databases contain only available located measurements without any additional processing.

The basic idea in constructing the interference cartography is to collect interference measurements from different network elements (mobile terminals, base stations, access points etc.) together with their corresponding geo-location information, and to combine them to form a complete cartography using adequate signal processing techniques intended to spatial interpolation.

Spatial interpolation [7] is a well known procedure, commonly used in Geographic Information Systems (GIS). GIS refers to any system manipulating geographically labelled data for analysis, capture, storage and management purposes in vast application areas like agriculture, meteorology, mining, geology, climate, urbanization etc. Ideas and principles originating from GIS constitute promising candidates for interference cartography construction.

This paper is organized as follows: Section II details the role of interference cartography in opportunistic spectrum usage, followed by the description of interference cartography. Section III describes spatial interpolation methods used for interference cartography construction, particularly a reliable method called as Kriging. Section IV presents an example of interference cartography in secondary spectrum access using radio network simulation data and section V yields concluding remarks.

II. INTERFERENCE CARTOGRAPHY FOR SECONDARY SPECTRUM USAGE

Secondary spectrum usage is a new policy of frequency usage which allows unlicensed users (called on secondary users), to operate in the frequency band allocated to the licensed systems (called on primary users). Secondary users should be able to detect available primary frequency band and use these spectrum opportunities without causing any harmful interference to primary users. A wireless system that implements this concept is already under standardization in IEEE 802.22 [12]. This standard aims to define a fixed point-multipoint WRAN (Wireless Rural Area Network) that operates in the TV bands as a secondary system, without causing harmful interference to incumbent services (TV receivers, wireless microphones). In this system, the base station (BS) coordinates and controls all the CPEs (Customer Premise Equipment). The CPEs perform spectrum measurements and report them to BSs which take spectrum allocation decisions. Besides, geolocation is set as a requirement in the standard: the BSs are supposed to be aware of CPEs locations.

In this work, we consider a more general scenario of a secondary wireless system where the spectrum management is performed by the network, based on measurements reported by the terminals. We suppose that wireless terminals are able to perform radio measurements and report them to the network with the corresponding geolocation information. We define the Interference Cartography (IC) which is a map of the measured quantity (for instance, the value of the total received signal power on the considered frequency band) on the whole area of interest. We define a functional entity, the IC Manager, in the network that collects terminal measurements and builds a complete IC. For each frequency band of interest, the corresponding IC is stored in a database in the network, as shown in Figure 1.

Based on the IC information, the Spectrum Manager assigns the appropriate frequencies to the terminals: The Spectrum Manager can evaluate the additional interference generated by a secondary user terminal on the surrounding receivers, and also the maximum power that the terminal can transmit without causing any harmful interference on primary users.

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In the remainder of this paper, we focus on IC construction. Our goal can be formulated as follows (see Figure 2): Given a finite number of localized radio measurements, how can we deduce the missing values of the measured quantity on the whole area of interest, with a given reliability degree?
III. INTERFERENCE CARTOGRAPHY BY SPATIAL INTERPOLATION

Spatial interpolation [7] is a well known procedure, commonly used in Geographic Information Systems (GIS). GIS refers to any system manipulating geographical referenced data for capture, storage, analysis and management purposes. Formally, spatial interpolation is a statistical procedure that estimates missing values at unobserved locations within a given area, based on a set of available observations of a random field. This interpolation is mainly based on an important principle in geography called the spatial autocorrelation. This stands for the first law of geography established by Tobler, assuming that everything is related to everything else, but near things are more related than distant things [8]. The main spatial interpolation techniques are the Inverse Distance Weighting (IDW), the Nearest Neighbor Interpolation, Splines and Kriging.

This description shows similarities with the notion of interference cartography and specifically with its construction process providing a given set of interference measurements. Thus, we propose to test the Kriging method for the interference cartography, which is a reliable and simple spatial interpolation technique, widely used in various domains [9].

A. Kriging

Kriging is a well-known spatial interpolation technique, often used in geostatistics – the statistics dedicated to geographical domains such as environmental science, meteorology and mining exploration.

Kriging was first used by a mining engineer Krige [9] for the establishment of mining maps based on scattered measurements. This technique is a linear spatial interpolation method, generally referred with the acronym B.L.U.E: Best Linear Unbiased Estimator. In fact, Kriging assumes that the missing values can be estimated with weighted linear combinations of the available neighboring values. Computation of the Kriging weights are based on the relation between the observed values, expressed through the spatial autocovariance function. Besides, this interpolation technique yields a zero mean residual error (unbiased property) and minimizes the mean square error. Besides, this interpolation technique yields a zero mean residual error (unbiased property) and minimizes the mean square error. The only condition for the applicability of this technique is the first and second order stationarity of the considered data. This means that the mean and the variance functions of the observations depend only on the distances between them but not on their specific localizations.

Mathematically, Kriging calculates the estimation of the unknown value of a function $f$ at the location $u_p$ based on the available values of this function in the neighboring locations $\{f(u_i)\}_{i=1}^m$ [10]. This is expressed through a weighted linear combination. The vector $u_i$ denotes the localization of the data. In case of two dimensional data, $u_i = (x_i, y_i)$.

$$\hat{f}(u_p) = \sum_{i=1}^K w_i \times f(u_i).$$  \hspace{1cm} (1)

$w_i$ corresponds to the Kriging weights and depend on the spatial correlation between the considered data samples. Thus, the calculation of the weights involves an entity called as the semi variogram. A variogram quantifies the relationship between the average field value differences at different locations and the distance separating them. The semi variogram is defined as:

$$\gamma(h) = \frac{1}{2} \text{Var}[f(u_i) - f(u_j)].$$ \hspace{1cm} (2)

where $u_j - u_i = h$, $\{u_j, u_i\}$ refer to two different locations and $h$ is the distance separating them. The main advantage of using the variogram is that it is independent of the mean value of the data contrary to the covariance function.

Three main types of Kriging are identified as follows:

1. Simple Kriging where the random variables are stationary with known mean,
2. Ordinary Kriging where the random variables are stationary with unknown mean,
3. Universal Kriging where the random variables are not stationary.

B. Application to interference cartography

Ordinary Kriging is probably the most appropriate spatial interpolation technique for the interference cartography. Here, the considered cartography has the form of a two dimensional grid. We assume that there are $N$ located interference measurements available $\{m_i\}_{i=1}^N$ (Figure 2). The aim of Kriging is to estimate the interference values in the unobserved locations within the target map $\{m_i\}_{i=1}^N$.

Due to practical considerations, we propose to apply an ordinary Kriging version developed by Sidler [10]. In [10], the Kriging interpolation is proposed with Von Karman covariance model [11] instead of the usual semi variogram function. The corresponding auto covariance function is:

$$C(h) = \frac{\sigma^2}{2^{\nu-1} \Gamma(\nu)} h^\nu K_\nu(h/a).$$ \hspace{1cm} (3)

where $h$ is the distance separating two locations, $\Gamma$ is the gamma function, $K_\nu$ is a modified Bessel function of order $0 \leq \nu \leq 1$, $\sigma$ is the variance and $a$ is the correlation length.

The semi variogram function can be obtained from the auto covariance function with the following relation:

$$\gamma(h) = C(0) - C(h).$$ \hspace{1cm} (4)

The Kriging interpolation includes the number of available neighboring observations $K$ in the calculation of the missing values at the unobserved locations (Equation (1)). This parameter $K$ influences considerably the performance of the spatial interpolation. Thus, a tradeoff has to be made for the number of neighborhood points involved in Kriging weight calculation. A high number leads to an increased computational
cost whereas a low number will probably deteriorate the performance of the interpolation. The parameter $K$ is highly related to the nature of computed data and is generally set between 12 and 32.

The performance evaluation of the Kriging interpolation can be realized through the calculation of the average error $m_p$ and its variance $\delta_p$, expressed as follows:

$$m_p = \frac{1}{p} \sum_{i=1}^{p} \left( \hat{f}(u_i) - f(u_i) \right),$$

$$\delta_p = \frac{1}{p} \sum_{i=1}^{p} \left( \left( \hat{f}(u_i) - f(u_i) - m_p \right)^2 \right).$$

The parameter $p$ refers to the number of estimated interference values using the Kriging method.

### IV. SIMULATION RESULTS

In this section, we present the results of applying the Kriging interpolation technique on an example of interference cartography, obtained through a wireless network simulator. The simulator yields the interference value that a mobile terminal is subject to, at a given location of the area of interest. In this way, we can obtain a map whose mesh points contain the experienced interference levels over a predefined region. Towards this end, we have worked with a mobile network simulator developed in Orange labs, which is dedicated to the evaluation of quality of service indicators on several radio access technologies (such as UMTS, GSM and WLAN).

In this study, we focus on the interference cartography of a simulated UMTS network in static mode, providing 3G voice service. The considered cartography is divided into meshes of size 25m and the total interference is calculated for each mesh. The interference value stands for the total interference $I_{tot}$ perceived by a probe mobile at a given location. $I_{tot}$ is calculated as:

$$I_{tot}(i) = I_{int,r}(i) + I_{int,e}(i) + P_N,$$

where:
- $I_{int,r}(i)$ is the intra cellular interference, originating from communications of the same cell $i$, and caused by the non-ideal orthogonality of the intra-cell multiple access,
- $I_{int,e}(i)$ is the inter cellular interference, caused by the adjacent cells $j \neq i$,
- $P_N$ is the thermal noise.

Figure 3 presents an example of interference cartography of dimensions $10^5 \times 10^5$ m. The unit of the interference is dBm. Generally, high interference values correspond to the cell edges.

To test the Kriging interpolation method, we extract a sub-cartography with a limited proportion of the initial cartography data. For reasons of simplicity, we have extracted the sub-cartography through regular sampling. For example, the proportion 25% is obtained by taking one out of every four samples in both x- and y-axes. In this example, the initial grid has the dimensions $100 \times 100$ (Figure 3). With a reduction of 25%, we have a sub-cartography of dimensions $25 \times 25$. The goal of the Kriging is to perform efficient spatial interpolation on the sub-cartography so as to obtain a high similarity between the interpolated (Figure 4) and original (Figure 3) cartographies.

Applying the Kriging interpolation method with $K=16$ and $\nu=0.98$ (see Equations (1) and (3)) has yielded the interpolated cartography of Figure 4 and the error cartography of Figure 5.

The average error is $m_p=0.0073$ and the error variance is $\delta_p=2.17$. $p$ denotes the total number of interpolated values and is equal to 75 in this example.

Figure 6 presents the error mean and variance for different reduction percentages. It shows that the error is inversely proportional to the amount of reduction. This is an expected result as a high reduction requires more interpolation and induces more errors.

These preliminary results demonstrate that the Kriging interpolation method is a valid solution for the construction of the interference cartography given a partial database of localized measurements.

### V. CONCLUSION

This paper has presented the interference cartography concept in secondary spectrum usage. Interference cartography involves combining measurements coming from different radio network entities together with the geo-location information, and applying effective spatial interpolation techniques to obtain a map which indicates interference levels at each mesh point over the area of interest. Utilization of interference cartography in a secondary spectrum usage permits the secondary network to be aware of local interference tolerance levels so that it becomes possible to detect, identify and use spectrum opportunities without disturbing the primaries or other secondaries.

As an example, a simple and efficient spatial interpolation method, Kriging, is applied on spatial interference data obtained from a radio network simulator. The original interference map is tried to be obtained from partial knowledge of interference data points. Different percentage values of partial knowledge are investigated and it has been shown that even with 25% of data points, Kriging achieves an average error level of 0.01% and an error variance of 2.2%. These promising results demonstrate that interference cartography constitute a viable solution for efficient secondary spectrum usage.
REFERENCES


