Mobile Terminal Positioning via Power Delay Profile Fingerprinting: Reproducible Validation Simulations

Mahdi Triki, Dirk T.M. Slock, Vincent Rigal, and Pierrick François
Eurecom Institute
2229 route des Crêtes, B.P. 193, 06904 Sophia Antipolis Cedex, FRANCE
Email: {triki,slock,rigal,francois}@eurecom.fr

***Abstract*— Non-Line-of-Sight and multipath propagation conditions pose significant problems for most mobile terminal positioning approaches. In contrast, power delay profile fingerprinting (PDP-F) thrives on multipath propagation. This multipath extension of T(D)oA is based on matching an estimated power delay profile from one or several base stations (BSs) (or other transmitters (broadcast, ...)) with a memorized power delay profile map for a given cell. With a single BS, an absolute time reference is required as for ToA. With multiple BSs, that requirement can be dropped as in TDoA. We propose a validation of PDP-F via simulations that can easily be reproduced. The multicellular environment consists of a big box in which multipath arises by reflection off the six sides. The resulting PDP depends on the positions of BS and terminal, the attenuation mechanism and the reflection coefficients of the six sides. We also propose an extension of the PDP-F (PSDP-F) taking into account spatial information available with an multi-antenna reception.PSDP-F can be considered as a multipath extension of the combined T(D)oA and AoA methods, without explicit requirement for antenna array calibration.**

***Index Terms*— positioning, localization, power delay profile, fingerprinting, non-LOS, multipath propagation simulation framework, ray tracing**

I. INTRODUCTION

Mobile positioning systems have received significant attention in both research and industry over the past few years [1], [2]. Indeed, the location of the mobile phone becomes one of the important features of communication system due its various potential applications (effective intra and inter-system handoff, location of emergency caller...). The basic function of location system is to collect information about the position of a Mobile Station (MS) and to study that information to get a location estimate .

Conventional location techniques aiming at higher accuracy than simple cell identification are based on two steps procedure [3]. The first step involves the measurement of given physical parameters of the transmitted signal (e.g. time, or time-difference of arrival (ToA, TDoA), angle of arrival (AoA), signal strength...). The later step combines multiple measurements from a convenient number of Base Stations (BS) to estimate the mobile position.
Weiss et al. underline the sub-optimality of the two-steps approach [4], [5]. In fact, the signal parameters are estimated separately and independently at each BS, ignoring the constraint that all measurements must correspond to the same source. The authors introduce the "Direct Position Determination (DPD) approach": Each BS transfers the observed signal to a central processing unit where the mobile position is computed as the best matches all the data simultaneously. Monte Carlo simulations demonstrate that the DPD method provides better localization estimate (especially in the presence of multipath [6]).

The main reason for inaccuracy observed in the conventional location systems is due to the propagation conditions imposed by the wireless channel: multipath and essentially Non Line-Of-Side (NLOS) condition. In fact, the conventional methods relay on the line-of-side path between the base station antenna and the Mobile station. However, in urban environment, the LOS assumption is rarely valid for three BSs at the same time, which degrades the location performance (availability and accuracy) of the conventional techniques and creates a need of development of more accurate location techniques suited for these areas.
To alleviate this problem, Porretta et al. suggest tracking the MS position to obtain more reliable position estimates [7], [8]. Based on the ToA and AoA measurements, the MS location is estimated by following two alternative procedures. When the MS is in the line-of-side condition, the location is determined through the parameters relevant to the first path received at the BS (AoA and ToA). Conversely, i.e. in the NLOS condition, the MS position is determined by minimizing a given cost function (tacking into account the ToA, the AoA, and the coordinates of the obstacles found along the AoA for the first N paths). An alternative approach is proposed by Nájar et al. [9], [10]. Once an estimate of the first arrival path has been determined, a Kalman tracker computes the position, and deals with the bias of these estimates. The use of the Kalman filter allows the tracking, not only the position and the velocity of

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mobile, but also the ToA bias caused by multipaths, and NLOS situation.

While previous techniques try to reduce the multipath and the NLOS effects, it cannot be eliminated, and the errors it produces are difficult to predict. So that, some location methods, e.g. Enhanced Signal Strength and Location Fingerprinting have been designed to obtain optimal performance in urban environment. Those techniques not only overcome the problems related to the propagation environment, but also take advantage from the temporal diversity of the wireless channel. The idea is to use a previously collected or predicted signal database (location dependent parameters) form the coverage area. The phone measures the same parameters, and sends it to the location server in the network. The position is then determined by a correlation algorithm, which compares the measured signal parameters with the information stored in the database.
The Enhanced Signal Strength (ESS) method is based on this principle, and has allowed the deployment of personal locator systems in PHS service areas in Japan. The position of the mobile is determined using the signal strength of preferably three to five base stations. From this input plus information from the base station database, the system can calculate the position of the MS [1]. The database is built by simulating the signal propagation characteristics of every wireless transmitting antenna in the area of interest. Heikki et al. propose building the signal strength database through measurements instead of computation [11].
Instead of exploiting signal strength, the Location Fingerprinting (LF) (introduced by U.S. Wireless Corp. of San Ramon, Calif.) relies on signal structure characteristics [1]. By combining multipath pattern with other characteristics, the LF creates a signature unique to a given location. The position of the mobile is determined by matching the transmitter's signal characteristics to an entry of the database. For LF, multipoint signal reception is not required: the system can use data for only a signal point to determine location. Ahonen and Eskelinen suggest using the measured Power Delay Profiles (PDPs) in the database [12], [13]. Thus, the location estimation is possible by using only one BS due to the additional information provided by the PDP, i.e., amplitudes and delays of the multipath components.

This paper is organized as follows. In section II, the PDP Fingerprinting approach is presented. The evaluation of the PDP-F localization technique based on ray-tracing multipath simulation is investigated in section III. In section **??**, we introduce an extension of the PDP-F approach for the multi-antenna reception scenario. Finally a discussion and concluding remarks are provided in section V.

II. PDP Fingerprinting, with and without Time Reference

A. Location Fingerprinting Method

Location Fingerprinting is a general location method that can be applied to any cellular or WLAN network. The key idea is to store signal structure information, from the whole coverage area of the location system, in a database. The database should contain collected or predicted position dependent signal information (a position signature), called fingerprints, with a resolution comparable to the accuracy that can be achieved with the method. The MS measures the same parameters, and sends it to the location server in the network. The position is then determined by a correlation algorithm, which compares the measured signal parameters with the information stored in the database.

The major effort in applying location fingerprinting is the creation and maintenance of the database. The signal fingerprints for the database can be collected either by:

- measurements: a vehicle drives through the coverage area collecting the signal fingerprints at each position.
- or by a computational network planning tool: by simulating the signal propagation characteristics of every transmitting antenna in the area of interest.

Measurements are more laborious but produce more accurate fingerprint data. Also a combination of measured and computed fingerprints can be used.

B. PDF Fingerprinting Method

A relevant issue with the location fingerprinting is the choice of the signal fingerprints. Any location-dependent signal information that can be measured by the MS or the BSs is useful for the location fingerprinting technique. The signal fingerprints could include signal strength, signal time delay, or even channel impulse response. Ahonen and Eskelinen suggest using the measured PDPs as a signal fingerprints for UMTS systems. The power delay profile shows the power and the arrival times of the different ray-paths between the selected transmitter and the selected receiver (see figure 1). In the

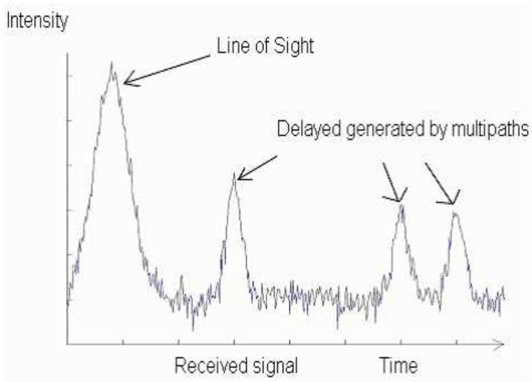

Fig. 1. Example of Power Delay profile with a LOS

case of synchronous network, the first peak of the measured PDP determines the time of arrival (TOA) of the received signal, which is used for the ToA algorithm. In addition, the PDP fingerprinting (with time reference) takes advantage of the entire measured PDP (the whole temporal diversity). Therefore, the system can use data from only a single point to determine location: multipoint signal reception is not required, although it is highly desirable.

In the case of asynchronous network, ToA information is not available. The measured PDP could match with any delayed version of the PDPs stored in the database. We call this variant ”PDP fingerprinting without time reference”. Multipoint signal reception is desirable specially in this situation: the measured PDP can determines the TDoA between the different BSs.

C. Matching Score Function

A second relevant issue with the location fingerprinting is the choice of the matching score [14]. In fact, for each location (x, y) a matching score can be computed from the measured PDP and the stored $PDP_{(x,y)}$. The MS position is determined by minimizing the matching score function.

For one-BS signal reception scenario, we minimize the Least Square (LS) cost function:

$$C(x, y) = \left\| PDP - PDP_{(x,y)} \right\|^2 \tag{1}$$

For multi-BS signal reception scenario, we can use the following LS cost function (or a weighted version):

$$C(x, y) = \sum_{k=1}^{K} \left\| PDP^{(k)} - PDP^{(k)}_{(x,y)} \right\|^2 \tag{2}$$

where K is the number of BSs, and $SNR^{(k)}$ denotes the signal to noise ratio at the k^{th} BS.

III. Ray Tracing Multipath in a Box

Simulation environment is a crucial issue for the validation of location algorithms. Indeed, generally we assume an approximate signal model to yield a practical implementation of the proposed location techniques. So that, a more accurate propagation and received signal models are needed. In the literature, two main strategies are adopted to validate the proposed algorithms:

- Evaluation in real or like-real scenario: the evaluation is done via an experimental location trial or by simulating the propagation environment using a network planning tool featuring a tree-dimensional ray-launching method.
- Evaluation on a fixed CIR: the delays and the gains of the different channel taps are fixed according to a given channel model (Vehicular A, B, indoor to outdoor A, B...).

There is no doubt that the most accurate evaluation technique will rely to real scenario evaluation. However, those techniques are often expensive, time-consuming, labor intensive, and not easy to reproduce. On the other hand, using a fixed CIR seems to be insufficient; and does not allow position tracking scenarios.

In this paper, we propose a validation of the PDP fingerprinting using a ray-tracing muti-path in a box. The proposed validation technique produces a new tradeoff between complexity and evaluation accuracy; and it can easily be reproduced. The multicellular environment consists of a big box in which multipath arises by reflection off the six sides (figure 2).

Note that even if this propagation environment may be a far cry from realistic wireless environments (except for certain indoor or street scenarios), it allows to generate realistic

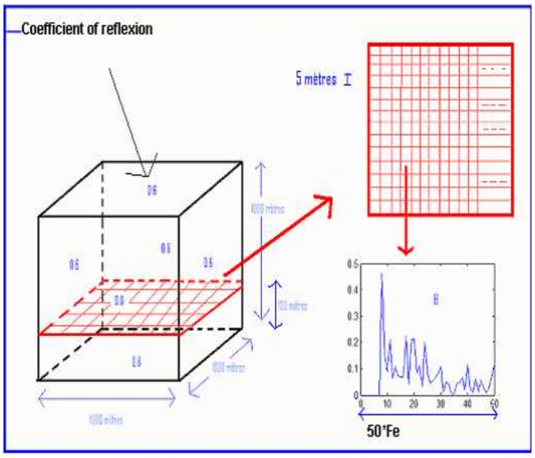

Fig. 2. The multicellular simulation environment

power delay profiles, which is the key ingredient of the method considered here.

The ray tracing multipath environment is taken from the acoustics word (figure 3). The method used for the simulation of the impulse response between the MS and the multiple BSs is similar the image method [16].

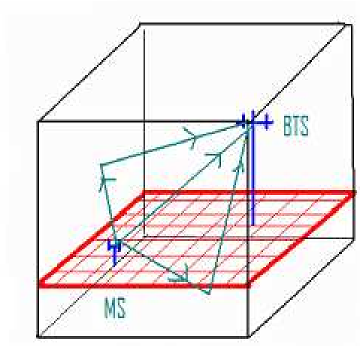

Fig. 3. The ray tracing simulator

The image method originates in geometrical acoustics. It states that only specular reflections of sound are important. The real scene is complemented with additional images of original space mirrored by walls that are to reflect the sound. The intensity of the new sound sources is decreased according to the absorption of walls and air. Only direct propagation of sound from the original source and from new sources (resulting from mirroring) is then taken into account [17].

However, as we consider electromagnetic propagation at a certain carrier frequency, several modifications should be taking into account:

- Due to the narrowband transmission at a certain carrier frequency, we should consider complex channel impulse response, and take into account the phase modification caused by the electromagnetic waves reflections.
- We include a wave attenuation model (with respect to the distance).
- We perform a more precise sampling operation via a pulse shape (instead of a simple delays ceiling).

An important freedom parameter is the sampling frequen (which depend essentially on the box dimensions). In fact, the sampling frequency is too large, the PDP length becom too long, and the computation complexity will increase. contrary, in the sampling frequency is too small, the sampl PDP do not distinguish different paths; and the signal finge prints will not be sufficient to characterize the MS location

A. PDP Fingerprinting Simulations using Ray Tracing Mul path Method

In this section, we propose a validation of the PDP finge printing via the ray tracing multipath environment proposed above. We consider a cubic box with dimensions $1000 \times 1000 \times 1000$. To simulate the channel impulse response we refer to the CDMA2000 standard. The CDMA chip-rate in the simulation is 3.8 MHz, with an up-sampling factor equal to 4. We also consider a raised cosine pulse-shape to perform more precise sampling operating.

Given an MS position, the channel impulse response is predicted using the ray-tracing multipath routine. A white Gaussian noise is added. And, the PDP estimate is computed by taking the magnitude of the noisy CIR. Finally, the MS position is determined by matching the estimated PDP and the pre-stored PDP database. Figure 4 plots the Root Mean Square positioning Error (RMSE) for the PDP-Fingerprinting function of the spatial resolution for $SNR = +\infty$, and $SNR = 10dB$.

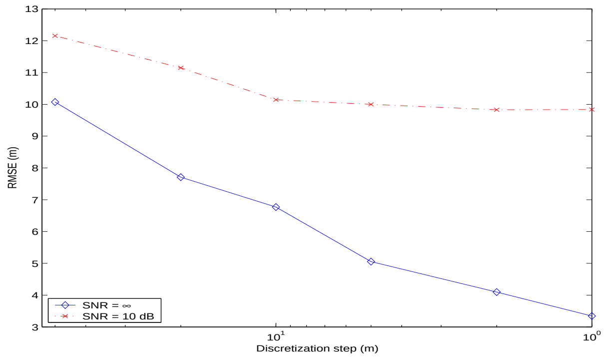

Fig. 4. RMSE vs. Discretization step for $SNR = +\infty$, and $SNR = 10dB$

We see that the sensibility of positioning error to discretization depends on the SNR of the channel estimation. Figure 5 compares the PDP-F using 1 and 2 base stations with and without time reference. For the case of 2 BSs, the noise power on the 2 BSs is assumed to be the same. The SNR in the x-axis corresponds the SNR at the strongest BS.

We see that for the one point signal reception scenario, the synchronization between the MS and BSs increases significantly the positioning accuracy. However, the effect of synchronization is not too spectacular for the multipoint signal reception scenario (TDoA-like information is sufficient to give satisfying precision).

IV. Power Space Delay Profile Fingerprinting for Mobile Localization

We consider Base Stations equipped with an M-element antenna array. Traditional techniques exploit the additional

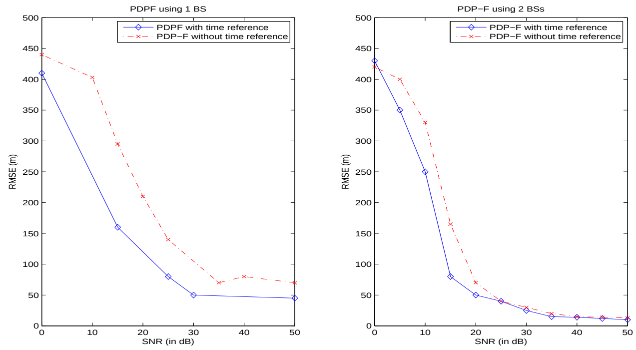

Fig. 5. Positioning accuracy for PDP-F with and without time reference using 1 BS (left) or 2 BSs (right)

spatial information by estimating jointly the Angle and the Time of Arrival which leads to an increase in the localization accuracy[18]. On the other hand, as the PDP removes all the phase information, classic PDP fingerprinting techniques cannot exploit the additional spatial information.

The received impulse response on a MS (positioned in (x, y)) can be written as:

$$\underline{h}_{x,y}(t, \tau) = \left(\sum_{l=1}^{L} A_l(t)\ \underline{g}_l(\theta_l)\ p(\tau - \tau_l) \right) e^{j2\pi f_c \tau} \quad (3)$$

where L denotes the number of mutipaths, $p(t)$ is the convolution of the transmit and receive filters, $A_l(t)$ is the complex fading envelope (varies rapidly with the position), $\underline{g}(\theta_l)$ is the vector response of the antenna array to the l^{th} path on direction θ_l, and f_c is the carrier frequency. Under the narrow-band assumption, $\underline{g}(\theta_l)$ reflects mainly the phase-shifts that the carrier signal undergoes when imprinting on the consecutive antenna elements from direction θ_l. We define the Power Spatial Delay Profile (PSDP) as

$$\begin{aligned} \underbrace{PSDP(\tau)}_{M \times M} &= E_A \left\{ \underline{h}_{x,y}(t, \tau) \underline{h}_{x,y}^H(t, \tau) \right\} \\ &= \sum_{l=1}^{L} \sigma_{A_i}^2\ |p(\tau - \tau_l)|^2\ \underline{g}_l(\theta_l) \underline{g}_l^H(\theta_l) \quad (4) \end{aligned}$$

where E_A denotes the expectation over the fading coefficients (assumed to be independent), which can be estimated by local spatial or temporal ergodicity. Remark that the m^{th} diagonal element of the PSDP corresponds to the PDP of the received impulse response between the MS and the m^{th} BS antenna array element. And as the PDP varies slowly with position, those diagonal elements are almost equal.

As in the PDP based approach, the matching score function is a critical issue. For each location (x, y), a matching score is computed on the estimated CIR, and the stored $\text{PSDP}_{x,y}$:

$$C(x, y) = \sum_{\tau} PDP_{x,y}^2(\tau) \left(\underline{h}^H(\tau) PSDP_{x,y}^{-1}(\tau) \underline{h}(\tau) - M \right)^2$$

Remark that for $M = 1$ (in which a case PSDP = PDP), we recover the PDP LS cost function in (1) for $PDP(\tau) = |h(\tau)|^2$.

We propose to investigate the PSDP fingerprinting via the ray tracing multipath environment. We consider $M = 2$, and we plot the Root Mean Square positioning Error (RMSE) as a function of CIR estimation SNR for 1 and 2 BSs (figure 6).

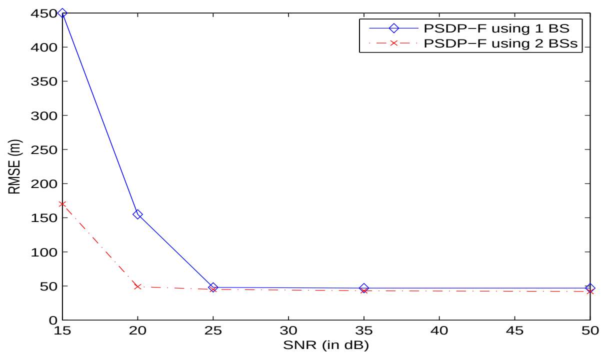

Fig. 6. Positioning accuracy for PSDP-F vs. SNR using 1 and 2 BSs

We remark that using multi-BSs reception is advantageous. As usual, performances saturate due to the discretization of the stored PSDP.

Next, we compare the PDP vs. PSDP based approaches (figure 7). We fix the spatial discretization for the PDP-F to twice that of the PSPD-F. Remark that with this resolution choice, we have a comparable number of score evaluations for the search algorithms for both PDP and PSDP. But on the other hand, the PDP database construction and maintenance is much more expensive and time consuming.

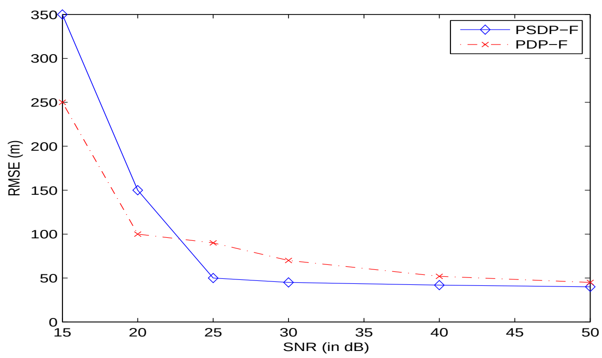

Fig. 7. Positioning accuracy for PSDP-F vs. PDP-F using 1 BS

We see that even using lower resolution, the use of PSPD is advantageous in the higher SNR region.

V. Concluding remarks

In this paper, we have investigated the PDP fingerprinting location technique on multipath propagation. This multipath extension of T(D)oA is based on matching an estimated power delay profile from one or several base stations (BSs)(or other transmitters (broadcast, ...)) with a memorized power delay profile map for a given cell. Not only the PDP fingerprinting is robust to the propagation conditions imposed by wireless communication, but also it exploit multipath instead of combating it. We have proposed a validation of PDP-F via simulations that can easily be reproduced. The multicellular environment consists of a big box in which multipath arises by reflection off the six sides. This ray tracing multipath environment is taken from the acoustics world, and adapted to electromagnetic propagation at a certain carrier frequency. The resulting PDP depends on the positions of BS and terminal, the attenuation mechanism and the reflection coefficients of the six sides. We have also proposed an extension of the PDP-F taking into account spatial information available with an multi-antenna reception. PSDP-F can be considered as a multipath extension of the combined T(D)oA and AoA methods, without explicit requirement for antenna array calibration.

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