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Multi-technology RF fingerprinting with leaky-feeder in underground tunnels

Fernando Pereira, Christian Theis
Radiation Protection
European Organization for Nuclear Research
Geneva, Switzerland
fernando.pereira@cern.ch

Adriano Moreira
Mobile and Ubiquitous Systems research group
Centro Algoritmi, University of Minho
Guimarães, Portugal
adriano.moreira@algoritmi.uminho.pt

Manuel Ricardo
UTM, INESC Porto
University of Porto
Porto, Portugal

***Abstract*— Techniques using RSS fingerprinting for localization have been studied over a number of different technologies in many different scenarios. In the case of underground tunnels localization can be quite challenging, yet it is extremely important for safety reasons. In the specific case of the CERN tunnels, accurate and automatized localization methods would additionally allow the workflow of some activities to become substantially faster. In a radiation area this would also have the added benefit of reducing the exposure time of personnel conducting so called radiation surveys which have to be carried out before access can be granted.**

In this paper Fingerprinting techniques for GSM and Wireless LAN are studied and enhanced to take advantage of both network technologies simultaneously as well as the channels RSS differential and an observed effect in the radiated power in the leaky-feeder cables. Besides the higher accuracy achieved for a single technology, this methodology looks promising for scenarios where several types of wireless networks are available or expected to be installed at a later stage.

Keywords- fingerprinting; multi-technology; leaky-feeder; gsm; wlan

I. INTRODUCTION

Location fingerprinting methods have received significant attention among indoor location methods and have been successfully applied in a wide range of scenarios. This success stems foremost from the fact that they require neither the installation of dedicated infra-structure hardware nor the allocation of extra radio frequency (RF) spectrum [1] [2]. Besides the potentially low costs, these properties make them extremely attractive for projects where restrictions in the installation of hardware apply. This is particularly important for the case of a particle accelerator tunnel in which the risk of hardware damage due to radiation or interference with pre-existing components is very high.

In the context of CERN (the European Organization for Nuclear Research) activities, localization in the vast underground areas have become of great importance mostly for safety reasons. Furthermore, it would also be highly advantageous to achieve good accuracy indexes, in the order of one to two meters, to allow for much faster processes carried out by various technical departments at CERN. Of particular interest to the radiation protection group are the frequent radiation surveys conducted throughout the entire accelerator complex. They involve radiation measurements in thousands of points around the accelerator facilities, for which an accurate position tag is required.

Nevertheless, the accuracy obtained with these methods is highly dependent on the type of the underlying radio network and on the specific environment characteristics that determine the conditions for the signal propagation. In the case of tunnels whose network coverage is implemented using leaky-feeders, the relatively low attenuation of the signal along the cable can be obfuscated by fluctuations occurring in the short-range due to fast-fading and signal coupling phenomena [3] [4], thus yielding very often unsatisfactory results.

To improve the accuracy under these conditions a new method, taking advantage of multiple network technologies deployed in the tunnel of CERN's Large Hadron Collider [5] (LHC), is being investigated. Since the performance achieved with GSM over leaky-feeder alone might not be sufficient for the intended application, the study evaluates how the Received Signal Strength (RSS) from the different available networks can be measured, processed independently and combined in an effective way in order to determine the position with higher accuracy.

This paper presents the measurement of the signal from the existing GSM network deployed over leaky-feeder cable as well as the signal from a Wireless LAN coupled into this cable via a set of high gain antennas. In addition, a novel hybrid method for location finding has been developed which takes advantage of the absolute RSS, the relative channel RSS differential and a strong correlation found, under certain conditions, between channels in the leaky-feeder. This method is then finished up with a KNN implementation and its performance evaluated for several values of K. First performance assessments indicated the approach to be very stable while yielding an accuracy of 20 m at 88% confidence level. The following sections contain a detailed description of the new algorithm and its application to combined GSM and WLAN input data.

II. Background

A large number of distance measurement principles and techniques for wireless localization exist and, depending on the application, different location parameters might be required. The three main distance measurement principles used today are: angle-of-arrival (AOA), received-signal strength (RSS), and propagation-time based measurements that can further be divided into time-of-arrival (TOA), roundtrip-time-of-flight (RTOF) and time-difference-of-arrival (TDOA) methods [6].

AoA techniques utilize directional antennas or antenna arrays and basically calculate the position by intersecting the received signal directions as detected by the various antennas. Besides being simple, this approach doesn't require cooperation from the target object and therefore has been used in cellular and other broadcast networks for a long time. Propagation-time based localization is arguably the technique delivering the highest accuracy levels. Although the measurement principle is very simple it must be implemented in dedicated and fast hardware as the flight time is proportional to the distance travelled by the signal. For instance, in a radar-like setup (RTOF) a positioning accuracy in the range of 10 cm requires a clock frequency in the order of 1.5 GHz. Other configurations (based on TOA and TDOA) further require precise clock synchronization among the receiver and transmitter units.

In turn, RSS systems are based upon the principles of path loss of electromagnetic waves and, therefore, they are virtually applicable to any existing wireless network. Although simple models exist for free space propagation, in indoor environments or urban areas multipath fading and shadowing effects have a dominant impact. These effects can only be mitigated with complex propagation models and computational approaches, including advanced algorithms and neural networks.

One of the best-known approaches to RSS-based positioning is fingerprinting. It calculates the best estimate of a position in two steps: in a first off-line (or calibration) phase a radio-map containing all the measured RSS is created, being then used in the online (or location-estimation) phase to calculate the best match with the RSS values collected at the location to be determined.

Two kinds of algorithms exist to estimate the location during the online phase: (1) Static, in which only the local fingerprint is considered in the determination of the current position and (2) Filtering, that also take into account previous fingerprints and employ pattern analysis principles. Fingerprinting methods have, however, the severe drawback of requiring an updated radio-map ensuring that the conditions of the off-line and on-line phases are sufficiently identical.

Although fingerprinting methods for indoor localization have been mostly explored over Wireless LAN (IEEE 802.11) in dense coverage limited areas (e.g. E.g.: RADAR [7]), they have lately been considered for other network technologies as well. GSM, due to its wide and dense availability in Europe, is a network technology being highly regarded for localization purposes, and has proved to achieve reasonable results in localization [8] [9]. Accuracies of up to 5 and 75 meters for indoor and outdoor environments, respectively, have been achieved [10]. Fingerprinting has also been tested with networks deployed over leaky-feeder cable, especially WLAN. Because they enable for better Line-of-Sight (LoS) conditions, localization accuracy is usually less sensitive to environmental changes [2]. Nevertheless, previous studies also show that when the cable insufficiently attenuates the signal being transmitted, RSS fingerprinting methods might be unable to deliver high accuracies in the range of up to a few meters [4]. This is particularly problematic for the case of GSM, whose lower frequency also imposes lower attenuation.

Under these circumstances a new fingerprinting method has been developed which tries to overcome these difficulties by analysing relationships between several channels from several available network technologies.

III. Case Study and Methodology

In order to study fundamental laws of particle physics the Large Hadron Collider (LHC) at CERN accelerates particles up to nearly the speed of light. This machine is installed in a circular underground tunnel located around 100m below the surface and measures over 27 km in circumference, divided into 8 sectors.

Communication networks coverage, including GSM, is available all along the tunnel's length via a set of leaky-feeder

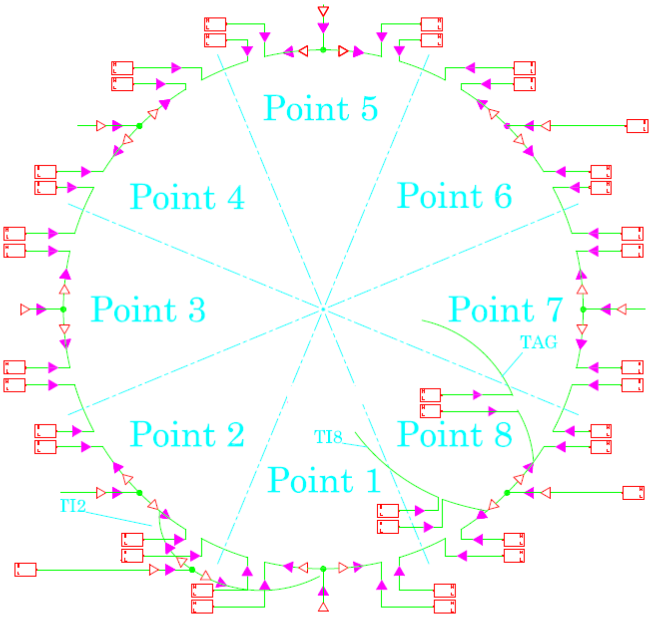

Fig. 1. LHC tunnel configuration and injection points of GSM signal (filled arrows)

cables installed at a distance of nearly two meters from the ground. Several GSM channels are injected in the cable at different points (see Fig. 1) and, in general, most parts of the tunnel are covered with two GSM channels while several traces of other channels can still be detected. In this configuration, while going along the tunnel, one of the radio channels gets stronger while the other attenuates. At 900 MHz the cable exhibits a longitudinal loss of 3.16 dB/100 m [11].

Two other network technologies are currently being tested in a limited region of the LHC and are expected to be soon deployed in the tunnel. Firstly, WLAN is going to be available in some predefined areas for bit-rate demanding applications during maintenance periods starting this winter. Secondly, Terrestrial Trunked Radio [12] (TETRA) is to be deployed over the same leaky-feeder serving GSM thoroughly and permanently in the tunnels as part of the security plans.

A. Data collection

Fingerprints from both the WLAN and GSM networks were collected. TETRA measurements were performed as well although there were insufficient samples to create a radio-map with sufficient statistics and process the data in conjunction with the other technologies. For the GSM signal, the samples were collected by two Nokia 6150 mobile phones in which the NetMonitor menus were activated. Making use of the Gammu utility and several capture and parsing tools specifically implemented for the purpose, one could individually acquire the RSS of the six strongest cells and store them in a local database. Each sample, including all the channels' RSS, was collected at an approximate rate of one sample per second.

Tests with the WLAN network were performed with a provisional setup in which two access points (APs) with high gain antennas (9 dBi) were used to provide network coverage with two distinct channels. In the experiment, as illustrated by Fig. 2, the APs were installed 150 m from each other and their antennas placed in parallel to the leaky feeder at a distance between 5 and 10 cm. This configuration promoted the injection and propagation of WLAN signal through the cable instead of direct LOS connection. Furthermore, LOS between the transmitters and the receiver unit was reduced by installing a reflexive shield, made out aluminium foil, near the APs.

RSS measurements for WLAN were performed using a USB WLAN adapter, based on the Realtek 8187L chipset, also featuring a 9 dBi antenna. The APs were programmed to send beacon frames every 30 ms, which were then captured by the mobile unit, parsed and stored in the database in a common format. This configuration also allowed for the subsequent processing of the data by different algorithms independently of the data-source.

B. Off-line phase

At first a radio-map was built based on several RSS measurements sessions performed in a slightly curved tunnel sector over a length of 270 m. Fingerprints were taken every 10 m for both the WLAN and GSM networks, yielding a total of 28 calibration points. For GSM, 30 samples per point were collected simultaneously by both mobile phones, and two complete subsequent sessions were performed. For WLAN, due to the fast beacon rate, 100 samples were collected per point and four sessions were carried out. By collecting samples in several sessions and using different mobile phones one aims at increasing the probability of capturing slightly different conditions in the tunnel, including accelerator equipment in different operational states, and thus performing the tests in the most realistic scenarios.

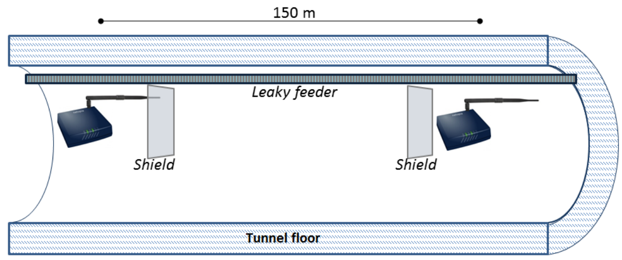

Fig. 2. WLAN experiment setup, promoting signal injection in the *leaky-feeder* cable.

Samples were pre-processed per point and network technology to improve performance during the online phase while considerably reducing the database size. Several statistical parameters describing each fingerprint distribution were calculated:

- Minimum and maximum
- quartiles
- histogram, fenced at 1.5*Inter-Quartile Range [13] (IQR)
- histogram high and low fence

By saving the histogram fenced according to the IQR, one significantly reduces the presence of outliers, while efficiently storing the samples RSS information. Moreover, from this representation one can very easily obtain other statistical measures, like the median (directly from the second quartile).

C. On-line phase / evaluation

During the online phase, the location algorithms were tested with the collected data. To assess their performance with a reasonable confidence level, a large number of location finding tests is required. To achieve that, all algorithms were tested with an independent set of samples taken in addition to those used to create the radio-map, and 10 samples were used for each online Fingerprint. In the current configuration of 2 measurement sessions with 2 receiver units, this yields 4 Fingerprints for each of the 28 points.

In order to simplify and automate the execution of the tests, a software framework for localization has been implemented in Python. It allows for transparent handling of different data sets, post-processing and final creation of the radio-maps and comparative performance analysis of the different implemented location finding algorithms. In this framework, for a given fingerprint used as input data the location-finding algorithms must return a list of the most probable discrete locations and their corresponding confidence measure. In the subsequent phases, further processing can be performed based on these results. For instance, a K-Nearest-Neighbour (KNN) approach was implemented by simply calculating a weighted average of the K most probable locations of the results. The respective weights are based on the obtained confidence levels.

Various methods were implemented to evaluate the effectiveness of each algorithm in determining location. At first, a scoring method assesses the quality of the location estimate according to the confidence levels obtained by the algorithm with respect to the true location. This method was created as an alternative to the one suggested in ref. [4], but since it is rather synthetic it doesn't take into account combined or post-processed results. Therefore, performance is also evaluated in terms of the actual achieved accuracy with KNN, calculated for K=1, 3, 5 and 7.

IV. Channel RSS differential

In a network configuration like the one presented, several channels propagate over a leaky-feeder cable. Along these cables the various channels suffer a certain level of attenuation, depending on the cable characteristics, the distance travelled by the signal and the signal's frequency. This property normally characterized for each cable in terms of an attenuation coefficient stated in dB/100m for a given set of frequencies. Assuming the factor is constant all along the cable, the same level of attenuation should be found in all the channels when moving from one position to another. Even though the measurement conditions are likely to change slightly (for instance due to self-shadowing of the person conducting the measurement, changing body postures, different configuration and operational state of the accelerator equipment, etc…) they would affect the channels the same way. In this scenario if two channels were injected from opposite directions, the RSS difference between these channels would be changing twice as much as the cable attenuation and, most importantly, this difference would be very robust against different measurement conditions. Unfortunately this effect hasn't been observed in channels propagating in opposite direction. However, the new measurements opportunely captured data of an additional GSM channel and provide strong evidence that two channels propagating in the same direction indeed suffer the same RSS oscillation levels independently of the measurement conditions. Previous measurement didn't capture this effect since a third channel can only be found with sufficient strength in certain regions of the tunnel. Therefore, the location algorithm will consider this information as optional and, whenever possible, take advantage of it to increase the accuracy.

Fig. 3 shows the RSS evolution for the GSM network along the tunnel section, in which one can clearly see the two dominant channels (ID 123 getting stronger and ID 97 attenuating) and a third weaker channel, also getting stronger. Despite the large RSS region for each channel, there is a noticeable similarity of their shapes between channel 123 and 121, which was not observed for channel 97 and any of the others. This fact motivated further analysis of this pattern and its inherent correlation

In order to analyse the visually perceived correlation of some of the channels' RSS in more detail, some statistical pre-filtering of the data was performed. In the first place the various RSS per channel and position were condensed into a single value by calculating the median over the samples

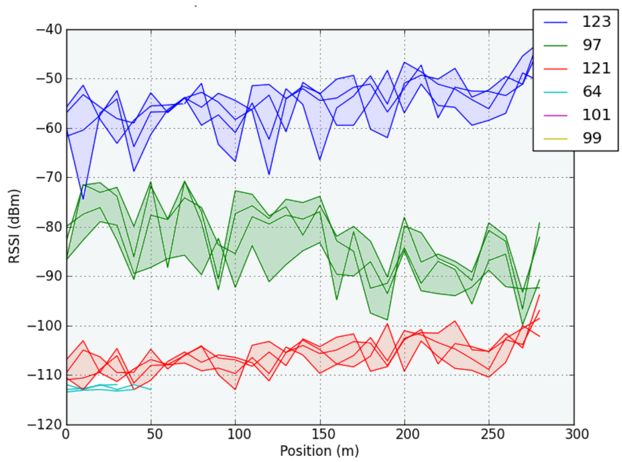

Fig. 3. GSM RSS evolution of different channels, measured in four sessions.

Table I. Approximated linear attenuation coefficients obtained from the measurements of different GSM channels.

Linear approximation	Slope (db/100m)	Offset (dBm)
Channel 123	2.95	-58.29
Chanel 97	-4.58	-76.35
Channel 121	2.29	-108.93

collected during one measurement session. Subsequently, the results were normalized by subtracting the linear attenuation coefficient obtained by least-square regression (Fig. 4). It was found that the approximated attenuation coefficients (see Table I) correspond very well to the value of the cable stated in its datasheet [11].

Finally Spearman's rank order coefficient and the Root mean squared deviation were used to quantify the actual level of similarity. The correlation among the channels has been studied for each measurement session individually as shown in Table II.

As can be seen, significant correlation exists generally between the channels 121 & 123, whereas lower dependence and larger deviations can be observed between the channels 97 & 123. The correlation is even more noticeable if the data of the different measurement sessions are not considered individually but combined - Fig. 4 - which yields a Spearman rank-order coefficient of 0.99 and a root-mean square deviation of 0.92.

Therefore, the RSS differential of these channels can be considered as a quite robust characteristic of a given location, which can then be explored for location finding. Henceforth, this measure is designated as the Inter Channel RSS Differential (ICRD), which for the case of two channels whose signal propagates in the same direction, becomes the Same-Propagation-Direction ICRD (SPD-ICRD).

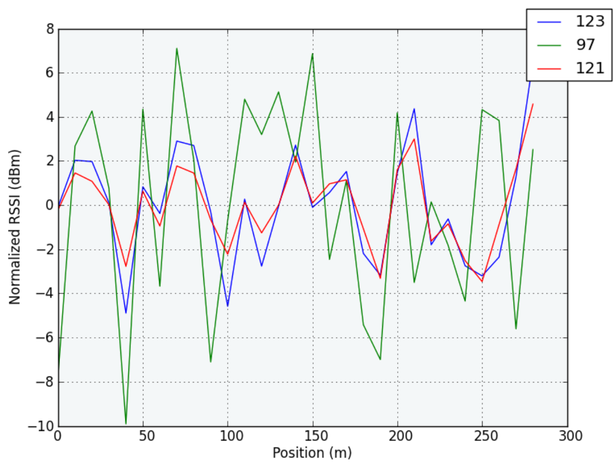

Fig. 4. Normalized GSM RSS, after filtering by the median and subtracting the approximated linear attenuation coefficients given in Table 1.

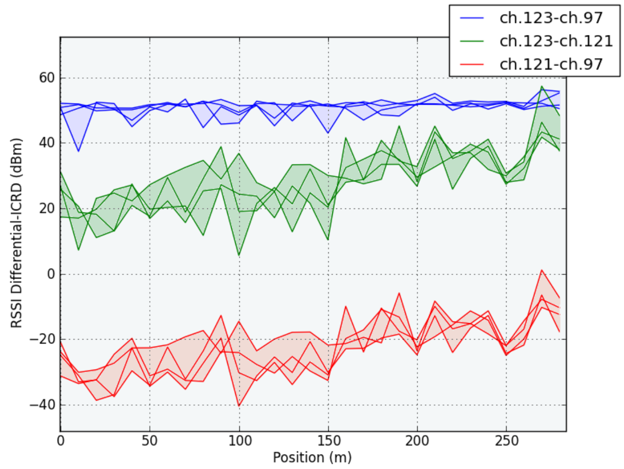

Fig. 5. GSM ICRD between several channel pairs, calculated for the four sessions

V. LOCATION MATCHING ALGORITHM

A. *Exploring channel RSS differentials*

The location matching algorithms are based in the KNN methods, having some decisions and parameters changed to meet the framework of the experiment. Among those parameters, the median was used as the base statistical function. For the absolute RSS value comparison an algorithm based on the one presented in ref. [4] is used which employs 2-norm (Euclidean) distances. Although relatively simple, KNN algorithms generally perform quite well in terms of achieved accuracy when compared with more complex filtering approaches. For the purpose of the current study – evaluate the combination of technologies – KNN methods were considered appropriate and relatively easy to adapt to the new measures.

Considering the ICRD metric as extra input for a localization algorithm, in addition to absolute RSS, allowed for the development of a hybrid method. On the one hand the Fingerprint collected in the online phase can be tested, with respect to absolute signal strength values, against an absolute RSS *radio-map* (Fig. 3) and on the other hand, it can be tested for the RSS differential among channels (ICRD - Fig. 5).

TABLE II. CORRELATION COEFFICIENTS AMONG THE CHANNELS, CALCULATED PER MEASUREMENT SESSION.

Correlation coefficients per session		**Spearman rank-order coefficient**	**Root-mean sq. deviation**
Channels 123 & 121	Session 1	0.976	1.845
	Session 2	0.978	1.755
	Session 3	0.963	2.269
	Session 4	0.971	1.951
Channels 123 & 97	Session 1	0.720	6.260
	Session 2	0.689	6.601
	Session 3	0.660	6.896
	Session 4	0.848	4.586

Besides taking advantage of the RSS differential for channels travelling in the same direction (SPD-ICRD) the algorithm also explores the visible trend of the differential of other channels. Furthermore, although the SPD-ICRD is robust to environmental changes and measurement conditions, it cannot be applied alone because of two reasons: first, two channels propagating in the same direction are not always available and, secondly, as shown in Fig. 5, this metric doesn't exhibit a high level of variability along the position axis, which is especially problematic for pattern matching in a large set. Therefore, the SPD-IRCD is effectively used as an additional parameter only if it is available in the *radio-map*.

After an initial step of identifying the channels common with the online fingerprint, the algorithm acting on the ICRD map works by calculating the differential between the channels in a circular order. For instance, if there are four common channels, e.g. channel 1, 2, 3 and 4, then only the differentials 1-2, 2-3, 3-4, 4-1 are used. With this technique the algorithm avoids the potentially large number of comparisons resulting from all the possible channel combinations. Moreover, due to the circular link, absolute RSS changes in any channel will always affect only two differentials independently of the total number of channels found in the radio-map.

$$score_{i,p} = \sum_{c=1}^{N} \left| D_{i,c} - D_{p,c} \right| + (k-1) \left| SD_{i,c} - SD_{p,c} \right| \quad (1)$$

Where D is the ICRD, SD is the SPD-ICRD, N is the number of channels, k is the SPD-ICRD weight, i is the online location index and p is the radio-map location index

According to equation (1), this algorithm takes all differentials (ICRDs), including the *Same-Propagation-Direction* one, and attributes them the same weight. In order to take advantage of the high correlation properties described in section IV, this differential is given a higher weight (k), but since it had been considered once in the summation part of the equation, the weight becomes (k-1). Values in the range of 3 to 10 were tested and experimental results suggest that higher values are better suited for radio-maps with higher resolution.

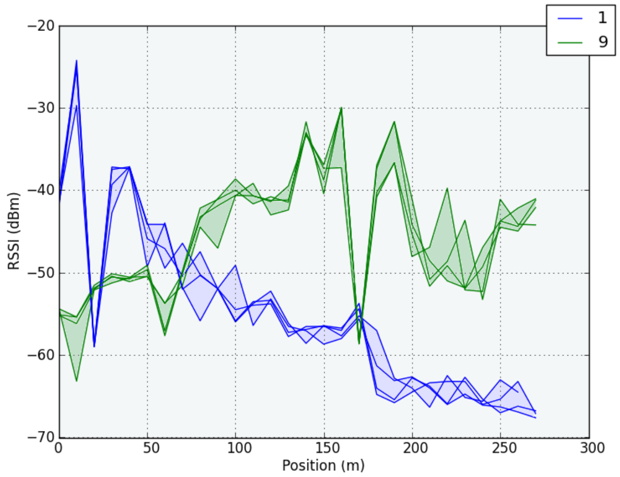

Fig. 6. WLAN RSS evolution of different channels, measured in four sessions.

When testing the new fingerprint against the *radio-map*, the resulting scores list is processed so that a confidence level is calculated for each probable match. The procedure is equivalent to that used in ref. [4] and is calculated as:

$$P_{i,j} = \frac{1/score_{i,j}}{\sum_{n=1}^{N} 1/score_{i,n}} \tag{2}$$

Where $P_{i,j}$ is the confidence of the online fingerprint i in matching radio-map point j

In the first phase, the algorithms were first tested stand-alone for each technology at a time. The various parameters are resumed in Table III. In a second phase, a hybrid algorithm takes advantage of the two fundamental ones and, by combining their results, creates a new set of locations and their respective matching confidence. Since all result sets share a common format, several processing steps could be combined or chained to create the final algorithm.

TABLE III. TESTING PARAMETERS FOR THE LOCATION-MATCHING ALGORITHMS. N IS THE NUMBER OF COMMON AVAILABLE CHANNELS.

Location finding algorithm		**Quantities compared**	**SPD-ICRD Weight**
Absolute RSS-based	match_abs_values	N	0
ICRD-based	match_single_diff	1	0
	match_diffs_spd_1	N	1
	match_diffs_spd_3	N	3
	match_diffs_spd_10	N	10
Hybrid	match_hybrid_spd_1	2N	1
	match_hybrid_spd_3	2N	3

TABLE IV. EXAMPLE COMBINING SCORES IN THE HYBRID METHOD

	Absolute RSS Scores		**ICDR scores**		**Hybrid scores**	
Rank	***Location index***	***Confd (%)***	***Location Index***	***Confd (%)***	***Location index***	***Confd (%)***
1	6	12.8	6	20.4	6	16.6
2	0	9.9	10	7.7	0	4.95
3	8	8.9	12	6.1	8	4.45

In order to combine the two result sets, the average of the relative confidence is calculated among the same suggested location points. The reason behind this choice is the fact that the relative confidence is a unit-less quantity (ratio) defined within 0 and 1. Therefore, contrary to the original absolute score (e.g. calculated by equation (1)), operations can be performed among several of these quantities, guaranteeing that all contribute with the same weight to the final result.

So, considering the example in Table IV, one can verify that location 6 is ranked first in the hybrid scores list since its confidence average is 16.6%, while the other locations' indices have a much lower average. Even though locations 0 and 8 are only present in one of the lists, their average is sufficient for them to be ranked second and third respectively. In this simplified example only the three best suggestions are shown, whereas, in fact, the complete scores list is considered by the algorithm.

B. Location matching algorithm – multi technology

When multiple technologies are available, results can be combined following the same idea. Although RSS magnitude and units are perhaps different from the various technologies, the relative confidence level can again be combined among the individual suggestions to create a list of locations with the overall best confidence.

In the case of WLAN, the *radio-map* presents only two channels, 1 and 9, as emitted by two installed access points. Therefore, the WLAN RSS differential map (ICRD) will contain a single differential channel and, given that the signals are propagating in opposite directions, the ICRD method alone will probably not yield the best results. Nevertheless, from its plot (Fig. 6) one can notice the considerable higher degree of attenuation relatively to GSM, in the order of 14 dB/100m. This factor generally favours the performance of fingerprinting methods and, consequently, in the WLAN case the algorithm should perform better by giving higher weight to absolute RSS other than IRCD.

The same question arises when combining both technologies, as it seems reasonable to give higher weight to results coming from a technology providing the best results, most probably WLAN relatively to GSM, due to its higher attenuation levels.

VI. RESULTS EVALUATION

Several approaches with different parameters were implemented, trying to take advantage of the previously observed effects. They were then evaluated according to the procedure described in part III.C.

A. *Single technology*

With GSM it is noticeable that the performance of all methods gets better as more locations (K) are considered by KNN – see Fig. 7. This might be due to the fact that, with such little differences in absolute value, finding the exact match of a location is very difficult and averaging the best guesses weighted by their degree of confidence indeed becomes a favourable option.

Another interesting point is that the algorithm working directly on the absolute RSS values performs already quite well, especially for K=1, when compared to the differential methods (ICRD). This behaviour is mostly related to the fact that in the differential method there is an additional uncertainty factor, as two RSS channels are used.

Despite this fact, the combined algorithm could effectively take advantage of both results and perform better that any base algorithm alone.

Evaluating the methods performance for WLAN (see Fig. 8), one can clearly observe the significantly better performance of the absolute RSS matching method than the differential one. Nevertheless, as expected, the absence of more ICRD channels and their inherently higher measurement uncertainty have a very negative impact, and the average location error using the ICRD method is above 30m. Yet, this value is still lower than the best method working over GSM. This comparison clearly demonstrates that the performance of location fingerprinting methods is highly dependent on the underlying signal propagation characteristics.

Additionally in this case, the best performance with KNN is obtained for the lower values of K. This result complies with the explanation given above, which can be summarised as: the higher the signal attenuation along the tunnel, the more accurate the first guesses of the methods. In this case, for K=1 the absolute RSS method yields an average distance error of 12.1 m.

Despite the already impressive accuracy when compared to GSM, the algorithms working with WLAN were combined with different weights in order to verify whether they could again perform better together. With a weight factor of 90%/10% the hybrid method – match_hybrid_spd1@10% – indeed performs quite well and, although slightly worse for K=3 and K=5, it achieves the overall best performance when K=1, yielding 10.6 m of average distance error. For a *radio-map* whose calibration step is 10 m, this result looks quite interesting.

To directly compare the achieved results from GSM and WLAN, Fig. 9 shows the performance in terms of error distances and their corresponding accuracy. In contrast to GSM, there are visibly substantial performance impairments among WLAN algorithms. In the end, the overall best

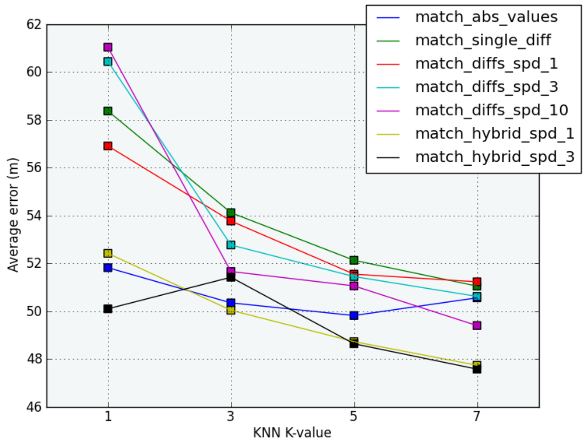

Fig. 7. Performance of the various matching algorithms with KNN, evaluated for GSM for K=1, 3, 5 and 7.

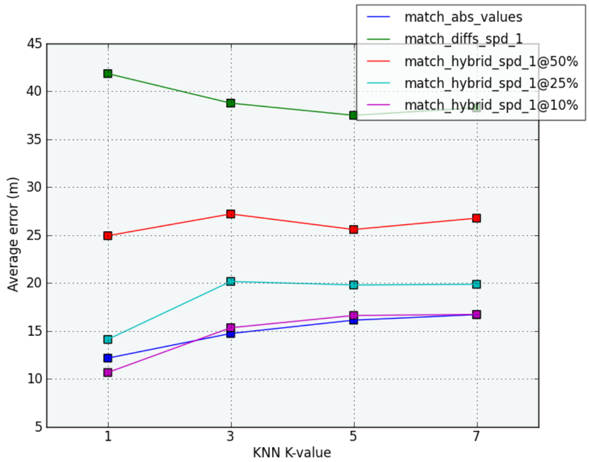

Fig. 8. Performance of the various matching algorithms with KNN, evaluated for WLAN for K=1, 3, 5 and 7.

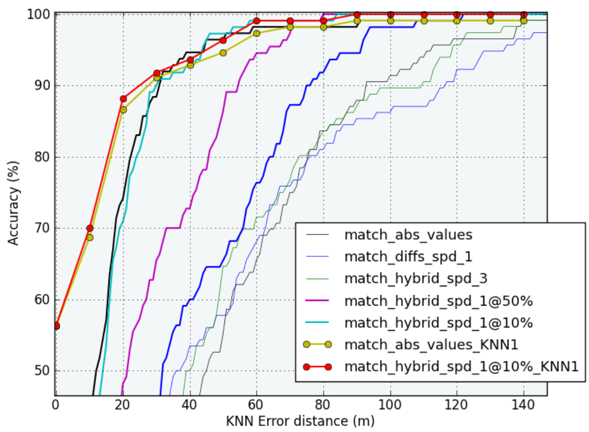

Fig. 9. Accuracy achieved by the various methods with KNN (K=7, otherwise indicated). Thin lines are relative to GSM while bold lines are realtive to WLAN. As can be seen the WLAN results clearly outperform the ones obtained with GSM, independently of the matching algorithm.

accuracy, like suggested before, is achieved by the hybrid method working over WLAN with KNN having K=1. Setting the distance error limit to 20 m, it provides an accuracy of 88.1%.

B. Multi-technology

To assess the performance achieved by combining multiple technologies, several possible configurations based on the previous algorithms were tested. A resume of the methods settings is presented in Table V and both simple, hybrid and multi-technology algorithms are considered. The results are shown in Fig. 10 and provide a good overall performance summary. The performance of the absolute RSS method for GSM (*gsm_abs_values*) and WLAN (*wlan_abs_values*) are included for base comparison, as both are then combined by the multi-technology method (*gsm-abs+wlan-abs*).

Even when given 50%/50% weights, the performance of this multi-technology method largely exceeds that from GSM alone, and approaches the one from WLAN. By giving 10% weight to GSM – method *gsm-abs+wlan-abs(10%)* – the global performance improves and achieves the same level as WLAN itself.

When combining hybrid methods from the different technologies (*gsm-hybrid-spd3+wlan-hybrid@10%*), a similar behaviour is observed. The algorithm yields an accuracy level identical to that achieved by the best underlying algorithm – *wlan-hybrid@10%* in this case. The fact that the multi-technology method doesn't improve on that result might be due to the highly uneven levels of accuracy achieved by the underlying technologies. Furthermore, in order to improve the already rather accurate guess with WLAN, one would need quite high confidence levels in the GSM matching (uncommon in the current data set) and eventually a location algorithm, other than KNN, that could take better advantage of the combined result set.

TABLE V. PARAMETERS OF THE COMPARED ALGORITHMS

Name	Technology (Weight)	Matching algorithm	ICRD Weight
gsm-abs_values	GSM (100%)	match_abs_values	0
gsm-hybrid-spd3	GSM (100%)	match_hybrid	50% (SPD=3)
wlan-abs_values	WLAN (100%)	match_abs_values	0
wlan-hybrid@10%	WLAN (100%)	match_hybrid	10%
gsm-abs+wlan-abs (50%)	GSM (50%)	match_abs_values	N/A
	WLAN (50%)	match_abs_values	N/A
gsm-abs+wlan-abs (10%)	GSM (10%)	match_abs_values	N/A
	WLAN (90%)	match_abs_values	N/A
gsm-hybrid-spd3+ wlan-ybrid@10% (10%)	GSM (10%)	match_hybrid	50% (SPD=3)
	WLAN (90%)	match_hybrid	10%

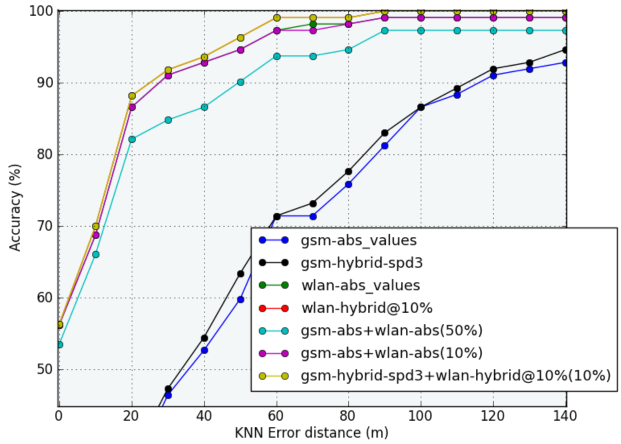

Fig. 10. Accuracy comparison among various methods, simple, hybrid and multi-technology, evaluated with KNN (K=1).
The methods paramters are explained in Table V.
Please note that red and yellow lines are totally coincident, while green and purple lines also coincide except for one point.

VII. CONCLUSIONS AND FUTURE WORK

This paper presents a study on fingerprinting techniques with WLAN and GSM network technologies over leaky-feeder for localization in a tunnel environment. Besides the absolute channels' RSS, a hybrid algorithm also takes advantage of the channels RSS differential and achieves slightly higher location accuracy. The fact that the RSS differential can actually be used for localization makes calibrations to be much more resilient to network changes, and thus reduces the need for re-calibration.

By exploring the signal strength of the WLAN network, much higher accuracy levels can be obtained, in the order of 20 m at 88% confidence. Combining results from both the GSM and WLAN technologies performs relatively well and, although significant improvement on the overall result could not be observable, the achieved accuracy is as high as the best underlying algorithms result. This might be due to the fact that there is a significant discrepancy between the achieved accuracy levels for WLAN and GSM. Additionally, performance comparison plots between WLAN and GSM also show evidence that the KNN parameter K should be chosen according to the attenuation factor of the network, where higher values of K only favour radio-maps having little attenuation between adjacent points.

The current setup, specifically deployed for the study, was limited to two Access Points. Larger deploys of WLAN and eventually other network technologies, like TETRA, might bring additional positioning value. Furthermore, algorithms taking into account sets of historic online fingerprints are being considered and, under the current scenario, first tests look promising.

REFERENCES

[1] A. Bensky, "Received Signal Strength," in *Wireless Positioning Technologies and Applications*, Artech house, 2008.

[2] M. Weber, U. Birkel and R. Collmann, "Indoor RF Fingerprinting using

leaky feeder cable considering environmental changes," in *6th International Conference on Mobile Technology, Application & Systems*, 2009.

[3] M. Weber, U. Birkel, R. Collmann and J. Engelbrecht, "Comparison of various Methods for Indoor RF Fingerprinting using Leaky feeder Cable," in *Positioning Navigation and Communication*, 2010.

[4] F. Pereira, C. Theis, A. Moreira and M. Ricardo, "Evaluating location fingerprinting methods for underground GSM networks deployed over Leaky Feeder," in *Indoor Positioning and Indoor Navigation (IPIN)*, Guimarães, 2011.

[5] "CERN - The Large Hadron Collider," [Online]. Available: http://public.web.cern.ch/public/en/LHC/LHC-en.html.

[6] M. Vossiek, L. Wiebking, P. Gulden, J. Wieghardt, C. Hoffmann and P. Heide, "Wireless Local Positioning," *IEEE microwave magazine,* vol. 4, no. 4, pp. 77-86, December 2003.

[7] P. Bahl and V. Padmanabhan, "RADAR: an in-building RF-based user location and tracking system," in *INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, Tel Aviv, 2000.

[8] V. Otsason, A. Varshavsky, A. LaMarca and E. de Lara, "Accurate GSM indoor localization," in *UbiComp*, LNCS, 2005.

[9] B. Denby, Y. Oussar, I. Ahriz and G. Dreyfus, "High-Performance Indoor Localization with Full-Band GSM Fingerprints," in *IEEE International Conference on Communications Workshops*, Dresden, 2009.

[10] A. Varshavsky, M. Y. Chen, E. de Lara, J. Froehlich, D. Haehnel, J. Hightower, A. LaMarca, F. Potter, T. Sohn, K. Tang and I. Smith, "Are GSM Phones THE Solution for Localization?," in *Mobile Computing Systems and Applications*, 2006.

[11] "1-1/4" RADIAFLEX® RLKW Cable, A-series," RFS, [Online]. Available: http://www.rfsworld.com/dataxpress/Datasheets/?q=RLKW114-50JFLA.

[12] ETSI, "TETRA Voice+Data Air Interface, TS 100 392-2," 2011-10.

[13] M. Frigge, D. C. Hoaglin and B. Iglewicz, "Some Implementations of the Boxplot," *The American Statistician,* vol. 43, no. 1, pp. 50-54, Feb 1989.