A Comparative Study of DECT and WLAN Signals for Indoor Localization

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***Abstract*—While there is more to context than location, localization and positioning must continue to be improved. Location-aware applications, such as Google Latitude, are enjoying great popularity. Location-based applications and services are widely used on platforms such as the iPhone. The localization itself thus remains an issue, especially in indoor scenarios.**

In this paper we discuss Digital Enhanced Cordless Telecommunications (DECT) and its potential for positioning and localization. While the technology itself is not new, the application of DECT for localization has so far not been thoroughly investigated, especially for combined indoor and outdoor usage.

We have collected and analyzed large data sets of DECT and WLAN fingerprints in urban, sub-urban and rural areas, both for indoor and outdoor situations. We show that DECT could improve the accuracy and robustness of existing localization schemes based on WLAN or GSM.

***Keywords*-radio position measurement, cordless telephone systems, mobile communication, DECT, ubiquitous computing, localization, location-based services**

I. Introduction

Only very few technologies have been designed to be pervasive when they were introduced, they became ubiquitous by use and adaptation. Cordless telephones for use at home are one example. While not everyone owns a wireless access point, nearly everyone has a cordless phone at home - including non-technologist and elderly people. This provides a node density in real world situations that suggest DECT may be an ideal candidate for localization.

DECT, Digital Enhanced Cordless Telecommunications, is an European Telecommunications Standards Institute (ETSI) radio standard for short-range cordless communications. DECT can be used in more than 100 countries for voice, data and networking applications with a maximum range of up to 500 meters. As the frequency band is exclusively available for DECT, there is no interference with other RF technologies.

Despite the availability of Global Navigation Satellite Systems (GNSS) such as GPS and Galileo for outdoor localization, and specialized and accurate indoor positioning systems based on ultra-wide band radio (UWB) or optical tracking of markers, there are few approaches requiring no artificially enriched environments and that work reliably and accurately both indoors and outdoors. Vision-based approaches, e.g. VisualSLAM, have not yet been reported to have been successfully been deployed in the field. Wearable approaches such as [1] have been demonstrated to work but have to be worn and are not so effective when incorporated into a personal device such as a mobile phone.

DECT so far has not been investigated regarding its potential for localization in real world scenarios for several reasons. First, DECT appeared before WLAN and before localization became an issue in ubiquitous computing. Second, there were no affordable systems available to researchers, only highly expensive systems in the telecommunications industry. Third, there was no free implementation of DECT that allowed DECT to be used "in the wild". Fourth, very few commercial cards are still available. Many products have have been discontinued after the rise of WLAN and VOIP. All this changed at the end of 2008 with the release of the first open source partial DECT stack implementation by http://www.dedected.org which we acknowledge to have used during our research. We want to provide measurements and analysis to determine whether DECT is suitable for localization in indoor and outdoor scenarios.

The measurements for this research have been taken indoors and outdoors in two major European cities in a sub-urban residential area, a rural residential area and an industrial area. The key results are:

- DECT localization can be used for both indoor and outdoor localization,
- DECT-based localization performs at least as well as WLAN-based localization in all scenarios,
- RSS stability of DECT is comparable RSS stability of WLAN,
- There are more DECT stations than WLAN stations in all but the urban outdoor scenario.

The paper is structured as follows. We first summarize the state of the art in localization and positioning. Then we introduce DECT as some readers will not be familiar with this technology. We will then present our measurement approach and investigate the potential of DECT for

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localization in three indoor and three outdoor scenarios and present quantitative and qualitative results. We conclude by summarizing the results and giving an outlook on future work in the field.

II. Related Work

Liu et al. [2] give an overview of wireless indoor positioning systems as of November 2007. They discuss state-of-the art localization algorithms used for calculating position, using approaches like fingerprinting, time-of-flight, time-difference-of-arrival, and others. They assess the performance of technologies such as RADAR [3], GSM fingerprinting, WLAN, and many more. They give an outline of current wireless-based positioning systems with respect to scalability and resolution. We refer the reader to this article for a complete overview and references to the individual works.

Zeimpekis et al. [4] provide a taxonomy for indoor and outdoor positioning systems for commercial mobile applications. We argue that DECT should not only be included in localization system for its accuracy, but also as it is cheap and simple (regarding chip set complexity) to integrate.

We are well aware that the signal propagation and thus the received signal strengths (RSS) are affected by the environment. Ferris et al. [5] show that Gaussian processes can be used to generate a likelihood model for RSS measurements and that the parameters necessary for such a model can be learnt from the measurement data. They verified this for indoor WLAN and GSM data. The approach of using Gaussian processes for localization has also been verified by Schwaighofer et al. [6] for DECT signals, but their work focuses on the algorithm rather than the inherent properties of DECT, and the method is evaluated in a single indoor setting only.

Only few systems can be used for both indoor and outdoor localization. Therefore, we argue that it is worth re-investigating the well-established DECT technology.

DECT positioning is a topic that has already been discussed as an option in controlled deployments [7], [8]. In contrast, the approach we take looks at how already deployed infrastructure that is not connected can be used as a basis for a location system. In addition, the results presented are more accurate than previous results, while using a much simpler algorithm. Our data has also been gathered in a wide range of environments out of the lab.

Methods using probabilistic models of signal strengths have been developed for WLAN-based location systems [9] but we chose to use a simple deterministic model which seems more appropriate given the relatively sparse measurement points.

III. DECT at a Glance

The most common frequency band for DECT is 1.880 GHz to 1.900 GHz for Europe. Outside Europe, available bands are from 1.900 GHz to 1.920 GHz and from 1.910 GHz to 1.930 GHz.

	WLAN (IEEE 802.11x)	DECT (ETSI EN 300 175)
TX Power	$<$ 100 mW EIRP indoors	$<$ 250mW ERP indoors
Avg. Range	30 m indoors	200 m indoors
Frequency	2.4 GHz, 5.7 GHz	1.8 GHz (1.9 GHz)
Channels	13 (11), 19 (24)	10 (5)

Table I
Comparison of key characteristics of WLAN and DECT standard. Figures in brackets denote values in the US.

DECT was standardized for cordless communications in 1995 in Europe and in 2005 in the US. Selected key features of DECT and WLAN are summarized in Table I. The lower frequency of DECT compared to WLAN allows DECT radio waves to better propagate through walls. This is supported by the higher effective radiated power (ERP) allowed in the dedicated DECT communication band. This design allows cordless phone users to use their equipment not only in the direct vicinity of the base station, but also throughout the house and garden. This feature is confirmed by our measurement results — in every location in our data sets, the amount of visible distinct DECT stations is larger than the amount of WLAN stations. Therefore, DECT is a suitable technology for indoor *and* outdoor localization.

In the early days of wireless telecommunications, combined DECT and GSM phones were available such as the SAGEM DECT/GSM DMC 830 (GSM 900/DCS 1800) mobile phone. It allowed the user to use it as a cordless telephone at home and as a mobile phone when out of reach of the DECT home base station.

Worldwide, about a third of all cordless phones are based on the DECT specification and it is predicted that by 2011 about 80% of the cordless phones will be DECT phones [10]. DECT is in particular extremely common in Europe. In Germany (40 million households, 2009) the majority of cordless phones are DECT phones. In 2009, there were estimated to be about 30 Million DECT phones in use. The total number of households with broadband internet access (mainly DSL) is only 20 million, of whom only a few have a WLAN base station. This would suggest that the number of visible DECT base stations is at least double the number of WLAN access points. As the range of WLAN in real environments (about 10-40 meters) is much shorter than the range of DECT systems (50–200 meters), this leads to a much higher ratio. In Germany we saw in the measurements 5 to 10 times more DECT base stations than WLAN access points. We expect a similar situation over most parts of Europe.

In the USA, however, DECT is only in use since 2005 and has not yet had a significant impact. We carried out measurements in different urban and suburban areas in California including in San Francisco, Mountain View, and Santa Cruz. The measurements in more than 20 locations did not give a single sighting of a DECT base station. In all urban and in the majority of the suburban locations, WLAN access points were visible. Hence, the findings are not applicable for the US *yet*, but they might be in the future.

There have been commercial DECT-based localization systems [8]. Contrary to our study, they require changes to be made to the environment. In Figure 7, we show that already 55% accuracy at 5 meter precision and 100% accuracy at 15 meter precision can be obtained by a simple algorithm. This exactly matches the data from the Siemens system without the need for a controlled environment. Siemens states they needed less than 10 seconds for localization with no active calls.

IV. Data Collection, Measurements and Analysis

We now introduce our data collection procedure, the measurement methodology, and compare the results for three indoor and three outdoor scenarios. We present qualitative and quantitative results for each scenario. In no case was any base station added nor the environment modified. The results are obtained in real world scenarios under realistic conditions.

A. Data Collection Procedure

The measurements were taken using an Ubuntu Linux based IBM T42 laptop with a built-in Intel Corporation PRO/Wireless 2200BG card and an 11 dBi external gain antenna. Without the external antenna, there would not have been enough visible WLAN access points in some locations. A quick comparison showed that this wireless card outperforms other cards commonly used for war driving, even when only a 5 dBi gain omni-directional antenna was used. We used a Dosch & Amand Com-on-Air PCMCIA DECT card with no external antenna. For outdoor measurements, a high-quality uBlox-chipset based GPS receiver was used for acquiring reference location information. This measurement setup of laptop and DECT, WLAN and GPS receivers was used as our data collection system. The data was analyzed offline after the collection procedure.

In each location, we measured the available networks using the iwlist command from the Linux wireless tools. All available stations on all available WLAN channels (IEEE 802.11b/g) were stored. Afterwards, we scanned and recorded all DECT channels for 60 seconds. The measurement time used for DECT was chosen as follows: a standard GPS fix using SiRF-III or uBlox-based chips takes around 30 seconds under normal conditions. This time is needed for one-shot positioning. We analyzed the code used for a DECT channel scan, and after discussion with the DECT developers, chose to give ourselves double the time needed for a GPS fix. The reason for this is that the DECT scanning code is currently in a very early stage and it is expected that the scan time will eventually be reduced by half. Thus, measurements that now take 60 seconds will soon take only 30 seconds — just the time necessary for a GPS fix which we set ourselves as benchmark. Shorter fix times with GPS are only achievable with “hot fixes”, which are unrealistic in many situations (e.g. leaving a long distance train after a trip, or just leaving your office building to go home). Dedicated chip sets are expected to perform the localization task in the order of few seconds.

In each single location, at least 5 consecutive measurements were taken to ensure that all available stations were seen in at least one of the five measurement sets and to be able to assess the RSS variance in the signal. Additionally, variations in the GPS signal can be averaged. In the suburban indoor scenario with sub-centimeter accurate reference points, at least 20 consecutive measurements were taken in each location as here there is no inaccuracy in the reference locations.

B. Algorithms

We analyzed our data using a simple approach from other fingerprinting research to make the results comparable. We discuss the results obtained with this approach as they highlight the potential of DECT-based localization.

With more sophisticated algorithms [9], [11] and specific tuning for DECT localization, we expect that the accuracy obtained for DECT can be significantly increased, thus underpinning the argument that DECT should no longer be ignored for both indoor and outdoor localization.

1) Principle: A fingerprint consists of a list of visible base stations identified by their respective hardware addresses and signal strengths. Fingerprints are recorded at various locations and stored in a lookup table during the initial offline training phase. Then during the online phase new fingerprints are compared to the fingerprints in the lookup table and the current location is inferred. This method assumes that fingerprints that are similar come from locations that are close and that fingerprints that are different come from locations that are far apart.

2) Metrics and estimation method: We use the Manhattan distance between fingerprints to evaluate their similarity — the smaller the distance the greater the similarity. Thus the distance between a fingerprint $\left\{s_1^{lookup}, \cdots, s_n^{lookup}\right\}$ from the lookup table and a fingerprint $\left\{s_1^{online}, \cdots, s_n^{online}\right\}$ taken during the online phase is $\sum_{i=1}^{n}\left|s_i^{lookup} - s_i^{offline}\right|$ where n is the total number of base stations from either of the fingerprints. A base station that is missing from one of the fingerprints is assigned a low signal strength close to the minimum value. We use -140 dBm.

When signal strengths are expressed in dBm (a logarithmic function of the power) they are close to uniformly distributed in the range of possible values. Figure 1 shows that after scaling and shifting, signal strengths from DECT and WLAN have similar distributions and ranges. This means the values can be directly compared to each other without any extra normalization process.

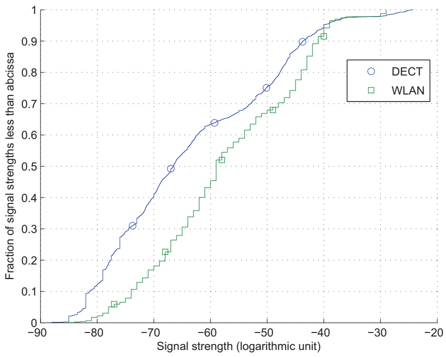

Figure 1. Comparable distributions of DECT and WLAN signal strengths

The weighted KNN (K-nearest neighbors) method is used to estimate the location of the online fingerprint. The locations of the K fingerprints most similar to the new fingerprint are averaged. This is a weighted average where the locations $location_i$ are weighted by the inverse of their fingerprint distances d_i^{fp}. The location is given by

$$\frac{1}{\sum_{i=1}^{K} \frac{1}{d_i^{fp}}} \cdot \sum_{i=1}^{K} \left(\frac{1}{d_i^{fp}} \cdot location_i \right)$$

We find that $K = 2$ gives good results but this may be an artifact of our choice of locations along the center line of corridors and roads. Bahl and Padmanabhan [3] show that values of K from 2 to 4 work well.

3) Evaluation: Fingerprints from the same location are similar, but show slight variations in the signal strengths and some base stations do not appear in all the fingerprints. The lookup table contains only one aggregated fingerprint per location containing the average signal strengths for each base station. This makes each location estimate faster than when we use the full set of fingerprints and also reduces the location error. A more complex alternative is to use the redundant measurements to compute a statistical model of signal strengths.

The location error is the Euclidean distance between the estimated location and the true location. We calculate the location error for the complete set of fingerprints. We present the individual results for the three indoor and three outdoor locations in the following sections.

A general result is that the combination of DECT and WLAN performs almost identically to DECT alone, with a slight reduction of the larger errors. We also show a baseline method where each location is estimated by selecting a random point from among the locations in the lookup table, this gives an idea of the scale of the experiment.

C. RSS Variance Analysis

As a starting point, we investigated how the received signal strengths vary for both DECT and WLAN. A large variation in RSS would result in lower performance of the localization algorithms and an increased position error. We used measurements from the indoor scenario. Three arbitrary locations out of 24 reference points were chosen. For each of these three points, 20 measurements were taken. The procedure was repeated four times at different times of the day.

Figure 2 shows the standard deviations of the RSS of both DECT and WLAN for each of the base stations detected at one of the three points. The variations in signal strengths are comparable for both technologies.

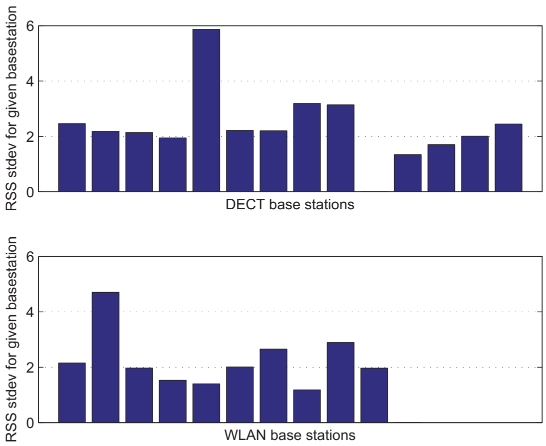

Figure 2. Received Signal Strength variation of DECT and WLAN stations.

D. Accuracy and Precision

Accuracy can be given in multiple ways. One option is to state that for x% of all measurements, the accuracy is below y meters. For the indoor measurements we opted to give the percentage with a fixed accuracy of 5 meters. This accuracy in most cases allows room level localization.

In the outdoor scenarios the GPS coordinates used to assess the performance of the localization algorithms have some error. We tried to cope with this by doing the measurements in a time window when the GPS location estimates would be the best according to almanac and ephemeris data.

The indoor office scenario features reference points of sub-centimeter accuracy. We thus argue that this scenario can be viewed as a benchmark scenario, taking into account that the algorithm used for localization is quite simple. With more sophisticated algorithms, we expect an additional increase in localization accuracy. In this indoor scenario, more than 55% of the location estimates have less than 5 meters error and more than 90% of the location estimates have less than 10 meters error. For an arbitrarily chosen real world scenario with no artificial DECT stations we consider this to be a very good result.

E. Indoor Measurements

1) Urban Scenario: For the urban scenario we used an apartment located in a residential area. The apartment was about 10×5 meters, with windows occupying half of the length.

While a maximum of only 3 WLAN base stations were encountered in a single fingerprint, up to 12 DECT base stations were sighted. As concrete walls shield a high percentage of WLAN radio waves, only the access points of the direct neighbors are visible. However lots of DECT stations including some from across the street are detected.

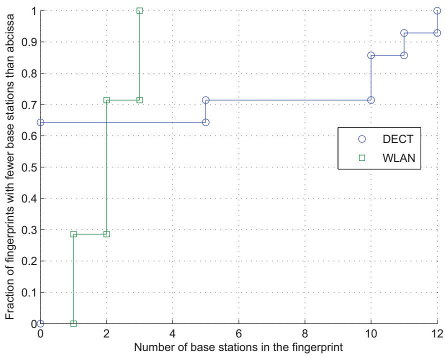

Figure 3. Comparison of the number of DECT and WLAN stations per fingerprint in the urban indoor scenario.

Figure 4 shows that in 40% of the measurements, the error for DECT was less than 5 meters. For WLAN the error was less than 5 meters in only 10% of the cases. Both DECT and WLAN fingerprinting performs very poorly, their results are comparable to randomly selecting a location. This is due to the very small number of basestations and access points, and there is little the algorithm can do.

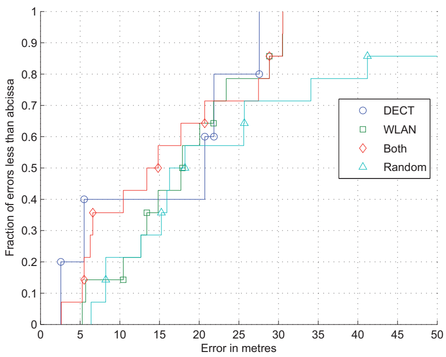

Figure 4. Comparison of localization errors in the urban indoor scenario. Markers serve only to distinguish between curves. Discrete steps are due to the limited number of measurement points and basestations in some data sets.

2) Sub-Urban Scenario: In this scenario, a common office environment in a sub-urban environment was analyzed. This location features reference points on multiple floors and in the garage with sub-centimeter WGS84 coordinates available. The office was not artificially augmented with DECT or WLAN stations, nor was the position of either type of station known. The measurements were taken at 24 of the available reference points on two floors. At each point at least 20 measurements were taken. Three points were used for the variance measurements discussed above. The distances between the measurement points in this scenario were between one and three meters. Figure 5 shows the floor plan of this scenario and the reference points.

Figure 6 shows that more DECT stations are visible than WLAN access points.

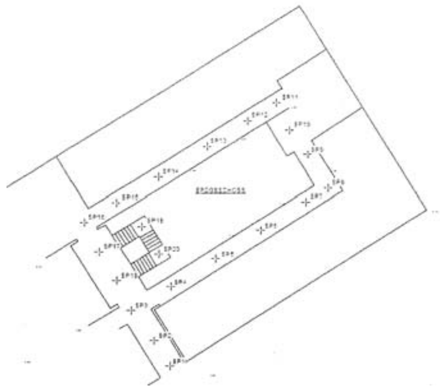

Figure 5. Indoor floor plan with reference points. A sub-urban office environment was augmented with GPS coordinates (WGS84) with sub-centimeter accuracy on two floors. 24 reference points were defined. Each floor is about 15×30 meters and has 12 reference locations.

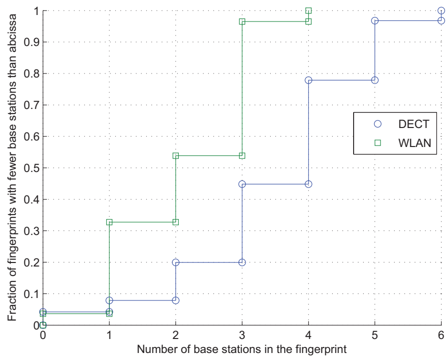

Figure 6. Comparison of the number of DECT and WLAN stations per fingerprint in the sub-urban indoor scenario.

In Figure 7, we compare the localization accuracy of DECT and WLAN for the sub-urban indoor scenario. The results clearly indicate that the accuracy achieved in a typical office environment using DECT for localization is better than that achieved using WLAN.

In 50% of all DECT-based estimates, the location error was less than 5 meters, but only in 30% of all WLAN-based estimates.

3) Rural Scenario: The location for the rural indoor scenario was an apartment in a rural city of about 1,500 inhabitants. It is located about 50 kilometers away from the nearest million-inhabitant metropolis. The measurements were taken near the closed windows in order to achieve GPS

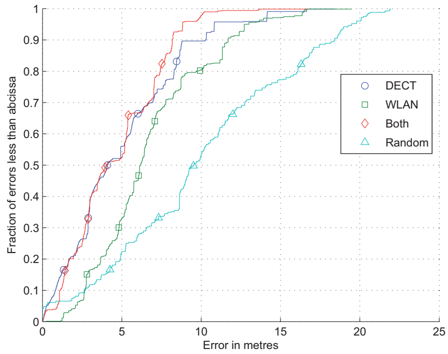

Figure 7. Comparison of the localization errors in the sub-urban indoor scenario. DECT outperforms WLAN significantly.

fixes. Due to the small number of windows the amount of measurements is significantly less than for the other indoor scenarios. Here only about 400 measurements were taken.

The number of WLAN base stations in this scenario is rather small. Only 2 WLAN stations are visible as shown in Figure 8. However up to 17 DECT stations were seen.

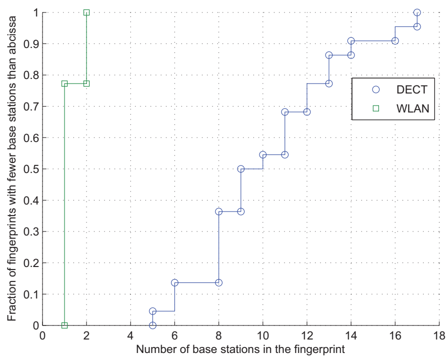

Figure 8. Comparison of the number of DECT and WLAN stations per fingerprint in the rural indoor scenario. Only 1 or 2 WLAN access points but 5 to 17 DECT stations.

Figure 9 shows that DECT again performs better than WLAN in this scenario.

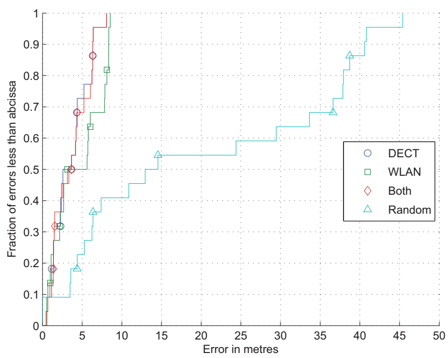

Figure 9. Comparison of localization errors in the rural indoor scenario.

For DECT in 80% of all measurements, the location error is less than 5 meters. For WLAN in 65% of all measurements, the location error is less than 5 meters.

F. Outdoor Measurements

1) Urban Scenario: For the urban outdoor scenario, we chose two roads in the city center of a metropolis with more than a million inhabitants. The two straight and parallel roads were separated by 100 meters separated by buildings. The length of each of the segments was about 750 meters. The city center was about one kilometer away.

As could be expected, at lot more base stations were visible compared to the indoor scenarios. As a university lies partially along a road segment, a high number of campus WLAN stations were encountered. Thus the maximum number of WLAN stations in all measurements was 37, while at most 49 DECT stations were visible.

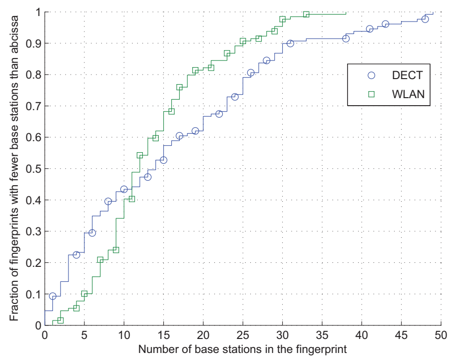

Figure 10. Comparison of the number of DECT and WLAN stations per fingerprint in the urban outdoor scenario. Half the fingerprints contained more than 12 stations for DECT and WLAN, and 20% contained more than 20.

In 50% of all measurements, the position error is less than 20 meters for both DECT and WLAN as depicted in Figure 11. With this data set WLAN appears to perform slightly better than DECT. This may be because there are similar numbers of DECT and WLAN stations in each fingerprint as shown in Figure 10 but WLAN has a shorter range and is therefore more accurate than DECT for the same number of base stations. Honkavirta et al. [9] show that more than 5 stations per fingerprint do not significantly improve the accuracy so the high number of base stations do not benefit us beyond a certain point. We want to note again that this is a realistic environment without any artificially deployed stations.

2) Sub-Urban Scenario: The sub-urban scenario was a residential area in the outskirts of a metropolis with more than a million inhabitants.

Figure 12 is an annotated Google Maps screenshot giving an overview of the environment. The map shows about half of the mapped measuring area.

Figure 13 shows that in there are up to 23 DECT stations per fingerprint but only up to 5 WLAN stations in this scenario.

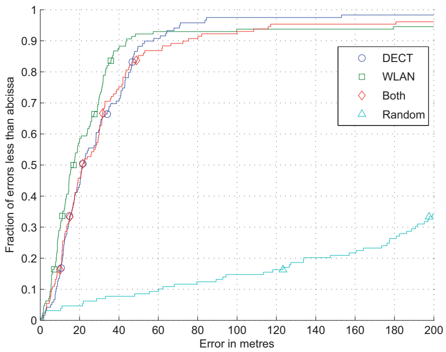

Figure 11. Comparison of localization errors in the urban outdoor scenario. WLAN performs slightly better than DECT.

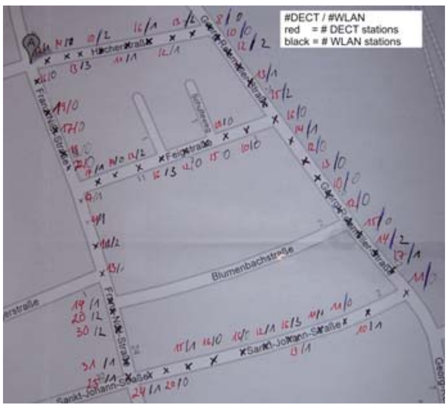

Figure 12. Part of a DECT/WLAN map of the sub-urban residential area. The annotated area is about 150 × 300m. The number pairs give a quantitative overview of the number of distinct base stations seen at each location, first DECT, then WLAN.

Figure 14 shows that in 50% of all measurements, the error for both WLAN and DECT is around 25 meters.

3) Rural Scenario: For the rural scenario a small city was chosen within a 50 km of a large city.

Figure 15 yet again shows that there are many more DECT stations observed than WLAN access points. Only up to 5 WLAN base stations were observed in the fingerprints, and 18% of fingerprints contained no WLAN data at all. This contrasts with a maximum of 20 DECT stations in a fingerprint and only 2% with no DECT data.

However Figure 16 shows that the median accuracy of DECT localization is just under 30 meters but that WLAN localization performs slightly better with a median accuracy of less than 25 meters. It seems that the high number of DECT stations does not give a definite advantage in this large scale scenario. But both WLAN and DECT produce location estimates with comparable accuracy.

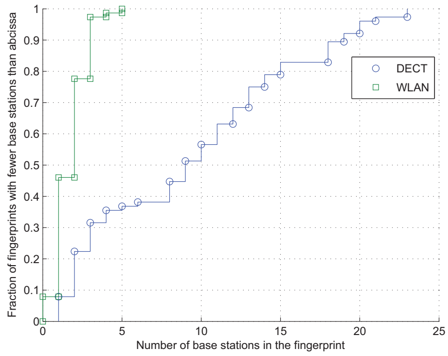

Figure 13. Comparison of the number of DECT and WLAN stations per fingerprint in the sub-urban outdoor scenario. Up to 23 DECT stations but only up to 5 WLAN stations visible.

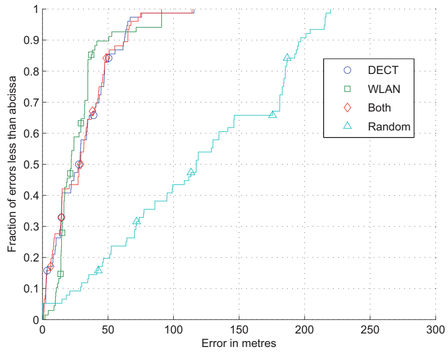

Figure 14. Comparison of localization errors in the sub-urban outdoor scenario.

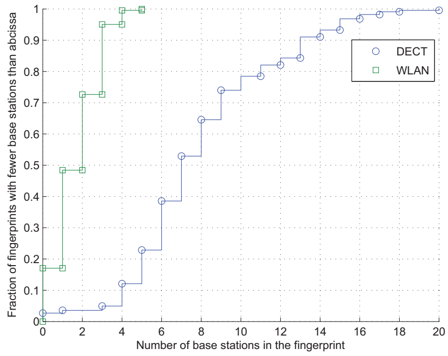

Figure 15. Comparison of the number of DECT and WLAN stations per fingerprint in the rural outdoor scenario. Many more DECT stations than WLAN.

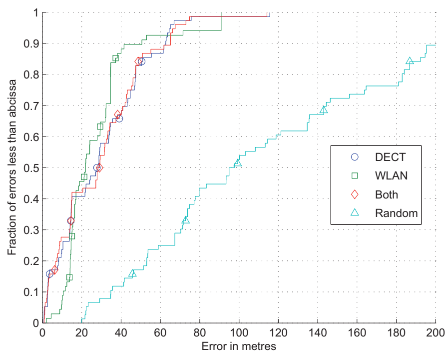

Figure 16. Comparison of localization errors in the rural outdoor scenario.

V. Conclusions and Discussion

A. Data Base

We collected DECT fingerprints on around five kilometers of roads in a rural town of around 1500 inhabitants, and on an additional five kilometers in other areas. Fingerprints were taken every 20 to 25 meters.

The localization algorithm used is basic but already shows that DECT outperforms WLAN in certain scenarios, particularly indoors. Both DECT and WLAN localizations perform similarly in large scale outdoor settings with a slight advantage for WLAN. We believe this is due to the shorter range of WLAN signals which provide better location estimates than the more powerful DECT signals when the area studied extends far beyond the range of a single station. However in almost all cases there were a lot more DECT stations visible than WLAN in each fingerprint and we expect that more advanced methods could use this to considerably improve DECT localization accuracy.

B. Economical Impact

DECT is quite an antique standard when compared to UMTS or Bluetooth for instance. From today's perspective this means that DECT chips are comparatively simple and cheap to manufacture. Prices for DECT handsets start at about 15 EUR and for a base station with one handset at 20 EUR. These prices not only include the manufacturing, but also the physical parts and charging electronics, and, more interestingly, the full DECT protocol stack at PHY/MAC/NET/APP level. For localization only the PHY and MAC layers are needed which further decreases the cost of a dedicated sensor. According to our investigations this results in costs of about 50 euro cents for an additional localization sensor chip to be included in modern mobile devices.

As the incorporation of a DECT chip is very cheap, future applications that require positioning information could greatly benefit. Especially for indoor localization, environments do not require any kind of location system to be deployed. The accuracy obtainable by DECT alone could already support a number of location aware services, and when combined with other technologies such as GSM or WLAN fingerprinting would provide a more robust and accurate system than with these technologies alone.

C. Applications and Services

Mass-marketed and consumer products are starting to feature location based services such as Google Maps Mobile running on location aware devices. Skyhook Wireless Inc. provide a localization service which is used on the iPhone and on Android devices. They use a database of WLAN and GSM fingerprints to estimate locations when GPS is not available. For indoor localization, the results vary and depend on the environment. Especially in rural scenarios with little to no WLAN base stations and only few visible GSM cells, this approach performs poorly. Even in cities localization errors of 200m in indoor scenarios are encountered. Given the high number of DECT signals we recorded in our experiments we believe that DECT would be a worthwhile enhancement to this database is terms of accuracy and robustness. This is supported by our experimental results.

D. Performance of DECT for localization

Our experiments show that DECT fingerprints are at least as accurate at predicting locations as WLAN fingerprints. Figure 17 shows that the distance in physical space is more closely correlated to the distance between DECT fingerprints than the distance between WLAN fingerprints. In all but one outdoor dataset, the correlation coefficient between physical distance and fingerprint distance was better for DECT than WLAN and this figure is typical.

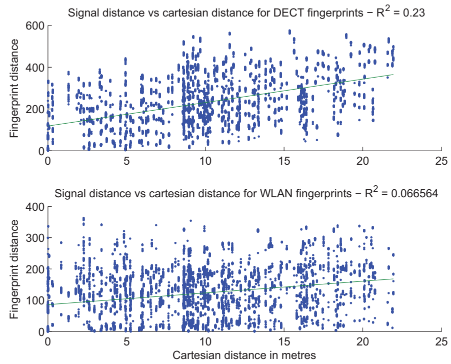

Figure 17. Correlation between fingerprint distances and distances in physical space for DECT and WLAN.

Another reason to expect better performance of DECT fingerprints is the higher number of DECT base stations in each fingerprint. Each of our collected fingerprints contains at least as many DECT stations as WLAN stations, even in high-density urban environments. DECT basestations may be moved more frequently than WLAN access points. We had no control over the basestations which appear in our data sets and some of them may have been moved during the few days separating the different data collections thus making the problem more difficult. This could be accounted for by constantly updating fingerprints as the system is used, a form of online recalibration. As shown in our data the number of visible DECT and WLAN devices varies a lot depending on how nearby buildings are equipped. This is why we suggest DECT fingerprinting as one additional component of a multimodal location system

In the future we want to explore if a decrease in the number of DECT base stations still permits accurate results. Such a reduction of visible DECT stations could result from the recently introduced DECT power saving mode. If performance remains similar with fewer stations the measurement time could be further shortened. As discussed earlier, with driver optimizations 30 seconds are realistic for a full channel scan. A reduction in the number of required stations would be equal to a "selective scan" on a limited number of channels. This additionally would reduce the power consumption of the DECT "sensor" and extend the battery life time of a mobile device.

The physical characteristics of DECT as introduced in Table I also support the suitability of DECT for localization. Lower frequency and higher effective radiated power in a dedicated frequency band ensures larger coverage and excludes other users from the frequency band. WLAN at 2.4 GHz has to share the industrial, scientific and medical (ISM) bands with other technologies. The longer range also means that DECT base stations can be visible further from houses than WLAN access points while providing finer grained locations than GSM signals.

Additionally, DECT outperforms WLAN systems in terms of power consumption. This suggests that for mere localization tasks, using DECT alone is a meaningful approach to save energy resources of end user devices. We have shown that DECT performed comparably to WLAN in most situations and outperformed WLAN localization in some scenarios.

We have conducted experiments in the US, UK and Germany. As discussed, there have been issues with the availability of DECT in the US. However we think that the recent standardization will support similar results as have been obtained in Europe.

VI. Outlook and Future Work

We intend to use more advanced localization algorithms on the available data sets to allow more precise positioning. The high number of DECT basestations visible in each fingerprint is not explicitly used is our current implementation and could potentially improve accuracy. We are also planning to use a particle filter in order to incorporate motion information captured by the accelerometers that are present on many recent mobile devices.

We will also develop a system that allows seamless positioning and localization in combined indoor/outdoor scenarios, for instance leaving home and commuting to work by foot, car or public transport all the way to the desk in the office. We assume that seamless and continuous positioning is feasible using a combined GPS, WLAN and DECT approach. Especially of interest will be the inclusion of movement models.

We recorded DECT and WLAN fingerprints in a large portion of a rural town. We want to extend this similarly to freely available WLAN maps such as Wigle.net, to allow other researchers to test their own algorithms, and users to develop their own applications in combination with other open data bases such as OpenStreetMap.org.

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