

FINDR: Low-Cost Indoor Positioning Using FM Radio

FINDR: Low-Cost Indoor Positioning Using FM Radio

(Invited Paper)

Andrei Papliatseyeu, Venet Osmani, Oscar Mayora

{apapliatseyeu, vosmani, omayora} @ create-net.org

Multimedia Interaction and Smart Environments (MISE),
CREATE-NET,
Via alla Cascata 56/D, Povo, Trento, 38123, Italy.

Abstract 3

Introduction 4

Related work 5

 Wireless positioning techniques 5

 Proximity-based 6

 Time-based 6

 Signal strength-based 7

 Legal considerations for short-range FM transmitters 8

FM positioning 9

 Our approach 9

 Relative position-dependent features 9

 Distinguishing beacons 10

 Experimental setup 10

 Experimental procedure 12

Results 14

 RSSI dependency on distance 14

 2D positioning 16

 Comparison with Wi-Fi 17

 RSSI stability over time 19

Conclusion 20

References 22

Abstract

This paper presents an indoor positioning system based on FM radio. The system is built upon commercially available, short-range FM transmitters. To the best of our knowledge, this is the first experimental study of FM performance for indoor localisation. FM radio possesses a number of features, which make it distinct from other localisation technologies. Despite the low cost and off-the-shelf components, our FM positioning system reaches a high performance, comparable to other positioning technologies, such as Wi-Fi for example. Our experiments have yielded a median accuracy of 1.0 m and in 95% of cases the error is below 5 m.

INTRODUCTION

Location awareness is an important requirement for many modern applications, spanning from mobile maps and geotagging up to various indoor systems. Applications of indoor localisation can also be found in the realm of social sciences, allowing inference of human relationships, for example colleagues that spend time in the same office, through analysis of sub-room mobility patterns (Eagle and Pentland, 2006). In health care, indoor localisation can be used to aid elderly locate misplaced objects (such as their mobile phone), or deliver location dependent reminders. These applications can be enabled by a low-cost, sub room location solution.

The Global Positioning System (GPS) is most widely used for location sensing, but it is limited to outdoors-only applications. A body of research has addressed indoor positioning using different technologies, like ultrasound and infrared beacons, Wi-Fi and GSM networks, or other types of radios (Hightower and Borriello, 2001). Most of these systems are limited in terms of expensive/custom hardware, laborious deployment or low performance.

FM has a number of advantages over other positioning technologies, like Wi-Fi. Firstly, although Wi-Fi infrastructure is readily available in office buildings, the installation of a localisation system in domestic environment requires additional hardware. Indeed, multiple WiFi access points would be required to provide positioning, since a single access point or a wireless router, typically found at home, is not sufficient. In this case, FM is a cheaper alternative to the deployment of multiple Wi-Fi access points per apartment. FM transmitters are available from many consumer electronics shops; the client device can be represented by a cellphone with an embedded FM receiver. Secondly, FM radio can be safely used in specialised environments, such as hospitals, whereas GSM, Wi-Fi or Bluetooth devices must remain switched off due to

potential interference with medical devices. Finally, FM is highly power-effective: an average FM receiver consumes about 15 mW, compared to almost 300 mW of Wi-Fi (in receiving mode) (“TDA7088”, 1996; “BCM4326”, 2006).

Our paper explores the applicability of short-range FM radio transmitters for indoor positioning. We have installed our FINDR (FM INDoOR) positioning system in our lab and this paper presents performance evaluation results of the system, as well as an overview of particular properties of FM radio with respect to localisation. A same-environment comparison with a Wi-Fi-based positioning system is also provided.

The paper is organized as follows. The section that follows provides an overview of the related work. The next section introduces our approach and our experimental testbed. The following two sections present results pertaining to performance evaluation of FINDR and describe the possible application scenarios of the system. Lastly, the final section reiterates the main points and draws the conclusions.

RELATED WORK

Wireless positioning techniques

In the last decade, a large body of research has been dedicated to the development of location-aware systems. Indoors positioning systems rely on several types of sensors: ultrasound (Fox et al., 2003; Priyantha et al., 2001), infrared (IR) (Fox et al., 2003; Liao et al., 2003), digital compass (Priyantha et al., 2001), RFID (Hightower and Borriello, 2004), and various kinds of radio: Wi-Fi (Bahl et al., 2000; Youssef et al., 2003), GSM (Varshavsky et al., 2007), Bluetooth (Kotanen et al., 2003), domestic powerline (Patel et al., 2006; Stuntebeck et al., 2008), and others (Bulusu et al., 2000; Krumm et al., 2003). Such systems usually rely on one or a number

of the following criteria: user proximity to some fixed beacons, time of signal propagation, and received signal strength. In the sections that follow we briefly describe each of these approaches to localisation.

Proximity-based

Given an environment with a number of beacons with known positions, the algorithm assumes that the user's position is that of the nearest beacon. Due to its simplicity, the method is widely adapted by the systems using custom radio beacons (Bulusu et al., 2000), as well as Bluetooth (Hallberg et al., 2003), IR (Fox et al., 2003) and GSM base stations (Laasonen et al., 2004; LaMarca et al., 2005). Unfortunately, the accuracy of such systems is low and depends on the density and the number of installed beacons.

Time-based

Time-based methods use information about signal propagation time between the mobile device and beacons with known positions, in order to estimate the position of the mobile user. The most prominent example of this class of methods is GPS. Using the signals from a set of GPS satellites, a basic GPS receiver is able to compute its position with the accuracy of about 8 m ("GPS Performance", 2008, p. 22). However, GPS has long start-up times (up to a few minutes) and does not work indoors and in dense urban areas, which limits GPS's applicability for ubiquitous location-based services. Ultrasonic localisation systems, like Cricket (Priyantha et al., 2001), also rely on the travel time of an ultrasound pulse. While providing a good accuracy, time-based systems usually require custom hardware and expensive installation.

Signal strength-based

There are two general positioning approaches that use Received Signal Strength Indication (RSSI), namely, propagation modelling and fingerprinting. The first approach attempts to build a model of the signal propagation in the space in order to identify the distance between the user and beacons. The fingerprinting approach, in turn, relies on a database associating RSSI measurements with corresponding coordinates and then uses statistics and machine learning algorithms in order to recognize user position among those learned during the training phase. RSSI-based methods are the most powerful, as they can provide rather high accuracy with a few beacons.

One of the pioneering projects in RSSI-based positioning was RADAR (Bahl and Padmanabhan, 2000). The authors applied both propagation modelling and fingerprinting within a Wi-Fi network, and, with some enhancements, the system error was as low as 2 m (Bahl et al., 2000). With more advanced probabilistic methods, the median error of a Wi-Fi based system can reach 1.2–1.45 m (Roos et al., 2002; Youssef et al., 2003). RSSI fingerprinting has also been successfully applied for indoor localisation using GSM base stations. Varshavsky et al. (2007) employed so-called wide fingerprints, which included RSSIs of up to 35 GSM channels, and thus managed to achieve a Wi-Fi-like median positioning accuracy. However, the topology of a GSM network can be changed at any time by the network operator, thus requiring system recalibration. Patel et al. (2006) proposed a more reliable approach for indoors positioning. In their system, two beacons were injecting high-frequency signals into domestic powerline. These signals could then be detected by a specialised receiver and associated with the user's location. An extended, wideband version of the system achieved a 90% accurate room recognition (Stuntebeck et al.,

2008). Despite the easy installation, the system requires specialised hardware with limited availability.

To the best of our knowledge, there is only one work dedicated to positioning with FM radio. Krumm et al. (2003) described their experiments on using prototype hand watch with an embedded FM radio, to localise using commercial FM broadcasting stations. The authors applied a Bayesian classifier to distinguish six areas of Seattle, based on RSSI ranking of the local FM stations. In the best case, the recognition accuracy was 82%. Although the paper does not provide any information about error distances, the system accuracy can be estimated as hundreds of meters to kilometres, which renders it impracticable for indoor environments. Our system, instead, is based on readily available hardware and is particularly suitable for indoor use.

Regulatory considerations for short-range FM transmitters

In most countries the usage of radio-frequency transmitters is governed by special regulations. While Wi-Fi is widely adopted and generally does not require licensing, different rules may apply to short-range FM transmitters, depending on local laws.

In EU countries, the usage of short-range FM transmitters operating within 88–108 Mhz frequency band is governed by European Commission Decision 2009/381/EC (“2009/381/EC”, 2009). According to it, the FM transmitters with effective radiated power of less than 50 nW do not require licensing. Complying devices bear the “CE” certification mark. In US, all radio devices must comply with the FCC Part 15 regulations. In particular, a short-range FM transmitter must produce less than 250 mV field strength in an average receiver placed 3 m away (FCC Part 15, section 15.239b). Certified devices have an explicit statement of their conformity to the FCC Part 15 regulations. For home-build transmitters, there is an additional limit of no more than five devices per person (FCC Part 15, section 15.23a).

FM POSITIONING

Our approach

The FINDR positioning system employs a set of short-range FM transmitters as wireless beacons and a programmable radio on the client device. Most of the beacon-based positioning technologies have two general requirements: measuring of user-to-beacon relative position and the ability to distinguish different beacons. In the next two sections we identify possible solutions how FM radio can address these requirements.

Relative position-dependent features

The relative position of the user with regard to a beacon can be characterised by angle between directed antennas, signal propagation time and RSSI. For the FM positioning, we have identified three features that can be used as a measure of distance between the beacons and the user.

The first feature is RSSI, defined as the amplitude of the received radio-frequency signal. Most of the current FM receivers employ RSSI value internally, to enable auto-tuning capability.

When RSSI is not available, one can use the signal-to-noise ratio (SNR) of the demodulated signal. In this case, the beacon is set to transmit a known periodic signal (for example, a sine wave of 1kHz) and the receiver performs a fast Fourier transform (FFT) of the demodulated signal, calculating the intensities of different frequency bands. Then, the intensity of the band of interest is divided by the average intensity of the all bands, thus representing signal-to-noise ratio. A similar method was applied by Patel et al. (2006) to an amplitude-modulated (AM) signal. However, our experiments show that SNR of an FM signal is almost a step function, which considerably limits applicability of this approach to FM-based positioning (see “Results” section).

Distinguishing beacons

For a beacon-based positioning system it is crucial to distinguish current beacon from the others. The beacons can be identified either by their carrier frequencies or by the signals they transmit (e.g. coordinates, ID, name, etc).

Unfortunately, due to the properties of FM, it is impossible to use the same frequency for all beacons. Due to the so-called “capture effect”, when a number of stations transmit on the same (or close by) frequency, the signal from the strongest one will dominate the others, while the weaker signals get attenuated (Leentvaar and Flint, 1976). Therefore, in our experiments we had to tune each transmitter to a different frequency and switch between them at the receiver side. Despite this, no special network planning is required for larger-scale deployments to avoid beacons interference, as any distant interfering beacons will not be observed due to the capture effect.

Experimental setup

The FINDR was evaluated with empirical measurements in the Multimedia, Interaction and Smart Environments lab of CREATE-NET (MISE, 2009). The room dimensions were 12 x 6 m, and the room contained ordinary office furnishing. Figure 1 presents the layout of the room. A grid of 1 x 1 m cells was created for testing, and measurements were carried out in all accessible points of the grid (totally 45 points).

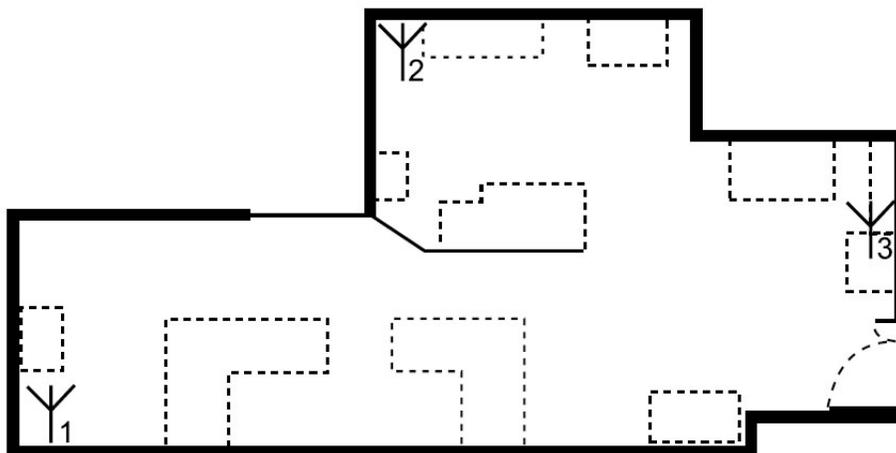


Figure 1. Floorplan of the measurement area. The antennas mark the positions of the three transmitters and the dashed lines mark room furniture.

The client device used in preliminary tests was a Nokia N800 Internet Tablet. The N800 is based on an ARM processor and features a built-in FM receiver. The N800 is running an open, Linux-based operating system, so developing low-level custom applications for the device is relatively easy. The prototype locating software was programmed in Python and used the PyFMRadio-library to tune the FM-receiver to each of the transmitter's frequency one after another and read the signal strength from the FM-receiver hardware. The signal strength was reported on a 16-step scale (normalized to range 0...1) and was measured 300 times in a row for each frequency, with about 0.01 second between the measurements. The standard N800 headset was used as an antenna.

For the evaluation of positioning accuracy of FM and Wi-Fi we used an HTC Artemis smartphone, which features a set of built-in wireless modules, including GSM, Wi-Fi, Bluetooth, and an FM tuner. The data collecting software was written in C# using .NET Compact Framework. The FM module was controlled through the routines implemented in a low-level C++ library. The FM signal strength was reported as integer values in range from 0 to 45. For

each location, one hundred of FM and thirty Wi-Fi RSSI samples have been recorded. The standard headset was used as an FM antenna.

The transmitters used were König MP3 players (“König MP3 player”, 2009), which feature a built-in FM-transmitter (Figure 2). To increase the range of the transmitters, a 1.8-meter audio cable was connected to the player's audio output to act as an antenna. Initially, the whole FM band was scanned and manually checked for frequencies with little interference from local FM-radio stations. The transmitters were then tuned to these frequencies. To avoid the effect of battery degradation, the transmitters were powered by USB power adapters.



Figure 2. MP3 player with an embedded FM transmitter, connected to power adapter. (The antenna is not attached.)

Experimental procedure

In general, the experiment has been planned and performed as follows.

First of all, we conducted a number of tests to determine which of the FM signal features discussed above demonstrate the best dependency on the distance between the transmitter and receiver. A suitable function should have been monotone and with distinct values at different distances. As a result, the signal strength (RSSI) was chosen.

At the next stage, the data acquisition has been performed. For each point of the grid (x, y) , a number of RSSI measurements $RSSI(x, y)$ were recorded from the FM and Wi-Fi beacons. These measurements, along with the corresponding coordinates formed a dataset of location fingerprints. Finally, the performance of the two positioning technologies was evaluated using leave-one-out approach and K-Nearest Neighbour (kNN) classifier (see pseudocode in Figure 3). The evaluation results and further details are presented in the next section.

```

//Dxy is the domain of possible coordinate values
errorDistances = {} //the list of absolute error distances
for each (x, y) ∈ Dxy do {
    testSet = { input: RSSI(x, y), output: (x, y) }
    trainSet = { input: RSSI(i, j), output: (i, j) }, for (i, j) ∈ Dxy, where i ≠ x and j ≠ y

    //Estimating coordinates by RSSI fingerprint, using kNN classifier
    classifierResult = kNN(trainSet.input, trainSet.output, testSet.input)

    errorDistance = euclidianDistanceBetweenPoints(classifierResult, testSet.output)
    errorDistances.add(errorDistance )
}

//Given the error distances, calculate and plot the error cumulative distribution function (CDF)
plotCDF(errorDistances);

```

Figure 3. The pseudocode of performance evaluation algorithm.

RESULTS

RSSI dependency on distance

In order to estimate the feasibility of the FM positioning, we first carried out a test to see which of the position-dependent features discussed above are more suitable for positioning.

The RSSI dependence on the distance from the transmitter is presented in Figure 4. To avoid any interference from the testbed's furniture, this test was performed outdoors. The graph is relatively smooth and monotone starting from 0.5 m, and proves RSSI to be a good feature for positioning. Eventual plateau-looking areas can be explained by the limited number of RSSI levels recognized by our receiver.

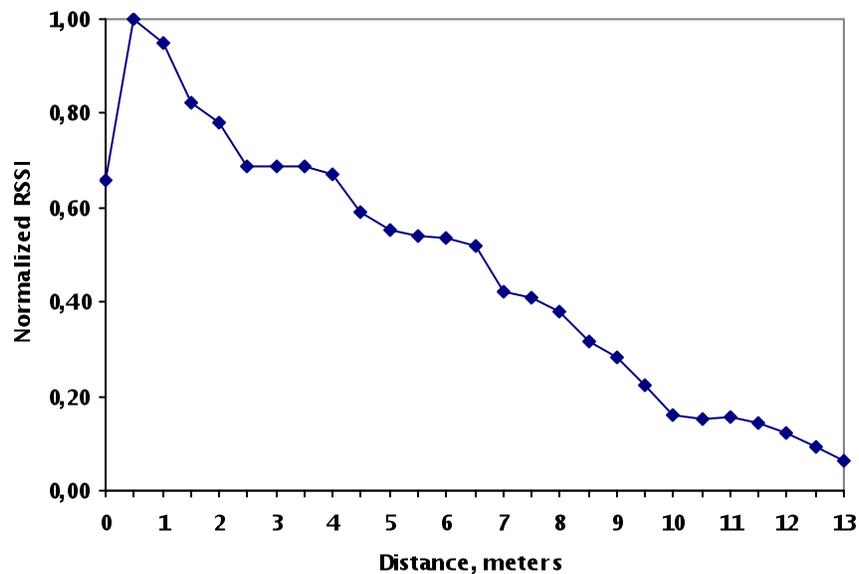


Figure 4. RSSI dependence on distance (Nokia).

Figure 5 corresponds to the indoors measurements and shows the RSSI from each of three transmitters while the user was moving from Transmitter 1 to Transmitter 3 (as of floorplan in Figure 1). The dependencies are not very smooth, which is caused by the distortions from the furniture and multipath propagation. Nevertheless, the general trends are clearly observable.

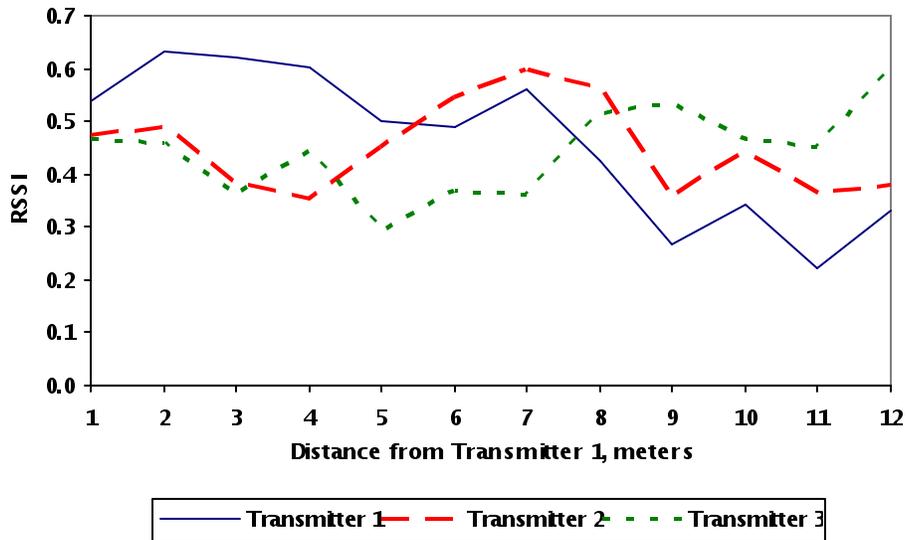


Figure 5. RSSI variation while moving from Transmitter 1 to Transmitter 3, with Transmitter 2 placed between them (Nokia).

For the $RSSI_{SNR}$ method, the transmitter was set to broadcast a continuous dual tone multi-frequency (DTMF) signal for digit “1” (1209 Hz and 697 Hz). At the receiver side, the audio signal from an FM radio was sampled by a laptop sound card at 8 kHz sampling frequency and transformed to the frequency domain using 1024-band FFT. For each point, 32 spectra were recorded and then averaged. $RSSI_{SNR}$ was then calculated as follows:

$$RSSI_{SNR} = \frac{band_{697Hz} + band_{1209Hz}}{mean(all_bands)}$$

The experimental results exhibited no clear dependency of $RSSI_{SNR}$ from the distance to the transmitter (see Figure 6). In range from 0.5 m to 3.6 m the mean $RSSI_{SNR}$ value barely changed, between 3.6 m and 4.5 m it became unstable, and then rapidly degraded to the noise level. Such behaviour can be explained by the capture effect, which improves the post-detection SNR for non-linear modulations (such as FM) when the pre-detection SNR is above a certain threshold, “capture threshold”; below this threshold the SNR drops dramatically (Linnartz, J. P, 1993). In our case, the capture effect is complemented by the receiver noise-reduction circuitry

which automatically mutes the audio output if the received signal is too weak (“TDA7088”, 1996).

Thus, $RSSI_{SNR}$ dependency on the distance is almost a step function due to intrinsic properties of FM. Therefore, we did not consider $RSSI_{SNR}$ for further experiments.

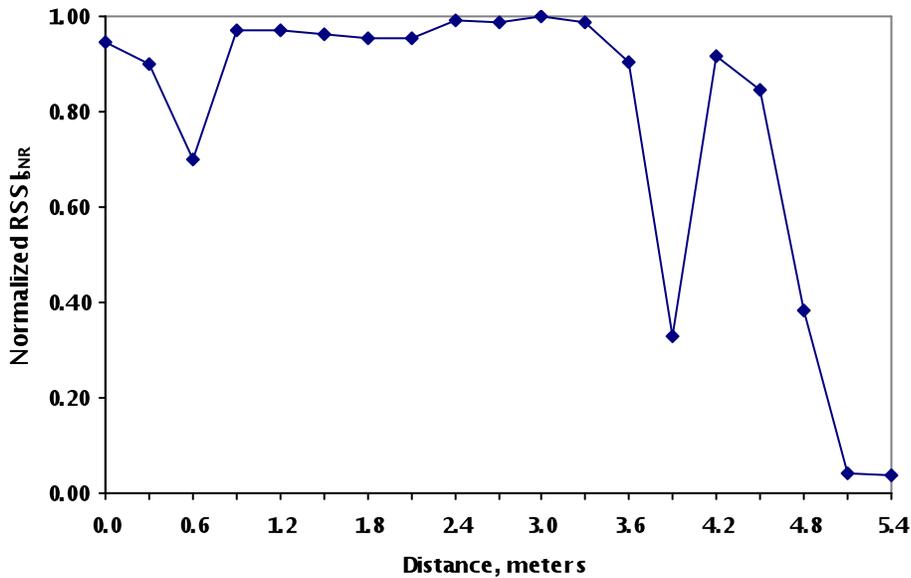


Figure 6. $RSSI_{SNR}$ dependence on distance (Nokia).

2D positioning

To estimate the FINDR accuracy in two-dimensional positioning, we have used a fingerprinting approach with leave-one-out validation, in which we sequentially selected one of the RSSI measurements and excluded all the measurements related to the same coordinates from the training set. The selected measurement was then used as test data. It should be noted however, that leave-one-out evaluation tends to worsen the actual positioning accuracy, as the classifier is unable to recognize the class it has not been trained on (that is, the error distance is always greater than zero) (Bahl and Padmanabhan, 2000).

For classification, a k -nearest neighbour (kNN) method was used (Mitchell, 1997). The kNN classifier evaluates the distance from the test RSSI sample to all the training RSSIs, and selects the labels (classes) of the k nearest training RSSI samples. From these k labels, the prevailing one is returned as the classification result. For our task, we employed the Euclidean distance measure. The optimal value of k ($k = 9$) was selected by leave-one-out validation.

The error distance distribution is shown in Figure 7. The baseline performance is represented by a random classifier, which returns random location disregarding the input RSSI values. The median accuracy is about 1.0 m, falling to about 5.0 m at 95% confidence level. The long tail of the distribution is caused by a single distant outlier.

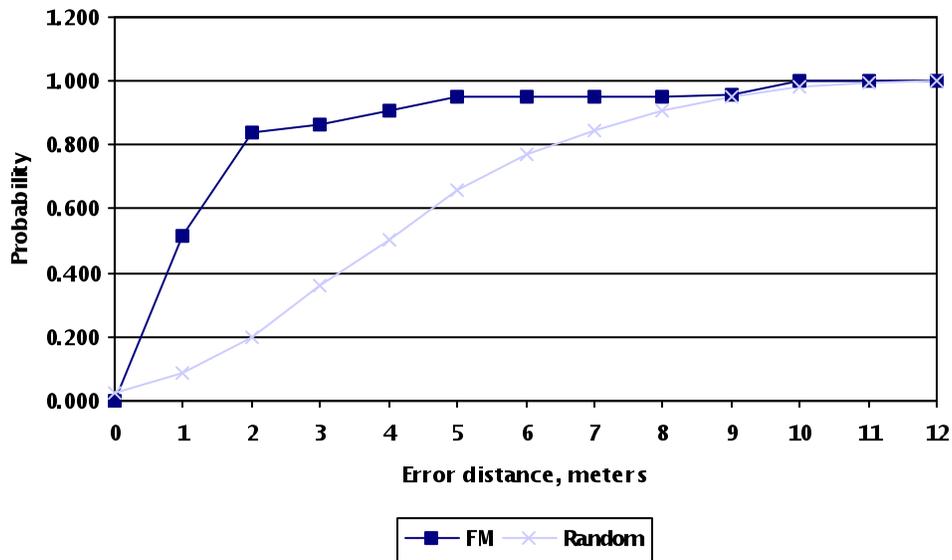


Figure 7. Error distributions for two-dimensional positioning (HTC).

Comparison with Wi-Fi

Wi-Fi (IEEE 802.11) is currently de-facto standard for indoor positioning, used in many commercial systems, such as Ekahau and Skyhook (“Ekahau RTLS”, 2009; “Skyhook”, 2009).

In order to prove the viability of the FM positioning, we compared it with the Wi-Fi-based approach.

The data has been collected simultaneously for FM and Wi-Fi, in the same environment, with the same device (HTC Artemis). For each of 46 locations, we have recorded 100 FM and 30 Wi-Fi signal-strength samples. The resulting dataset contained data from 3 FM transmitters (as depicted in Figure 1) and 19 Wi-Fi access points, with unknown locations. To make the comparison fair, we evaluated the positioning accuracy for all the possible combinations of 3 Wi-Fi access points out of 19. The set with the best median accuracy was then used for comparison. The evaluation method was the same as the one described in previous section.

Due to the firmware limitations, the device reported Wi-Fi RSSI data in a rather coarse manner: there were only 6 different RSSI values (from -90 dB to -50 dB with step of 10 dB, corresponding to “Very low” and “Excellent” extreme signal strengths, while 0 corresponded to “No signal”). In this regard, to make the comparison fair, we converted the original FM RSSI values (integers from 0 to 45) to 6-level range, as of Table 1. This expectably worsens the performance of FM (cf. Figure 7 and Figure 8), but provides an insight into relative performance of FM and Wi-Fi positioning.

Table 1. FM RSSI level conversion

Original FM RSSI	6-level FM RSSI	Wi-Fi RSSI
40 to 45	-50	Excellent
30 to 39	-60	Very good
20 to 29	-70	Good
10 to 19	-80	Low
1 to 9	-90	Very low
0	0	No signal

The comparison results are presented in Figure 8. As evidenced from the figure, our FM and Wi-Fi positioning systems exhibit similar performance in terms of accuracy.

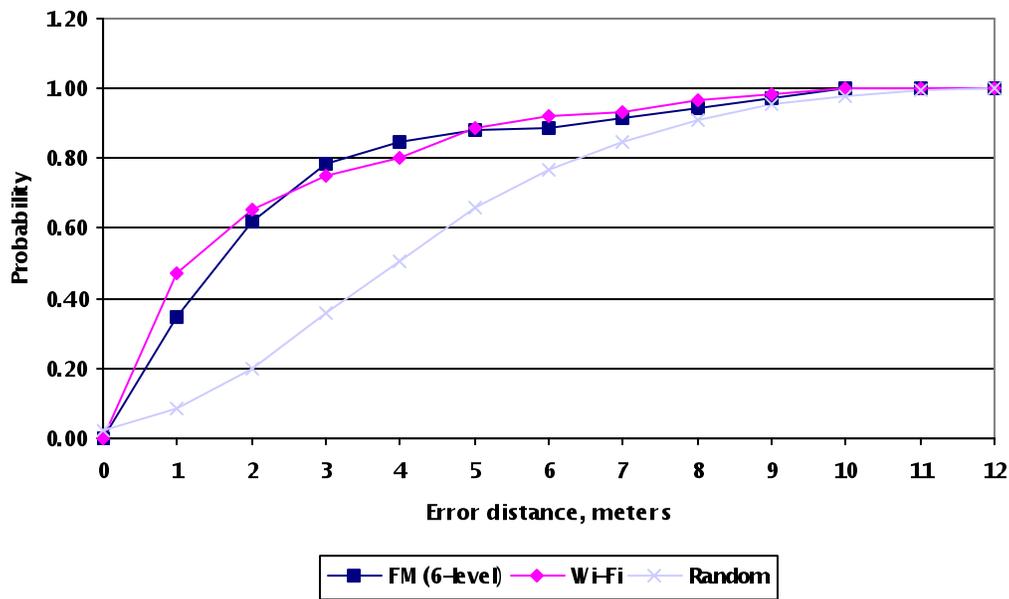


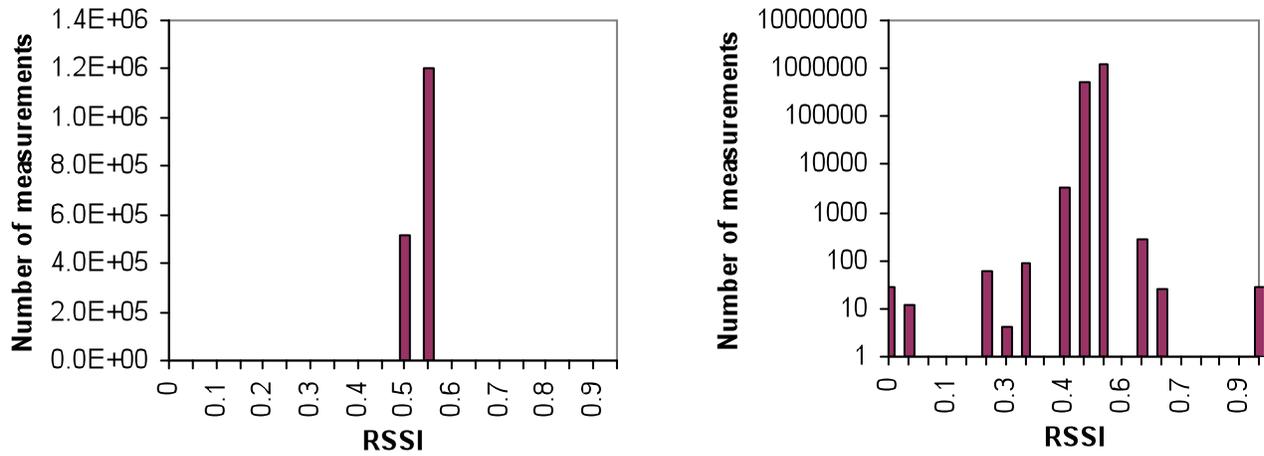
Figure 8. Comparison of Wi-Fi and FM error distributions (HTC).

Given the other characteristics of FM, such as price (an FM transmitter is up to 10 times cheaper than a Wi-Fi access point), power effectiveness (15 mW of FM radio compared to 300 mW of Wi-Fi), safety in specific environments (an FM receiver is not found to interfere with medical or other sensitive equipment, unlike Wi-Fi devices) and availability (FM tuners are built into various mobile devices like cellphones or PDAs), we can conclude that the FM positioning is a viable alternative to Wi-Fi-based location systems.

RSSI stability over time

For a fingerprinting-based system, it is very important that the values measured during calibration phase do not drift over time. Otherwise, the system accuracy may diminish significantly, and the system will require recalibration. It has been demonstrated, that many current fingerprinting-based systems are affected by the signal stability problems (Kaemarungsi, 2006; Stuntebeck et al., 2008).

In order to estimate the stability of the FM signal strength in FINDR, we placed a transmitter 4 meters apart from the receiver and left it recording the RSSI over the weekend. However, in four hours the device ran out of memory and only 1.7 million samples have been recorded. Their mean value was 0.57975 and the variance was 0.00097.



a) Normal scale

b) Logarithmic scale

Figure 9. RSSI distribution for 4-hour long measurements (Nokia).

The RSSI distribution in Figure 9 proves the FM RSSI to be rather stable. The two peaks are different by one quantization step only. There are about 4000 outliers, which constitute only about 30 seconds of the whole 4-hour dataset. Although the readings are limited, the obtained results are a good indication that the system will maintain high positioning accuracy for longer period, without frequent recalibration needed to address RSSI drift.

CONCLUSION

This paper presented the FINDR, an indoor positioning system based on FM radio technology. The system is a low-cost solution that does not require any specialised hardware. FM transmitters, used as beacons, are easily available in the most of electronics shops. Virtually any cellphone or PDA with an embedded FM tuner can be used as a client device. FM receiver is by

an order of magnitude more power-efficient than Wi-Fi. The results of the system evaluation show a median accuracy of about 1.0 m and 5.0 m at 95% confidence level. A comparison with a Wi-Fi positioning system deployed in the same environment showed that FM and Wi-Fi have a similar performance.

As a positioning technology, FM has a number of advantages over Wi-Fi. FM transmitters are easily available from consumer electronic shops and are 3 to 10 times cheaper than Wi-Fi access points. Unlike Wi-Fi modules, an FM receiver is a zero-emission device, which makes it safe for use in sensitive environments where Wi-Fi is restricted. Moreover, a typical FM receiver consumes only about 15 mW of battery power, one twentieth of Wi-Fi consumption (“TDA7088”, 1996; “BCM4326”, 2006). Although Wi-Fi infrastructure is readily available in many office buildings, it is uncommon to have more than one access point at home, which is insufficient to provide localisation. Given these considerations, FM positioning is a more cost-effective alternative for positioning than Wi-Fi.

ACKNOWLEDGEMENTS

The research was funded by the Autonomous Province of Trento, Call for proposal Major Projects 2006 (project ACube).

References

- Bahl, P., Padmanabhan, V., and Balachandran, A. (2000). *Enhancements to the RADAR User Location and Tracking System*. Technical Report MSR-TR-2000-12, Microsoft Research, Redmond, WA, USA.
- Bahl, P. and Padmanabhan, V. N. (2000). *RADAR: an in-building RF-based user location and tracking system*. In Proceedings of 9th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2000), volume 2, pages 775–784.
- BCM4326 Datasheet*. (2006). Retrieved July 14, 2009, from <http://pdf1.alldatasheet.com/datasheet-pdf/view/175096/BOARDCOM/BCM4326.html>
- Bulusu, N., Heidemann, J., and Estrin, D. (2000). *GPS-less low-cost outdoor localization for very small devices*. Personal Communications, IEEE, 7(5):28–34.
- Eagle, N. and Pentland, A. (2006). *Reality mining: sensing complex social systems*. Personal and Ubiquitous Computing, 10(4):255–268.
- Ekahau Real-Time Location System (RTLS) Overview*. (2009) Retrieved July 26, 2009, from <http://www.ekahau.com/products/real-time-location-system/overview.html>
- Fox, D., Hightower, J., Liao, L., Schulz, D., and Borriello, G. (2003). *Bayesian Filtering for Location Estimation*. IEEE Pervasive Computing. Hallberg, J., Nilsson, M., and Synnes, K. (2003). Positioning with Bluetooth. In Proceedings of 10th International Conference on Telecommunications (ICT 2003), volume 2, pages 954–958.
- GPS SPS Performance Standard*. (2008). Retrieved on July 14, 2009, from <http://www.navcen.uscg.gov/gps/geninfo/2008SPSPerformanceStandardFINAL.pdf>.
- Hightower, J. and Borriello, G. (2001). *Location systems for ubiquitous computing*. Computer, 34(8):57–66.

- Hightower, J. and Borriello, G. (2004). *Particle Filters for Location Estimation in Ubiquitous Computing: A Case Study*. In Proceedings of UbiComp 2004, pages 88–106. Springer.
- Honjo, K. and Simpson, Jr., D. L. (1995). *Stereo FM receiver, noise control circuit therefor*. US Patent 5432854.
- Kaemarungsi, K. (2006). *Distribution of WLAN Received Signal Strength Indication for Indoor Location Determination*. In Proceedings of the 1st International Symposium on Wireless Pervasive Computing, pages 1–6.
- König MP3 player with FM transmitter*. (2009) Retrieved July 14, 2009, from <http://www.koniggaming.com/mp3withfmtransmitter.html>
- Kotanen, A., Hännikäinen, M., Leppäkoski, H., and Hämäläinen, T. D. (2003). *Experiments on local positioning with Bluetooth*. In Proceedings of the International Conference on Information Technology: Coding and Computing (ITCC'03), pages 297–303.
- Krumm, J., Cermak, G., and Horvitz, E. (2003). *RightSPOT: A Novel Sense of Location for a Smart Personal Object*. In Dey, A. K., Schmidt, A., and McCarthy, J. F., editors, Proceedings of UbiComp 2003, volume 2864 of Lecture Notes in Computer Science, pages 36–43, Seattle, WA, USA. Springer Berlin / Heidelberg.
- Laasonen, K., Raento, M., and Toivonen, H. (2004). *Adaptive On-Device Location Recognition*. In Proceedings of Pervasive 2004, volume 3001 of Lecture Notes in Computer Science, pages 287–304. Springer.
- LaMarca, A., Chawathe, Y., Consolvo, S., Hightower, J., Smith, I., Scott, J., Sohn, T., Howard, J., Hughes, J., Potter, F., Tabert, J., Poweldge, P., Borriello, G., and Schilit, B. (2005). *Place Lab: Device Positioning Using Radio Beacons in the Wild*. In Gellersen, H. W.,

- Want, R., and Schmidt, A., editors, Proceedings of Pervasive 2005, volume 3468 of Lecture Notes in Computer Science, pages 116–133, Munich, Germany. Springer.
- Leentvaar, K. and Flint, J. H. (1976). *The capture effect in FM receivers*. IEEE Transactions on Communications, 24:531–539.
- Liao, L., Fox, D., Hightower, J., Kautz, H., and Schulz, D. (2003). *Voronoi Tracking: Location Estimation Using Sparse and Noisy Sensor Data*. In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'03).
- Linnartz, J. P. (1993). *Analog Transmission over Fading Channels*. Retrieved July 14, 2009, from <http://www.wirelesscommunication.nl/reference/pdfandpds/analog.pdf>
- MISE: Multimedia, Interactions and Smart Environments Group, Create-Net. (2009). Retrieved July 26, 2009, from <http://www.create-net.org/mise>
- Mitchell, T. (1997). *Machine Learning*. ISBN 0070428077. McGraw Hill.
- Patel, S. N., Truong, K. N., and Abowd, G. D. (2006). *PowerLine Positioning: A Practical Sub-Room-Level Indoor Location System for Domestic Use*. In Dourish, P. and Friday, A., editors, Proceedings of UbiComp 2006, volume 4206 of Lecture Notes in Computer Science, pages 441–458, Orange County, CA, USA. Springer Berlin / Heidelberg.
- Priyantha, N. B., Miu, A. K. L., Balakrishnan, H., and Teller, S. (2001). *The cricket compass for context-aware mobile applications*. In Proceedings of the 7th Annual International Conference on Mobile Computing and Networking, pages 1–14. ACM Press New York, NY, USA.
- Roos, T., Myllymäki, P., Tirri, H., Misikangas, P., and Sievänen, J. (2002). *A Probabilistic Approach to WLAN User Location Estimation*. International Journal of Wireless Information Networks, 9(3):155–164.

Skyhook Wireless. (2009). Retrieved July 26, 2009, from <http://www.skyhookwireless.com>

Stuntebeck, E. P., Patel, S. N., Robertson, T., Reynolds, M. S., and Abowd, G. D. (2008).

Wideband powerline positioning for indoor localization. In Proceedings of UbiComp 2008.

TDA7088 Datasheet. (1996, May 14). Retrieved July 14, 2009, from

<http://pdf1.alldatasheet.com/datasheet-pdf/view/19431/PHILIPS/TDA7088.html>

Varshavsky, A., de Lara, E., Hightower, J., LaMarca, A., and Otsason, V. (2007). *GSM indoor localization*. *Pervasive and Mobile Computing*, 3(6):698–720.

Youssef, M. A., Agrawala, A., and Shankar, A. U. (2003). *WLAN location determination via clustering and probability distributions*. In Proceedings of the 1st IEEE International Conference on Pervasive Computing and Communications (PerCom), pages 143–150.

European Commission Decision 2009/381/EC of 13 May 2009 amending Decision 2006/771/EC on harmonisation of the radio spectrum for use by short-range devices. (2009). *Official Journal of European Union*, 52(L119):32–39.

FCC Part 15 regulations. (2008). Retrieved 2009.09.20 from

http://www.fcc.gov/oet/info/rules/part15/PART15_07-10-08.pdf