New Insights into WiFi-based Device-free Localization

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Abstract
WiFi-based device-free localization is a main indoor localization technique that has attracted much attention recently. Typically, due to the complex wireless propagation in indoor environments, WiFi-based device-free localization requires a construction of a fingerprint map that captures the signal strength characteristics when the human is standing at certain locations in the area of interest. This fingerprint requires significant overhead in construction, and thus has been one of the major drawbacks of WiFi-based device-free localization. In this paper, we leverage an automated tool for fingerprint construction to study novel scenarios for WiFi-based device-free localization training and testing that are difficult to evaluate in a real environment. In particular, we examine the effect of changing the access points (AP) mounting location, AP technology upgrade, and outsider effect; on the accuracy of the localization system. Our analysis provides recommendations for better localization and provides insights for both researchers and practitioners.

Author Keywords
Wifi-based Localization, Device-free localization, Passive localization

ACM Classification Keywords
C.2.1 [Computer-Communication Networks]: Network Architecture and Design–Wireless communication; C.3 [Special-Purpose And Application-Based Systems]: Real-time and embedded systems; C.4 [Performance Of Systems]: Design studies

General Terms
Design, Experimentation, Measurement, Performance

Introduction
Recently, WiFi-based localization using fingerprinting has been an active research area due to the growth of wireless networking inside public and private places such as offices, malls, and hospitals. WiFi-based localization techniques use existing WLANs to provide accurate indoor localization without any additional hardware. It can be classified into two categories: device-based, e.g. [1, 14], and device-free techniques [9, 12, 13, 16]. A device-based system tracks a WiFi-enabled device (based on the received signal strength (RSS) at this device) while a device-free system tracks entities that do not carry any devices based on their effect on the RSS at the infrastructure devices. Typical applications for device-free systems include intrusion detection, smart homes, and sensor-less sensing.

Due to the complex propagation characteristics of WiFi signals in indoor environments [15], both categories require the use of a fingerprint or radio-map that stores the RSS characteristics at different locations in the area of interest (Figure 1). Traditional methods of radio-map construction require the use of manual calibration, which is a tedious and a time consuming process. Therefore, traditionally, radio map construction has been based on simple scenarios, usually involving one entity in a specific environment.

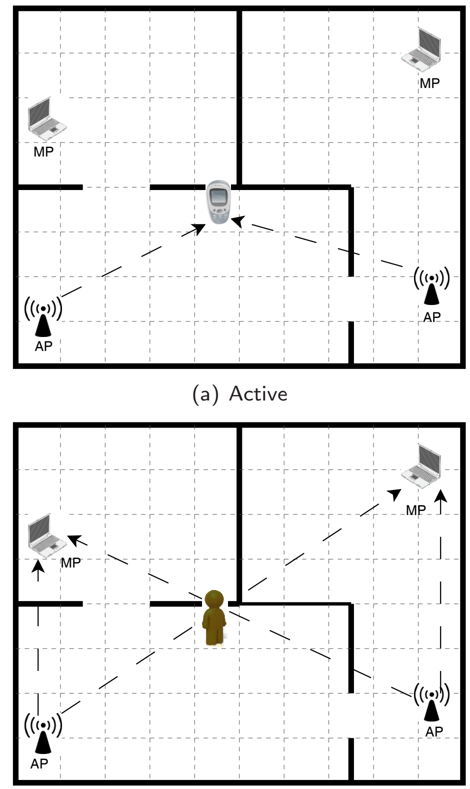

Figure 1: Difference between device-based and device-free radio-map construction.

Received signal strength gets affected by different system configurations, environmental parameters and human presence. This effect was pointed out in number of research papers e.g. [1, 6, 7] for device-based and [2, 8] for device-free localization. Analysing the RSS characteristics can help in easing the localization system design and improving the localization accuracy. In [6], the authors investigated the effect of user's presence, and user orientation on the RSS of a device-based system. They also studied the effect of having multiple APs and the relation between their RSS. In [7], they further investigated other parameters affecting the RSS such as the effect of the hardware used (e.g. WLAN cards from different vendors) and the technology used (IEEE 802.11b and 802.11g) for device-based localization. In [2], authors showed the effect of human movement on the variance of the received signal strength and in [8] authors investigated the effect of temporal and spatial changes in the environment on the accuracy of the device-free localization system and also the effect of the APs and MPs locations.

Different from those experiments we used AROMA [3, 4], a state-of-the art accurate system for the automatic generation of WiFi-based radio-maps, to analyze different what-if scenarios for device-free WiFi-based localization that is hard to evaluate in real environments. In particular, we study the effect of upgrading the hardware, APs mounting locations, and outsider effect on device-free localization. Through these scenarios, we show different factors affecting device-free localization that were not explored before, giving new insight into WiFi-based localization that can be leveraged by users, developers, and researchers.

The rest of the paper is organized as follows: We first give an overview of the AROMA system in the next section. Then we present our device free scenarios showing their effect on the accuracy. Finally, we conclude our work highlighting our recommendations for better localization.

The Aroma System

AROMA [3], [4] is a system that supports automatic radio map generation for both device-based and device-free localization systems. It is the first system to consider radio map generation for device-free systems and the first to consider human effects in the device-based systems. AROMA uses site-specific ray tracing, augmented with the uniform theory of diffraction (UTD) [10], to predict the RF propagation in a 3D site. It models the human body as a metallic cylinder [5]. Figure 2 shows the architecture of the AROMA system.

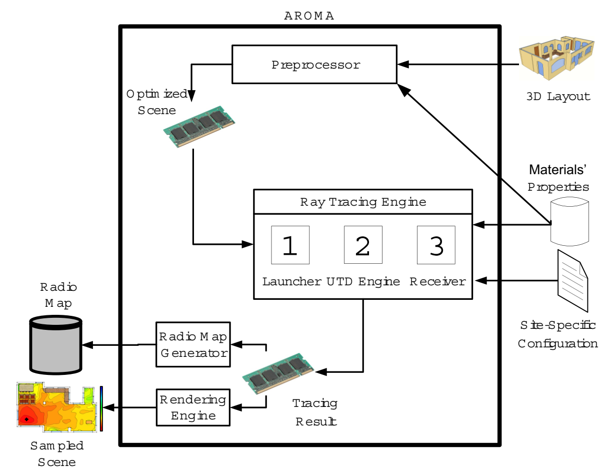

Figure 2: The AROMA system architecture.

AROMA takes a 3D model of the site of interest as an input and the site-specific configurations (the APs and receivers, e.g. laptops, locations and antenna configurations). It also comes with a built-in database of the values of the RF propagation properties of common building materials such as bricks and concrete. The user has the options of using this database or providing customized values using the user interface tool. The Ray Tracing Engine is the core of the AROMA system and is composed of three modules: the Ray Launcher, the UTD Engine, and the Ray Receiver. The Ray Launcher is responsible for emitting electromagnetic waves from APs [11]. Ray tubes propagate on the complex indoor environment experiencing reflection, transmission, or diffraction causing multipath fading. Rays are traced up to a user-defined depth; each time the ray makes an interaction with the environment, its depth is incremented. The tracing of a ray ends if the depth reaches the maximum user-defined value or the power associated with the ray decreases below a defined minimum value. The UTD Engine handles the changes in the electric field associated with the ray tubes resulting from their interactions with the environment. These changes are modeled with Geometric Optics (GO) augmented with the Uniform Theory of Diffraction (UTD). The Ray Receiver finds the contribution of each ray to the final RSS at the receivers, using the reception sphere model [11]. Different optimization techniques are used for efficient computations.

New Device-Free Scenarios

In this section, we focus on different device-free scenarios, where entities are tracked without carrying any device based on their effect on the RSS at the infrastructure devices. In particular, we study the following scenarios: effect of the devices mounting locations, upgrading the APs hardware (changing the operation frequency), and outside-entities effect. We end the section with a summary of our findings. We start by describing the experimental testbed and evaluation metrics.

Experimental Testbed and metrics

We used a 3D model of a typical apartment with an area of $700 ft^2 (66\ m^2)$. The environment is composed of different materials and contains some furniture. The radio-map locations are marked in Figure 3; they are forty four different locations covering the entire area of the apartment. The default APs configurations are summarized in Table 1. Note that the figure also contains the locations of the laptops (i.e. the monitoring points (MPs)) that are used as the infrastructure receivers. We have a total of four RSS streams each corresponding to an (AP, MP) pair. Location-zero in our results represents the RSS values with no human in the area of interest (silence event).

To study the effect of the different scenarios, we used two metrics: the change in the RSS and the change in the average localization error in meters when using a nearest neighborhood classifier, e.g. [1].

P_t	2 mW
Antenna gain (G_{max})	3 dBi
Frequency (f)	2.4 GHz.
Antenna type	Isotropic
Location	Wall-mounted ($1.5\ m.$)
Ceiling height	$2.7\ m.$

Table 1: Default APs configuration.

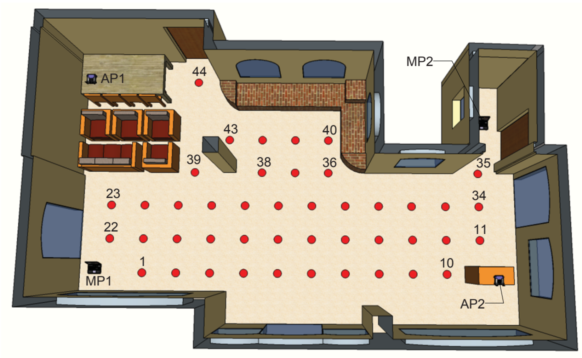

Figure 3: Device-free experiments layout. The figure highlights the locations of APs, MPs and radio map locations.

Exp. 1: AP Mounting Location
For this experiment, we investigate the effect of using wall-mounted vs. ceiling-mounted APs. The laptops (MPs) where placed at a height of 0.5 m. Figure 4 shows the effect for the four streams. The figure shows that the locations that are most affected are those that lie on the line-of-sight (LOS) between the AP and MP. For example, the most affected locations for the RSS stream from AP2 to MP1 (Figure 4) are locations $1-7$ because those are the locations where the entity cuts the LOS between the AP and MP as shown in Figure 5. Therefore, wall-mounted APs lead to a higher chance of the entity cutting the LOS, as compared to ceiling mounted APs, and hence lead to better accuracy as quantified in Table 2.

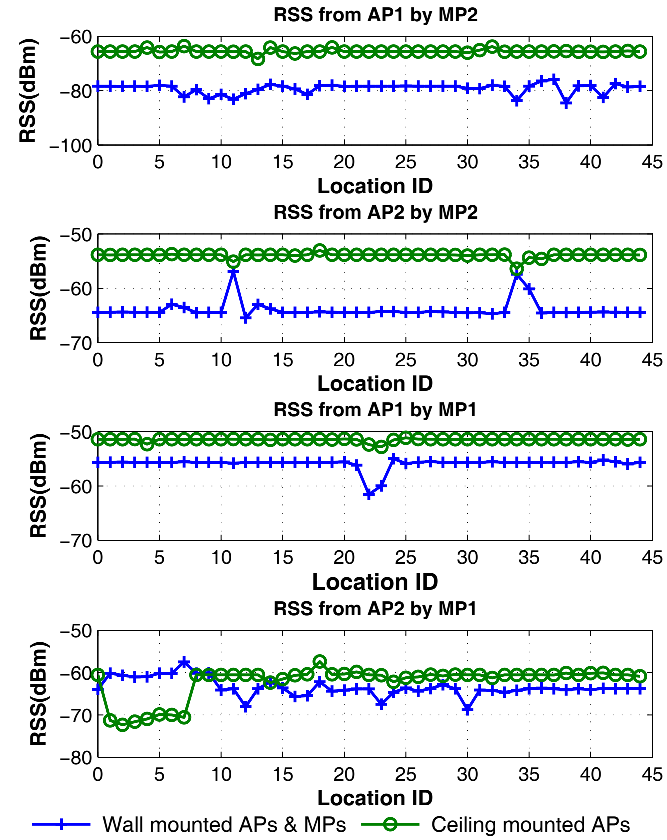

Figure 4: Effect of APs locations on the RSS from the four streams.

Experiment	Accuracy (m)
Base experiment (params. in Table 1)	1.44
Exp. 1: Ceiling-mounted APs	4.48
Exp. 2: Freq. 5.7 GHz.	1.77

Table 2: Average localization error in meters for the device-free scenario.

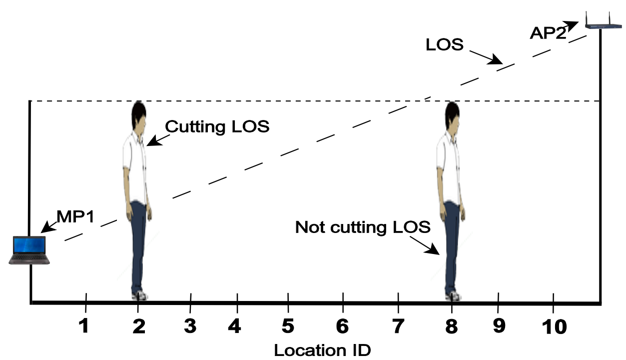

Figure 5: The human entity cuts the LOS between the AP and the MP only at locations 1-7, explaining the attenuation pattern in the RSS stream from AP2 to MP1 (Figure 4). AP2 was mounted to the ceiling and MP1 was at a height of $0.5m$.

Exp. 2: Updating the AP H/W (Changing the Operating Frequency)

In this section, we investigate the effect of switching the frequency from the 2.4 GHz band to the 5 GHz band. Figure 6 shows the effect on the RSS while Table 2 shows the effect on the localization accuracy.

As expected, increasing the frequency to 5.7 GHz leads to more attenuation and hence a lower RSS. This leads to decreased RSS variance between the different locations and hence reduced localization accuracy.

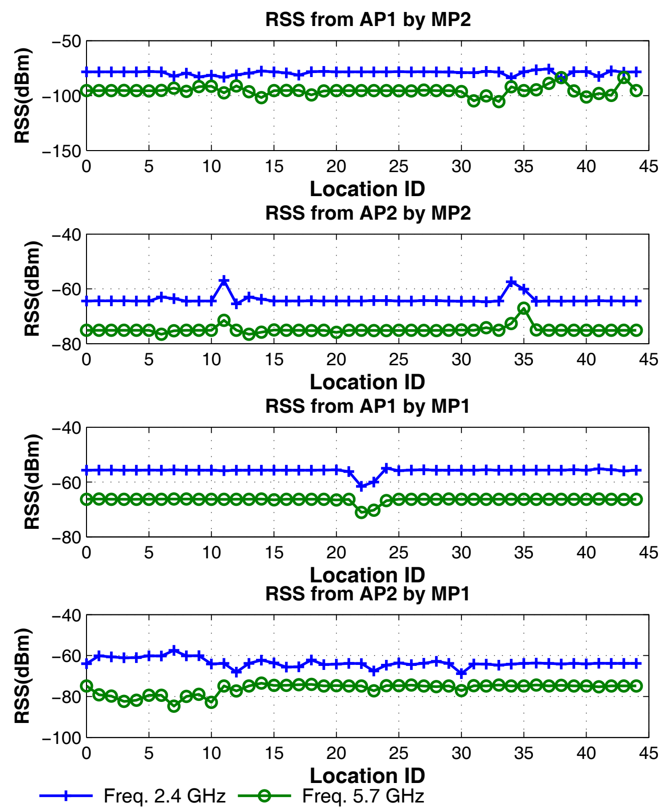

Figure 6: Effect of changing the frequency from the 2.4 GHz to 5.7 GHz on RSS.

Exp. 3: Outsiders Effect Scenario
Our target in this scenario is to study the effect of entities moving outside the area of interest on the RSS streams of WiFi hardware inside the area. This is a common scenario, e.g., when the device-free system is used inside a home and we want to study the effect of people moving in the street or neighboring homes on the system. For this experiment, we took the locations on the far right of the testbed (locations 8-14 and 31-35 in Figure 3) as the area of interest and we study the effect of a person moving at all locations on the RSS of the stream (AP2, MP2), which is the only stream completely inside the area of interest. Figure 7 shows the results. The figure shows that when a person moves outside the area of interest, the RSS values are not affected. This highlights that device-free localization can be used for large scale intrusion detection as different areas will not be affected by movement of people moving outside these areas.

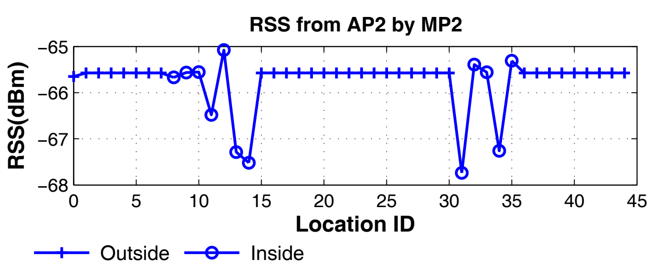

Figure 7: RSS values for the outside effect scenario. The area of interest is on the far right of the testbed (locations 8-14 and 31-35 in Figure 3). The x-axis represents the person location. The y-axis represents her effect on the stream inside the area of interest.

Summary of Findings
Through this section, our experiments lead to the following conclusions:

- Wall-mounted APs lead to higher device-free localization accuracy.
- Using a higher frequency (e.g. 802.11a as compared to 802.11b or g) leads to lower localization accuracy.
- People moving outside the area of interest do not affect the streams that are completely inside the area of interest.

Conclusion
We explored different scenarios for device-free localization, highlighting factors that affect the localization process, and showed how to tune them for better localization. Our recommendations from this study are: Use wall-mounted APs for better accuracy; the 2.4 GHz band is preferred over the 5.7 GHz band for both the accuracy and coverage; Our analysis also shows that people moving outside the area of interest do not affect the device-free system inside the area. We believe that our analysis gives new insights for a wide range of entities interested in WiFi-based localization, both practitioners and researchers.

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