Indoor localization using audio features of FM radio signals

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Abstract. Typical localization systems use various features of the signal to estimate the distance, including received signal strength indicator (RSSI), timing information or angle of arrival (AoA). However, there are a number of signal features of FM radio that may also be suitable for localization, namely stereo channel separation (SCS) and signal to noise ratio (SNR). This paper investigates the feasibility of indoor localization using fingerprinting of audio features of FM radio signals emitted by low-power FM transmitters using SNR and SCS values. The experimental results demonstrate the possibility of audio-based localization, when signal strength readings are not available.

1 Introduction

Majority of wireless localization systems estimate the distance to the positioning beacons using either timing information or properties of the received signal, with received signal strength indicator (RSSI) being most widely used signal-related feature. However, the RSSI readings are not always available from the hardware, or are reported with a very low granularity, which significantly limits the accuracy of the positioning system. To address this issue, other signal features might be used for estimating the distance between the mobile unit and the positioning beacons.

A promising technology for indoor localization is FM radio, which is widely available, power-effective and low-interference, and provides a positioning accuracy comparable to Wi-Fi based systems [1]. However, many FM receivers do not report any RSSI information to the software layer. At the same time, the FM signal carries an audio component; the received audio quality depends on the radio-frequency (RF) signal properties and thus it may be possible to utilize audio features for localization.

The aim of this paper is to evaluate the feasibility of RSSI-less indoor localization using audio features of the FM radio signals. To achieve this, we first estimate dependence of audio features on the transmitter-to-receiver distance. In this regard, two suitable audio features were identified, namely, signal-to-noise ratio (SNR) and stereo channel separation (SCS). Then, we evaluated the localization performance of the system using SNR, SCS and RSSI fingerprinting approaches.

2 Distance-Dependent Audio Features of FM Radio Signals

The relative position of the user with regard to a beacon can be characterized by the angle between directed antennas, signal propagation time and certain properties of the received signal. For the FM radio, we have identified three distance-dependent features, namely: received signal strength (RSS), audio signal quality (represented by SNR), and stereo channels separation (SCS). As the RSS' dependence on distance has already been studied before [1], this paper focuses on the audio-related features.

The audio information is encoded in the RF signal by means of modulation, and the quality of extracted audio depends on the quality of the received RF signal that degrades with the distance due to path loss. Thus, it is reasonable to assume that audio signal quality depends on the distance between receiver and transmitter: as the signal strength decreases with the distance, the SNR for the RF signal drops, and the demodulated noise passes through to the audio part, thus affecting the audio SNR.

To test the feasibility of audio SNR method for FM positioning, a short-range FM transmitter (embedded into a König MP3 player) has been set to broadcast continuous dual-tone multi-frequency (DTMF) signal composed of 1209 Hz and 697 Hz sine waves [2]. This signal was received by Brando USB FM radio, with noise-reduction turned off. The audio signal, sampled at 44.1 kHz, was transformed using 8192-band FFT and the SNR was then calculated as follows:

$$SNR = \frac{band_{697Hz} + band_{1209Hz}}{mean(all\_bands)} \, . \qquad (1)$$

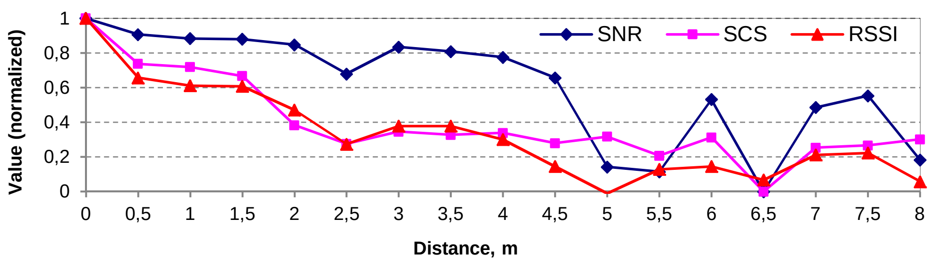


Fig. 1. SNR, SCS and RSSI dependence on distance.

The results in Fig. 1 demonstrate that audio SNR does in fact reflect the distance from the signal source, even though the dependence is less smooth than in the case of RSSI. At short distances, the reception quality is high and the SNR value is limited only by the characteristics of the transmitter and receiver. As the distance increases, the SNR declines. Thus, audio SNR can be utilized as a distance-dependent feature (provided that audio quality augmentation features of the receiver are switched off).

The motivation for considering the stereo channel separation (SCS) as a measure of distance was two-fold. Firstly, the stereophonic signal is more sensitive to noise than the monophonic one [5]. The inherent white noise of the RF signal mostly affects the 19-kHz stereo pilot subcarrier and the differential L–R part of the encoded stereo signal [4, 5], where L and R denote the left and the right audio channels, respectively. The summary L+R signal, however, is less sensitive to the RF noise. Secondly, the distortions in the pilot subcarrier also affect the quality of the stereo signal. At longer distances, where the RF signal quality degrades, the receiver circuitry gradually combines the stereo channels to maintain the sound quality [6], and the L+R part starts to dominate in the output of the receiver, which results in the reduction of SCS.

In order to evaluate SCS feature, the transmitter was set to broadcast a stereophonic sound; each stereo channel contained a sinusoidal signal with DTMF [2] component frequencies (1209 Hz for the left channel and 697 Hz for the right one), which guaranteed no overlapping of signals of different channels, or their harmonics. Then, a 8192-band FFT was performed over the right channel of the received signal, and the SCS value was calculated as the difference between the 697 Hz band (the one transmitted on right channel) and the "ghost" 1209 Hz band (transmitted on the left channel, but appearing on the right one due to channel crosstalk). Thus, when the reception quality is high, only a minimal fraction of the left-channel signal appears on the right channel, resulting in a high SCS value. However, if the stereo separation is poor, the two frequency bands are almost equal and thus the SCS value is minimal. The experimental results in Fig. 1 confirm that, as the distance increases the SCS quickly deteriorates, reaches its minimum and remains constant thereafter. The minimum SCS corresponds to mono reception.

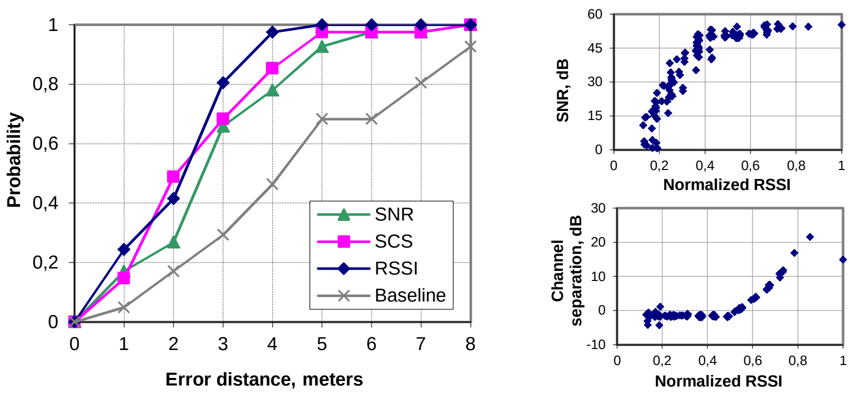
The use of stereo channel separation as a measure of distance is unique for FM positioning and, according to the literature, has never been evaluated before. However, it has certain limitations. Firstly, the transmitters must broadcast a known stereo signal, so that the client can estimate the channel cross-talk. Secondly, the SCS method is appropriate only for shorter distances than the RSSI since at long distances the RF signal is too weak and the stereo reception is not feasible.

3 Positioning Performance

An experimental evaluation of the audio-based FM positioning performance has been performed in the 12×6 m room described in [1]. Three short-range FM transmitters were setup to broadcast a stereophonic signal, as described above. The mobile client was a laptop equipped with a Brando USB FM Radio receiver. For each accessible point of a 1-m grid in the room, the laptop recorded a 5 second long audio sample from each transmitter and simultaneously acquired the RSSI values for the beacon being recorded (at 10 Hz rate). The recorded audio samples were processed to estimate the SNR and SCS values as described in previous section. Finally, the SNR, SCS and RSSI measurements for each point were averaged. The localization performance was evaluated using the fingerprinting approach with nearest neighbor classifier and leave-one-out evaluation [7]; the algorithm was implemented in R [8].

The results presented in Fig. 2a confirm the feasibility of FM positioning based on audio signal properties, as all methods perform better than the baseline (where the system returned a random training point for any input fingerprint). The SCS approach demonstrates a slightly better performance than the SNR approach, and provides the best median accuracy (2.1 m) over all competitors. However, the best 95th-percentile accuracy is demonstrated by the RSSI.

In order to understand the reasons behind the inferior performance of audio-based methods, let us consider the dependencies between the collected SNR, SCS and RSSI



a) Positioning performance

b) SNR and SCS vs. RSSI

Fig. 2. (a) Accuracy of FM positioning system using audio signal features. (b) Relationship between SNR, SCS and RSSI.

values (see Fig. 2b). For low RSSI values the SNR increases linearly or quasi-linearly; at certain point, however, it saturates to its maximum of about 50 dB. Thus, the SNR approach is usable for positioning only at relatively long distances (low RSSIs); at shorter ranges the SNR's dependence on the distance is weak. This explains why SNR demonstrated lower positioning accuracy than SCS: the power of the used transmitters was sufficient to provide a good audio quality (that is, maximum SNR) in the whole test environment. For SCS, when the signal is weak, the reception is monophonic and the channel separation is low. As the RSSI increases, the receiver eventually switches to stereophonic mode, where the channel separation continues to improve (up to hardware capabilities) as the RSSI grows.

The experimental results demonstrate that audio features are suitable for localization. While the FM-specific SCS approach works only at shorter distances with high RSSI levels, the audio SNR method is more suitable at longer ranges with low RSSI values. The RSSI approach, in contrast, is applicable for all distance ranges and provides better accuracy. The audio-feature based localization may however prove useful when RSSI readings are imprecise or not available.

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