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Enhancing indoor radio tomographic imaging based on interference link elimination

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ABSTRACT

Radio tomographic imaging (RTI) is a promising technique to localize and track the target without wearing any electronic device. However, the performance of traditional shadowing-based RTI (SRTI) degrades in indoor environments due to the existence of interference links caused by multipath. The interference links can bring false spots in the imaging results of RTI and make the true spot drift, resulting in position estimation error of the target. In this paper, we propose an interference link canceling technique to improve the performance of RTI where temporal and spatial properties of shadowed links are jointly used to detect the interference links. Since the spatial detection relies on the prior knowledge of the position of the target, we use Kalman filter to provide the position estimation. Moreover, a mean-shift clustering method is adopted to obtain the initial position estimation of the target. The experimental results demonstrate that the proposed enhanced SRTI (ESRTI) method outperforms the existing methods in terms of both image quality and tracking accuracy.

1. Introduction

Radio tomographic imaging (RTI) has emerged as an attractive technology to localize the target without attaching any electronic device. So far various schemes of RTI including coherent RTI and non-coherent RTI have been proposed by research community in the past decades [1]. Among them, RTI based on received signal strength (RSS), which is a type of non-coherent RTI, has attracted a lot of attention because RSS can be easily obtained from most wireless communication devices without extra hardware. Thus, RSS-based RTI offers a cost-effective solution to image the monitored area. Recently, RSS-based RTI has been used in a variety of applications including roadside surveillance [2], through-wall sensing [3–6], floor plan formation [5–7], residential monitoring [8] and health care [9].

Shadowing-based RTI (SRTI) was originally proposed by Patwari and Wilson [10] which exploited RSS variation obtained from a network of low-cost radio sensors to generate an attenuation image about the monitored area. The major assumption behind SRTI is that when the target obstructs the wireless links, the links will suffer from large shadowing loss. In addition, the RSS of links which are not blocked by the target will almost keep unchanged. The assumption is valid for open environments where the line-of-sight (LOS) path of a link is dominant. However, it does not hold in cluttered indoor environments due to the existence of multipath which makes RSS change unexpectedly. Diversity has proven to be an effective method to combat the multipath. For example, Kaltiokallio has proposed a channel diversity method which chose the best channel from different channels or weighted them by fading levels [11]. A fade-level based spatial model for RTI was also proposed, which divided the links to fading links and no fading links and treated the two types of links differently [12]. Bocca [13] found that by changing the orientation of antennas, the performance of RTI can be improved dramatically. But diversity requires measuring RSS on different channels or orientations, which results in increased measurement burden. Wei [14] employed electronically switched directional (ESD) antennas which have narrow beamwidth to mitigate the multipath. However, using directional antennas will increase the size and also the cost of radio sensors.

In this paper, we attempt to cope with multipath problem from another perspective of canceling interference links. The interference links refer to the links whose RSS measurements are observed to have unexpected change. For example, the RSS measurements of some links are noticeably increased, which is rarely observed in outdoor environments. In addition, the RSS measurements of some links whose LOS paths are not obstructed also exhibit great attenuation. This may be caused by dominant multipath obstruction or fast fading due to the motion of the target. The participation of

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interference links will impair the performance of RTI. Specifically, if interference links are used to perform RTI, the image may be severely corrupted by false spots and noise. The true spot corresponding to the position of the target may also drift significantly. Both can result in large position estimation errors.

Therefore, in this paper, we propose to enhance the RTI by interference canceling technique and the proposed method is referred to as enhanced SRTI (ESRTI). In summary, the paper has the following contributions:

1) We employ both temporal and spatial properties of shadowed links to detect the interference links. Considering that the RSS of the obstructed links slowly varies, in the temporal domain a moving average filter is utilized to avoid the links corrupted by fast fading. Further, we detect the interference links according to the spatial property where the intersection points of the interference links are far away from the true position of the target. Note that the spatial detection phase requires the position of the target, which is unknown in advance. To tackle this problem, we replace the target's position with the position prediction obtained by Kalman filter. The links excluding interference links are used to generate the image about the monitored area.
2) Since ESRTI requires that the initial position of the target is known, we propose to estimate the initial position of the target based on mean-shift clustering approach [15].
3) The effectiveness of ESRTI method is also verified by experiments. We observe that the imaging results given by the proposed ESRTI are considerably enhanced, where the false spots disappear and the localization accuracy is significantly improved.

The remainder of this paper is organized as follows. In Section 2 we briefly review related work about RTI. Section 3 presents the problem formulation of indoor RTI and the motivation of the proposed method. In Section 4, we give the details of the interference link elimination. Section 5 shows how to obtain the initial position of the target. In Section 6, the overall framework of ESRTI method is described. Section 7 validates the effectiveness of the proposed method by field experiments. Section 8 concludes the paper.

2. Related work

Typically, RTI employs a network of distributed radio sensors to image the target in the monitored area. The presence of the target will influence the radio signal in different ways including reflection, scattering and shadowing. The role of radio sensors is to provide the measurement with respect to the received signal. According to the type of metric RTI uses, RTI can be roughly divided into two categories: coherent RTI and non-coherent RTI [1].

Coherent RTI employs the principle of inverse scattering to image the monitored region, which relies on the knowledge of the amplitude and phase of the received signal. Wicks' group has made considerable contributions in the area of coherent RTI including developing a theoretical framework of the coherent RTI [16] and applying RTI to detect deeply buried targets or tunnel [16–18]. Further, Soldovieri [19] utilized RTI to perform through-wall imaging. Monte [20] improved coherent RTI by introducing a more accurate forward model, mitigating the direct-path wave and using a more robust inversion scheme. However, it is noteworthy that coherent RTI requires specialized hardware because most commercial off-the-shelf (COTS) devices are unable to provide accurate phase measurement. Thus, the system cost of coherent RTI can be high. In order to implement coherent RTI on COTS devices, Qiu [1] proposed a phase reconstruction method to retrieve the phase information from the amplitude-only measurement. Bonior [21] experimentally verified Qiu's method by using COTS devices called Universal Software Radio Peripheral (USRP). Moreover, Hu [22] proposed a machine learning method to implement noise reduction of the amplitude-only measurement to improve the accuracy of phase reconstruction. However, perfect phase reconstruction strongly relies on accurate amplitude measurement while some COTS devices can only provide rough amplitude measurement, especially for the low cost COTS devices.

Non-coherent RTI also only requires amplitude measurement of the received signal but it does not need to recover the phase. Considering that rough amplitude measurement such as RSS obtained from simple and cheap devices is sufficient for non-coherent RTI, the system cost can be greatly reduced. It should be noted that non-coherent RTI leverages the influence of the target on the direct-path signal rather than the scattered signal. As we have mentioned before, non-coherent RTI was first proposed by Patwari [23], motivated by computerized tomography (CT). Kaltiokallio [11] and Bocca [13] utilized channel diversity and angular diversity to improve the SRTI in cluttered environments. Instead of using attenuation of links, Wilson [3] proposed a variance-based RTI (VRTI) which was free of calibration and also had the capability of seeing through walls. Zhang [24] proposed the subspace VRTI (SubVRTI) method which used subspace decomposition method to reduce the influence of noise and also proposed Kernel RTI (KRTI) method which exploited both attenuation and variance of RSS [25]. Due to the sparsity that the target usually occupies little space compared to the whole monitored area, sparse recovery based on compressive sensing was used to enhance the imaging results of RTI [5,6,26,27] as well. Edelstein [28] proposed a background subtraction method to perform online calibration which obtained the RSS values when the monitored region is empty of target.

In this paper, we focus on non-coherent RTI because of its low cost. In particular, we are interested in SRTI in indoor environments. The major challenge that SRTI encountered in indoor environments is interference links caused by multipath. The interference links can greatly corrupt the formed image of SRTI and bring large localization error of the moving target. In this paper, we employ the temporal and spatial properties of LOS path obstructed links to eliminate interference links. As a result, the performance of proposed ESRTI is remarkably enhanced compared to SRTI.

3. Problem formulation

Fig. 1(a) shows a 2-D radio tomography network consisting of η RF sensors with known coordinates (α_i, β_i), $i = 1, 2, \dots, \eta$, respectively. The sensors are placed in an indoor environment in the same plane, constituting a monitored area with size $[x_{\min}, x_{\max}] \times [y_{\min}, y_{\max}]$. A target moves in the monitored area with coordinate (x_t, y_t) at time instant t. Each sensor can transmit or receive wireless signal and measure the RSS. Thus, a pair of sensors can constitute a unique link and there are $L = \frac{\eta(\eta-1)}{2}$ links in the monitored area. The presence of the target can alter the radio environment, leading to variation of RSS. RTI uses the RSS variation of the links to construct an image reflecting the attenuation happened in the monitored area. The brightest spot in the image reveals the position of the target, as illustrated in Fig. 1(b).

3.1. Motivation

In outdoor environments like the grassy area where Wilson's experiment was conducted [10], LOS path is strongly dominant. As a consequence, links will ideally behave: the links whose LOS paths are blocked will suffer from large shadowing loss while the RSS of other links are almost unchanged. In other words, there are few interference links in outdoor environments and thus SRTI