Evaluation of the Indoor Time-Reversal Based RF Locating Method

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Abstract　An indoor Time-Reversal (TR) Based RF locating method is proposed to locate a RFID tag in rich scattering environment. Unlike the conventional locating methods based on Received Signal Strength Indicator (RSSI), Time of Arrival (TOA), and Direction of Arrival (DOA) estimation which are sensitive to the multipath effects, TR method utilizes the multipath propagations as useful information. The proposed method first requests a RFID tag to emit a locating pulse, the scattered pulse is received by a sparse antenna array with 3 wavelengths spacing, and then the received signals are time-reversed and retransmitted in a simulation domain by using numerical electromagnetic calculation methods. Because the information of the environment (such as rooms, doors, et al) can be known in advance, the propagation paths of the pulse can be accurately reconstructed. In order to locate the RFID tag, a location estimator based on TR inversion is also given. By monitoring the output of this location estimator or the energy distribution in both time and spatial domains, the RFID tag can be located. This TR based RF locating method has great advantages over the traditional back-projection method because the multipath propagations in this rich scattering environment have been well utilized. Simulation results show the effectiveness of the proposed method. Furthermore, originating from the well utilization of multipath propagations, TR based method can still work very well for locating with this very sparse array.

Key words　multipath propagation;　RF locating;　RFID;　sparse array;　time reversal

基于时间反转的室内射频定位方法评估

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【摘要】提出一种种基于时间反转的室内多散射环境射频定位方法。不同于传统的对多径效应敏感的采用接收信号强度、到达时间估计、到达角估计的射频定位方法，时间反转方法充分利用了多径传输作为有用信息。该方法首先要求RFID标签发射一个定位脉冲，该脉冲经过环境散射与多径传播后被阵元间距为3倍波长的稀疏天线阵接收。利用电磁场数值计算方法在仿真空间内将接收到的信号进行时间反转并重新在接收天线阵元位置分别发射。由于室内环境分布（如房间、门等）可视为已知信息，利用该信息可在仿真空间内建立完整而准确的电磁波多径传播模型，用于反演时间反转定位脉冲信号的传播过程。为了估计目标的位置，给出了基于时间反转的反演估计算子。通过监测估计子或时空域电磁场能量分布，即可获得RFID所在位置。仿真结果证实了该方法的有效性，并且由于时间反转方法充分利用了多径传输过程，故在稀疏天线阵下同样有很好的定位性能。

关　键　词　多径传输;　射频定位;　射频识别;　稀疏天线阵;　时间反转

中图分类号　TN 011　　文献标志码　A　　doi:10.3969/j.issn.1001-0548.2013.06.011

Indoor locating and tracking is very important in logistics and surveillance applications. Compared with the outdoor locating method such as the GPS system, the indoor locating method is much less developed due to its rich scattering environment, where the Non-Line of Sight (NLOS) situation is very common. In order to estimate the location of an indoor target, some methods based on RFID[1] system have been proposed[2-11]. All

Received date: 2012 – 02 – 15;　Revised date: 2013 – 09 – 16

收稿日期：　2012 – 02 – 15；修回日期：　2013 – 09 – 16

Foundation item: the fundamental research Funds for the central universities of china (ZYGX2011YB012).

基金项目：中央高校基本科研业务费(ZYGX2011YB012)

Biography: ZHU Xiao-zhang was born in 1984, and his research interests include target imaging and inversion in complex environment and heterogenous medinm.

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the methods can be classified into two main categories: active method and passive method.

The active methods are based on scene analysis (sometimes called fingerprint). The target to be located is a RFID reader[2-5]. Usually several passive RFID tags with known locations are mounted on the ceiling [3, 5], floor or walls[4]. They are used as references. The RFID reader can determine its own location by finding nearby RFID tags as many as possible. Based on the IDs of the tags, the reader can estimate its own location. This method requires the target has all the information of the tags mounted in the environment and has the ability to calculate complex 3-demension locating problem, which limits its application[2].

The passive methods are based on the traditional trilateration method similar to the RF fox hunting sports. The target to be located is a RFID tag[6-11], while several readers are mounted in an indoor environment. Each reader will detect the RFID tag separately. Based on the echo, conventional Received Signal Strength Indicator (RSSI)[6-7,10], direction of arrival (DOA), and time of arrival (TOA)[7] or time difference of arrival (TDOA)[8-9] are measured. The trilateration technique is used to acquire the position of the tag. The passive method is more widely applied because the target to be located only carries a RFID tag, which has much lower cost and size than the reader. Nevertheless literature[10] experimentally proved these passive methods are significantly affected by many factors such as multipath fading, obstructions, antenna pattern, and polarization. The reason is that the above range estimation methods are all based on the assumption of Line of Sight (LOS), but the actual environment of indoor locating problem usually provides a NLOS transmission for electromagnetic waves. Even the combination of scene analysis and trilateration in literature[4,11] still gives limited performance. In order to improve the performance of RF locating in the NLOS indoor situation, the rich scattering environment must be seriously taken into account.

Aiming to improve the locating performance in rich scattering environment, a TR (Time reversal) based RF locating method is proposed in this paper. This method utilizes the multipath and scattered echo in a complex environment. The TR technique can refocus a source or a scatterer by time reversely retransmitting the received echo. The TR technique has been widely researched and demonstrated both theoretically and experimentally in acoustic and ultrasonic area[12]. In recent years, TRM has also been approached[13-14] for imaging[15-16], detection [17-20], and communication[21] in electromagnetic area. In the indoor locating applications, such as locating a cargo in warehouse, tracking a person in a sensitive building, the information of environment is well known in advance and can be used to build the inversion model of TR procedure. With the matched environment, the TR technique can fully utilize the multi-path and the rich scattering to achieve the best refocusing performance, even for sparse antenna array[17]. Originated from this theory, a TR-Based RF locating method is developed and verified in this paper. In the simulation system, a sparse antenna array with spacing is used as a receiver. Compared to the traditional back-projection method, 7dB of image SNR improvement and sub-wavelength locating precision have been obtained.

The remainder of the paper is organized as follows. In Section 1, the new TR-Based RF Locating method is proposed. The propagation of pulse signal from the RFID tag to the antenna array, and the procedure of TR inversion in the simulation domain, is described and derived by the Green’s function in frequency domain. A location estimator is also given at the end of this section. Some numerical results are shown in Section 2 to demonstrate the performance of the proposed method, compared to the back-projection method which shares the common basis of LOS assumption with RSSI, TOA or DOA method. Conclusions are drawn in the last section. Some discussions are given as well.

1 Theory and system description of TR-RF locating

The aim of this paper is to locate a target in a complex scattered environment with complete NLOS situation. The environment is illustrated in Fig. 1. In this sample, the area we care about has 8 rooms, separated by concrete walls. A target shown as a star in Room 7 needs to be located. A RFID tag is mounted on the target. A sparse antenna array (RFID readers) is placed along the aisle. For this kind of situation, the performance of traditional methods, such as those based on RSSI, will be significantly degraded[10].

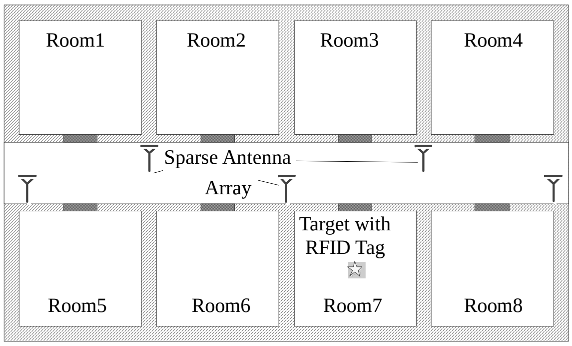

Fig 1 Sketch of a typical TR-based RF locating application

In the common indoor environment, two main effects, which will degrade the performance of traditional locating methods, are the multipath propagations caused by rich scattering and the sparse array caused by decoration difficulties and costing down. Rather than the traditional locating methods, the TR method[12-21] will effectively utilize the multipath effect by rebuilding the propagation procedure if the information of the environment is well-known. The ambiguity of DOA caused by sparse array can also be suppressed due to the refocusing characteristic of TR method in rich scattering environment. Originated from these advantages of TR method, a TR-Based RF Locating method is induced in this paper.

The main idea of the TR-based RF locating method is to effectively utilize the information of the environment. Fig. 2 shows the block scheme of the proposed method. It has the following major steps:

a) The RFID reader sends a specific locating command to the tag;

b) Once the tag receives the locating command, it will send back a single pulse waveform;

c) The scattered signal is received by the sparse antenna array (all the RFID readers) and sequentially stored.

d) Numerical TR procedure: The received signals are time reversed and retransmitted in a simulation domain, where the EM wave propagation progress is numerically simulated by time domain methods, such as PSTD (Pseudo-Spectral Time Domain) method;

e) Target location: The EM energy is summarized in each room or space unit along the simulation time steps. Then according to the distribution of the EM energy in the whole spatial and time domains, the original position of the target (the RFID tag) will be located.

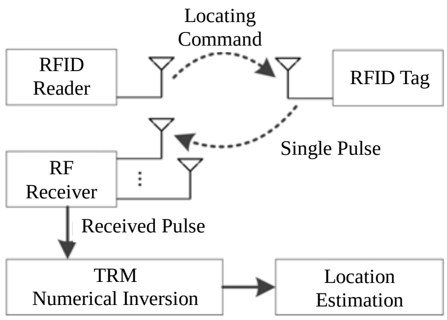

Fig 2 Block scheme of TR-Based RF Locating method

To illustrate this method theoretically, suppose a single pulse waveform $p(t)$ is sent out by a RFID tag located at position $\boldsymbol{r}_s$, the pulse propagates through a multipath environment with Green's function $\hat{G}(\boldsymbol{r},\boldsymbol{r}_s,\omega)$ and reaches an antenna array. The receiver array has K elements $\boldsymbol{r}_k \mid k\in[1,2,\cdots,K]$, the electric field strength recorded at the $\boldsymbol{r}_k$ is given by

$$E_R(\boldsymbol{r}_k,t)=\int_{-\infty}^{+\infty}\hat{p}(\omega)\hat{G}(\boldsymbol{r}_k,\boldsymbol{r}_s,\omega)\mathrm{e}^{\mathrm{j}\omega t}\mathrm{d}\omega \tag{1}$$

where $\hat{p}(\omega)$ is the Fourier transform of the pulse $p(t)$,

$$\hat{p}(\omega)=\int_{-\infty}^{\infty}p(t)\mathrm{e}^{-\mathrm{j}\omega t}\mathrm{d}t \tag{2}$$

and $\hat{G}(\boldsymbol{r}_k,\boldsymbol{r}_s,\omega)$ is the Green's function from the tag to the antenna element K.

The received signal is then time reversed into $\tilde{E}_R(\boldsymbol{r}_k,t)$, which is the phase conjugate of $E_R(\boldsymbol{r}_k,t)$ in frequency domain. The relationship is illustrated by

$$\tilde{E}_R(\boldsymbol{r}_k,\omega)=E_R(\boldsymbol{r}_k,\omega)^*=p(\omega)^*\hat{G}(\boldsymbol{r}_k,\boldsymbol{r}_s,\omega)^* \tag{3}$$

The time reversed signal $E_R^{\sim}(\boldsymbol{r}_k,\omega)$ is transmitted in the simulation domain by the antenna element $\mathbf{r}_k \mid k\in[1,2,\cdots,K]$, respectively. During the propagation, the strength of this space-time signal is

$$I(\boldsymbol{r},t)=\int_{-\infty}^{\infty}\sum_{k=1}^{K}\tilde{E}_R(\boldsymbol{r}_k,\omega)\hat{G}_{\mathrm{TR}}(\boldsymbol{r},\boldsymbol{r}_k,\omega)\,\mathrm{e}^{\mathrm{j}\omega t}\mathrm{d}\omega \tag{4}$$

where $\hat{G}_{\mathrm{TR}}(\boldsymbol{r},\boldsymbol{r}_k,\omega)$ is the numerically calculated Green's function according to electromagnetic model of environment.

According to the Reciprocity Law of wave propagation, the space-time signal strength will refocus on the original position of the source, where the tag is located. The field strength at $\boldsymbol{r}_s$ is derived as

$$I(\boldsymbol{r}_s,t)=\delta(\boldsymbol{r}_s,\boldsymbol{r})\cdot I(\boldsymbol{r},t)=$$
$$\int_{-\infty}^{+\infty}\sum_{k=1}^{K}\tilde{E}_R(\boldsymbol{r}_k,\omega)\delta(\boldsymbol{r}_s,\boldsymbol{r})\hat{G}_0(\boldsymbol{r},\boldsymbol{r}_k,\omega)\mathrm{e}^{\mathrm{j}\omega t}\mathrm{d}\omega=$$
$$\int_{-\infty}^{+\infty}\hat{p}(\omega)^*\sum_{k=1}^{K}\hat{G}(\boldsymbol{r}_k,\boldsymbol{r}_s,\omega)^*\hat{G}_{TR}(\boldsymbol{r}_s,\boldsymbol{r}_k,\omega)\mathrm{e}^{\mathrm{j}\omega t}\mathrm{d}\omega \qquad (5)$$

Because the building is a co-operative object with given information on structure, material, et al. the $\hat{G}_{\mathrm{TR}}(\boldsymbol{r},\boldsymbol{r}_k,\omega)$ can be numerically calculated and stored in advance. And the $\hat{G}_{\mathrm{TR}}(\boldsymbol{r},\boldsymbol{r}_k,\omega)$ can be very close to the real Green's function $\hat{G}(\boldsymbol{r},\boldsymbol{r}',\omega)$. With this assumption, the whole process can be regarded as a process of match filtering.

In this paper, a simple location estimator is used to locate the position of the target, which is expressed as

$$L(i,t)\Big|_{i=1,2,\cdots,8}=\sum_{\boldsymbol{r}\in Z_i}I(\boldsymbol{r},t) \qquad (6)$$

The maximum of $L(i,t)$ indicates in which room the target is located and at what time the time-reversed pulse signal is refocused.

2 Numerical Simulation

In order to evaluate the performance of the proposed method, numerical simulation for typical indoor RF locating scenery is performed and analyzed. The EM engine for simulating the EM propagation is the Pseudospectral Time Domain (PSTD) method. The 3D environment model is shown in Fig. 3. The building has eight rooms. The size of each room is $3*3\ \mathrm{m}^2$. The width of the aisle is $2\ \mathrm{m}$. The thickness of the outside concrete wall are 36 cm. The thickness of the interior concrete walls is 12 cm. All the concrete walls are set with $\varepsilon_r=4.2$. The target is set at the 8th room, with a RFID tag working at UHF band. Eight antenna elements are uniformly mounted in the aisle as shown in Fig. 3. The antenna array is very sparse with an element spacing of 3λ in the Y-axis and 1λ in the X-axis.(In the following experiment, we assume the center frequency to be $300\ \mathrm{MHz}$).

The single pulse sent by the RFID tag is simulated by a time domain pulse given as [16]

$$p(t)=\frac{j}{[j+2\pi f*(t-t_0)/4]^5} \qquad (7)$$

with a center frequency $f=300\ \mathrm{MHz}$, band width from 250 MHz to 350 MHz.

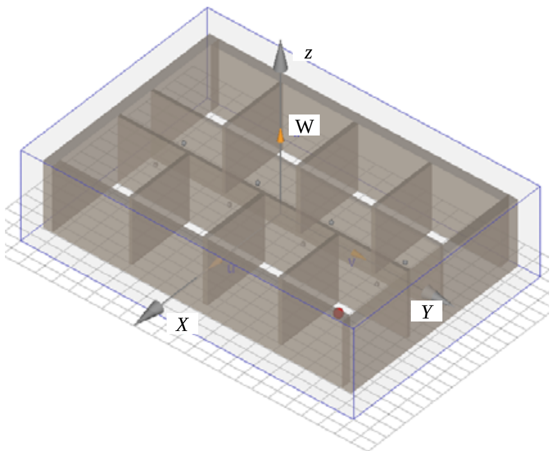

Fig 3 Overview of the simulation model

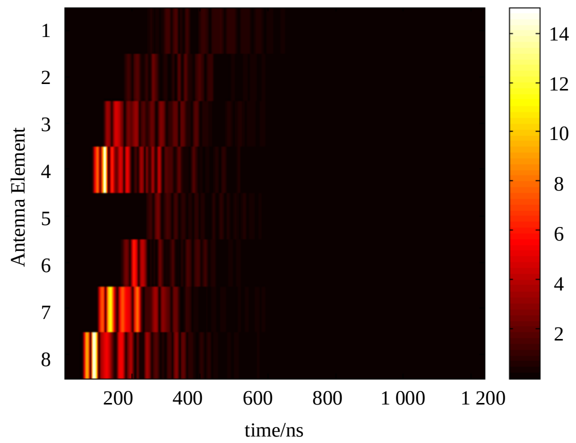

Fig 4 Received signals of the 8 elments in the forward procedure

In the simulation of TR system, the first pass is a forward procedure. The RFID tag (the target) emits a pulse given by (7). The pulse is scattered by the environment and received by the antenna array. Fig. 4 shows the received signal sequences of the 8 elements. Obviously, the signals are spread due to the serious NLOS scattering situation. This spreading will greatly affect the precision of location.

In the TR-Based RF Locating method, the received signal of each element is time reversed. Then the reversed TR signal is re-transmitted back to environment in the second pass of simulation (backward procedure). This procedure is realized in a numerical way. One thing needs to be mentioned is that all the receiving antennas are transferred into transmitting antennas at their original locations in order to satisfy the Reciprocity Law. The distribution of EM energy in the simulation domain is monitored and stored during the simulation. The curve of maximum value of electric field strength versus time is given in Fig. 5. At t=175 ns, the energy is focused. In order to detect in which room the target is located, the estimator given in equation (6) is used to calculate the energy distribution. Fig. 6 shows the energy distributions versus time for rooms 3, 4, 7 and 8. It is shown that room 8, in which the target is located, has the strongest peak at 175ns. This is consistent with the result in Fig. 5. Indexing the spatial energy distribution with this particular time (t=175 ns), an image of energy distribution of the whole simulation spatial domain is given in Fig. 7. From the figure, it is easy to detect a target in room 8. The half peak width in room 8 is about 0.5m∗1.2m, which means the sub-wavelength focusing is achieved by the sparse antenna array (1∗λ in X-axis, 3∗λ in Y-axis). The duration of TRM inversion procedure is about 30 minutes on two Intel X5590 CPU with 26.4 GB RAM for the simulation program.

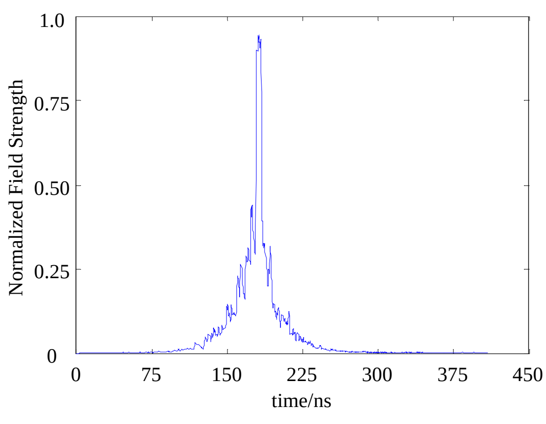

Fig 5 Maximum electric field strength versus time

The common used BP method is adopted as a comparison. Fig. 8 shows the results of the BP method. As we expect, the result of the TR method is much better than that of the BP method in both resolution and contrast. Under the evaluation standard mentioned in literature[16], the image SNR (ISNR) of TR result is 27.14 dB, while that of the BP result is 14.13 dB.

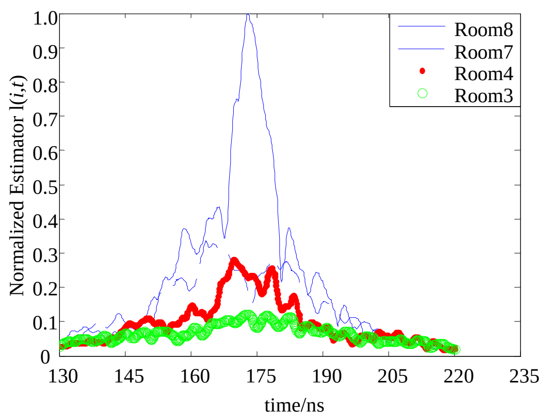

Fig 6 Room level estimator vs. Time

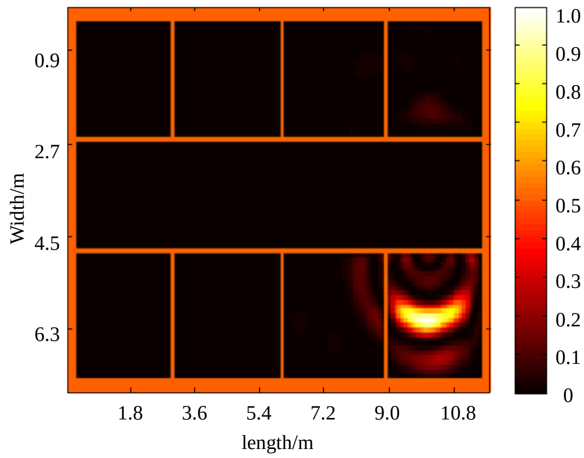

Fig 7 TR-Based image of located target (ISNR=27 dB)

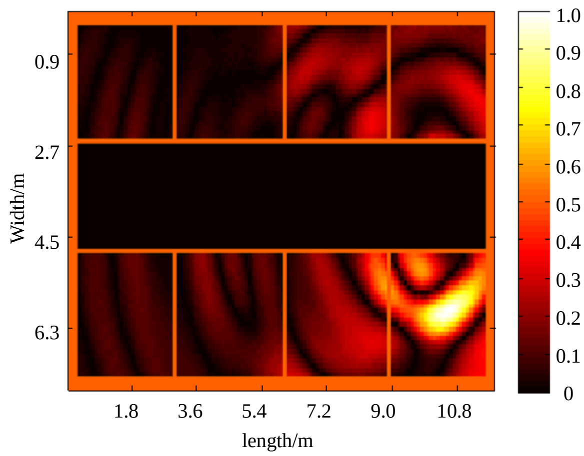

Fig 8 BP image of located target (ISNR=14 dB)

In traditional signal processing locating methods, especially those based on DOA estimation, the array element spacing should be less than 0.5λ. But with this TR-based method, the multi-path propagation is utilized so that the scattered environment enlarges the equivalent aperture size of the antenna and also cancels the grating lobe due to the mismatch of the spatial environment which will cause the energy in grating lobe to defocus and decay rapidly. The performance of the TR-based RF locating method is clearly shown by the simulation.

3 Conclusions

Aiming to improve the location performance for indoor RF locating, some traditional active locating methods for RFID reader and the passive methods for RFID tag based on RSSI and DOA estimation are briefly reviewed. In order to solve the locating problem in the NLOS situation, a TR-Based RF locating method is proposed. Its theory is introduced by following the propagating progress of the signal presented with Green's function. Numerical simulations verify and evaluate the locating performance of the method in a typical indoor situation and a sparse antenna array. The results prove that the proposed method can accurately locate the target while a sub-wavelength focusing accuracy is achieved.

The TR procedure used in the proposed method is not limited in RF locating. Its capability of refocusing and sensitivity to the propagating environment can be applied in many other detection and imaging areas.

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