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Research and Simulation on the Time Varying Enhancement Characteristics of IPTRM for Multipath Signal

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Abstract: Time Varying Enhancement (TVE) is an important technology to deal with multipath fading often encountered in communication and measurement using electromagnetic wave, sound or laser. The self-focusing function of Time Reversal Mirror (TRM) makes it effective in blind TVE by realizing the thought of TVE automatically. Iterative Passive TRM (IPTRM) further strengths its TVE competence by using iterations. This study illustrated and analyzed the principle of TVE of IPTRM for the multipath signal in mathematics, presented the formulas of Gain Ratio and its times in 2nd IPTRM and also simulated and discussed the characteristics of IPTRM in both TVE and noise-removing. Based on the characteristics, study further pointed out the optimal selection of interesting part in IPTRM result and the method to select optimized original gain ratio, so that to get more remarkable TVE without any decreasing the SNR promotion. Contrasted to the present ways of TVE, IPTRM in this study is more simplified and practicable by realizing blind TVE and de-noising at the same time. It is much better that the TVE's performance can be controlled by simply changing the original gain ratio in estimated channel.

Key words: Passive time reversal mirror, iteration, time varying enhancement, multipath signal

INTRODUCTION

Time Varying Enhancement (TVE), or called Time Varying Gain (TVG), is often used to cope with multipath fading in ranging, locating and communication by radar, sound and laser. TVE can give a larger gain to the long path signal than to the short path one, hence to decrease the energy losing in the transmission in the medium.

TVE has two ways to realize, one is by hardware and another is by software based on certain signal processing algorithms. In the hardware way, some automatic gain control devices should be adopted, AD603 for example, they can amplify signals with rather large range of amplitude into a relatively small range. They can do this work fast, but can't distinguish signal and noise and amplify the noise also (Fan *et al*., 2013). At present, most of the software ways of TVE must analyze the energy losing model according to the signal's propagation features in the medium and then realize TVE by inversion (Zou *et al*., 2007). For example, according to the extension, absorbing and scattering in the propagation losing and the fading rule, TVE in ultrasonic signal always includes three relevant parts (Gu *et al*., 2008).

From the principle and processing of TVG, in order to fulfill the TVG, at least three parameters of TVG must be determined. They are so closed related to the signal and medium features that it's very hard to get the proper ones, although some experiences or experiments can be depended on. Furthermore, this process is high complex and has more problems in real application.

Time Reversal Mirror (TRM), firstly put forward by professor Fink M. in France Paris University, has been already used in ultrasonic field. For instance, real practical experiment of TRM in smashing kidney stone (Fink, 1992), using TRM to healing brain (Thomas and Fink, 1996) and etc. In ultrasound field, the first TRM experiment in shallow sea was taken in April, 1996 at the Italy west coast (Kuperman *et al*., 1998). TRM absorbs more focus recently, mainly in the fields of detecting and locating of the underwater targets (Pautet, *et al*., 2005), space-time filtering (Ma *et al*., 2007), reverberation decreasing (Kim *et al*., 2004) and underwater acoustic communication (Yang, 2003), etc. Prof. Fink M.'s research group, Prof. Kuperman's group, Wang's group in Acoustics of Chinese Academy of Sciences and Hui's group in Harbin Institute of Technology, they all have deep researched in TRM and its application (Yin and Hui, 2008). From the principle and characteristics, TRM is a technology which can fulfill the blind enhancement of the multipath signal. This study explained and analyzed the principle of TVE of Iterative Passive Time Reversal Mirror (IPTRM) in time domain for multipath signal and gave out the formulas of

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Gain Ratio and its times in 2nd IPTRM. It also researched and simulated the characteristics of IPTRM in the aspects of TVE and de-noising. Just based on the characteristics, study pointed out the optimal selection of interesting part in IPTRM result and the method to select original gain ratio G0, so that to control the iterative processing and get more remarkable TVE while keeping the similar de-noising capability. Contrasted to the hardware way and other software algorithms of TVE, the method based on IPTRM in this study is more simplified and practicable and it can realizes blind TVE and de-noising in the same processing, what makes it better is that the TVE's performance can be controlled manually by simply changing the G0 in the estimated channel.

PTRM'S TVE PRICIPLE AND ITS ITERATION

TRM has several types at present, such as multi-array-elements TRM and single-element TRM; active TRM (ATRM) or passive TRM; normal TRM or virtual TRM (VTRM). Among these TRMs, PTRM and VTRM are all no need of re-transmitting and highest efficiency, but their channel estimation is important. If the estimated channel is well matched with the real channel, PTRM also can do as well as the ATRM.

Principle of the signal enhancement based on PTRM: Relative to the ATRM, PTRM has two features, one is no need of combining transmitter and receiver together in one transducer and another is no need of re-transmitting. When the transducer combines transmitter and receiver together, PTRM can be processed as shown in Fig. 1.

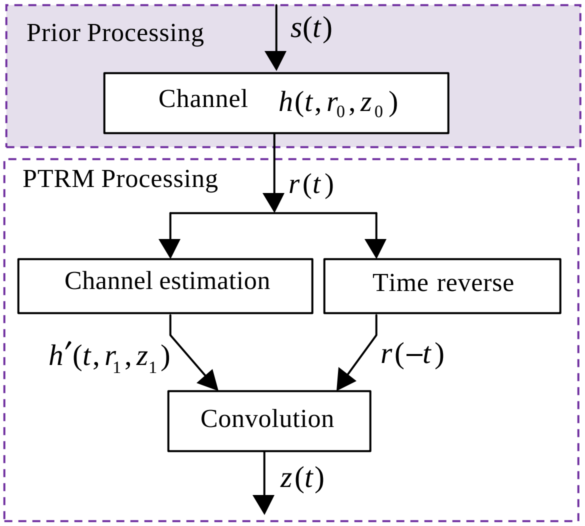

Fig. 1: Block diagram of PTRM

Take the single-element PTRM for example to explain the principle of the TVE of PTRM. Assuming the propagation environment is a coherent multipath channel, when without considering the non-uniform of the medium and the randomness in the non-uniform interface, space varying characteristics of the channel can be expressed by the system impulse response of the coherent multipath channel. System function of channel is h(t, r_0, z_0), where (r_0, z_0) denotes the transmitter location. Without considering noise, the originally received signal r(t) is:

$$r(t) = s(t)\times h(t, r_0, z_0) \qquad (1)$$

Here, symbol '*' stands for the convolution operator. s(t) is the transmitted signal. Estimate the channel through the received signal and get h'(t, r_1, z_1). Then the re-transmitting and receiving is simulated by convoluting the reversed received signal to the estimated channel h'(t, r_1, z_1) and the new received signal of PTRM z(t) is:

$$z(t) = r(-t)\times h'(t, r_1, z_1) = s(-t) * h(-t, r_0, z_0)\times h'(t, r_1, z_1) \qquad (2)$$

Let C(t) = h(-t, r_0, z_0)×(t, r_1, z_1) and C(t) is the correlation function of h(t, r_0, z_0) and h'(t, r_1, z_1). If the estimated channel is right that is, $r_1 = r_0$, $z_1 = z_0$ and h = h', C(t) will has a high correlation peak at the time zero. This shows the transmitted signal virtually will be focused at the originally transmitter location by PTRM and this is so-called the principle of space-time focusing. Because PTRM has rather high space-time gain at the focus point, with same transmitted signal s(t), the virtual received signal of PTRM z(t) has higher amplitude than r(t). Therefore, PTRM processing can enhance the multipath signal itself.

Iterative PTRM: Iterative PTRM (IPTRM) is a processing of repeating PTRM multi-times. Assuming the gain of the single PTRM is A, after n^{th} IPTRM, the gain is up to A^n. Known from former section, the received signal of the first IPTRM is:

$$z^{(1)}(t) = s(-t)\times h(-t, r_0, z_0)\times h'(t, r_1, z_1) \qquad (3)$$

If repeat the PTRM based on $z^{(1)}$ and then get the second IPTRM's output as:

$$\begin{aligned} z^{(2)}(t) &= z^{(1)}(-t)\times h'(t, r_1, z_1) = s(t)\times h(t, r_0, z_0) \\ &\times h'(-t, r_1, z_1)\times h'(t, r_1, z_1) \end{aligned} \qquad (4)$$

Then the received signal of kth IPTRM is:

$$z^{(k)}(t) = z^{(k-1)}(-t) \times h'(t, r_1, z_1) \tag{5}$$

Above equation have k+1 convolution processing of channel and its reversal. When the channel is completely matched, if k is an odd, k = 2n-1 and $z^{(-1)}(t) = r(t)$, then:

$$z^{(k)}(t) = z^{(k-1)}(-t) * h'(t, r_1, z_1) = s(-t) * \underbrace{C(t) * C(t) * \cdots * C(t)}_{n} \tag{6}$$

If k is an even, k = 2n, then:

$$z^{(k)}(t) = z^{k-1}(-t) * h'(t, r_1, z_1) = r(t) * \underbrace{C(t) * C(t) * \cdots * C(t)}_{n} \tag{7}$$

In view of C(t) is the autocorrelation of channel, its Fourier Transform is real nonnegative numbers, the output of IPTRM in Eq. 6 is similar with the reversal of the transmitted signal and the output in Eq. 7 is similar with the originally received signal. Therefore, with the aim of enhancement and according to the requirement of minimum distortion, k should be an even.

ANALYSIS OF THE TVE CHARACTERISTICS OF 2nd IPTRM

IPTRM has the capacity of TVE, but in practice, limited by gain, calculation and time cost and signal complexity and etc., the number of iteration can't be too high. For briefness, we firstly explain the TVE characteristics of the 2nd IPTRM and then expand to the 4th and 6th IPTRM.

To simplify the explanation, supposing the channel has two paths and then h(t) can be written as:

$$h(t) = a_1\delta(t - t_1) + a_2\delta(t - t_2) \tag{8}$$

Here, a_1, t_1 are the gain and time delay of the first path, respectively; a_2, t_2 are that of the second path. Supposing the second path is longer and more damping than the first one, then $a_1 > a_2$, $t_1 < t_2$. Now assuming the transmitted signal of sender is s(t). When without considering noise, then received signal of the receiver r(t) is:

$$r(t) = s(t) * h(t) = a_1 s(t - t_1) + a_2 s(t - t_2) \tag{9}$$

For simplifying, we call the part which has the same structure as s(t) as sub-wave. Then, r(t) includes two sub-waves which come from the two paths, respectively: $a_1s(t-t_1)$ and $a_2s(t-t_2)$. The Time Delay Difference (TDD) and Gain Ratio between the second and first sub-waves are $\tau_0 = t_2-t_1$ and $G_0 = a_2/a_1$. From Eq. 7, the output of the second IPTRM is:

Table 1: Time delay difference, τ_{ij}

$\tau_{21} = t_1 - (2t_1 - t_2) = t_2 - t_1 = \tau_0$
$\tau_{32} = t_2 - t_1 = \tau_0$
$\tau_{43} = (2t_2 - t_1) - t_2 = t_2 - t_1 = \tau_0$

Table 2: Gain ratio, G_{ij}

$G_{21} = (a_1^3 + 2a_1a_2^2)/(a_1^2a_2) = G_0(2 + a_1^2/a_2^2) > 3G_0$
$G_{32} = G_0(2a_1^2 + a_2^2)/(a_1^2 + 2a_2^2) > G_0$
$G_{43} = (a_1a_2^2)/(a_2^3 + 2a_1^2a_2) = G_0/(2 + a_2^2/a_1^2) < 0.5G_0$

Table 3: Times of the gain ratio, T_{ij}

$T_{21} = G_{21}/G_0 = 2 + 1/G_0^2$
$T_{32} = G_{32}/G_0 = 0.5 + 1.5/(1 + 2G_0^2)$
$T_{43} = G_{43}/G_0 = 1/(2 + G_0^2)$

$$z^{(2)}(t) = r(t) * C(t) \tag{10}$$

C(t) in above formula is the self-correlation of h(t). From Eq. 8-9, we can get:

$$\begin{aligned} z^{(2)}(t) &= r(t) * C(t) = s(t) * h(t) * C(t) \\ &= a_1^2a_2s(t - 2t_1 + t_2) + (a_1a_2^2 + a_1^3a_2^2)s(t - t_1) + \\ &\quad (a_1^2a_2 + a_1^2a_2^3)s(t - t_2) + a_1a_2^2s(t - 2t_2 + t_1) \end{aligned} \tag{11}$$

From $z^{(2)}(t)$ in (11), it has four sub-waves and numbers them as 1-4 from left to right. Define the Time Delay Difference (TDD), denoted as τ_{ij} and Gain Ratio, denoted as G_{ij}, of the two neighboring sub-waves, where i and j are the numbers of the sub-waves. τ_{ij} and G_{ij} are shown in Table 1-2.

From the Table 1-3, TDD between the two neighboring sub-waves in 2nd IPTRM is same with that in the originally received signal r(t) and the Gain ratio G_{ij} and its times T_{ij} are all the function of the original gain ratio G0. Except G_{43}, other two Gain ratio G_{21} and G_{32} are all larger than G0 and the gain ratio times T_{21} and T_{32} are all more than 1. Expanding from this, in 4th and 6th IPTRM, the TDD between the two neighboring sub-waves are supposed to equal to that of the originally received signal, the gain ratio and its times are supposed to have the similar feathers with that of the 2nd IPTRM. So, IPTRM can enhance the multipath signal in a time varying way and compensate the more fading for longer path to some degree. Compensation degree depends on not only which part is selected as the further research object, but also G0. Study the enhancement features of different possible interesting output can make it clear how to get the optimal selection. At the same time, study the TVE feather under different G0 can give some clues to control the TVE results manually.

SIMULATION OF THE ENHANCEMENT CHARACTERISTICS BASED ON IPTRM

Simulations of IPTRM were taken out in two aspects: TVE and de-noising. Here, a1 is in the range of 0.1-12, with interval of 0.2; G0 is in 0.05-0.95, interval 0.01; Signal Noise Ratio (SNR) in originally received signal, called snr0, is in-30dB-60 dB, interval 5dB. Figure 2a-e are transmitted signal s(t), received signal r(t), 2nd IPTRM output signal z2(t), 4th IPTRM output signal z4(t) and 6th IPTRM output signal z6(t), respectively.

The output signal of IPTRM has more sub-waves than the originally received signal. For example, in the above two paths channel, the output signal of 2nd IPTRM has 4 sub-waves; 4th IPTRM has 6 sub-waves; 6th IPTRM has 8 sub-waves. Since, the TDD of every two neighboring sub-waves in IPTRM output is same with that in the originally receive signal r(t), in the applications of ranging or velocity measurement and etc., where, only the TDD carries interesting information, every two neighboring sub-waves selected to study is ok. Hence, to be brief, the sub-waves are numbered from left to right. The possible interesting part from 2nd IPTRM has three selections: the first two sub-waves, denoted by r12; the 2nd and 3rd sub-waves, r23; the 3rd and 4th sub- waves, r34. Likewise, z4(t) of 4th IPTRM have 5 kinds of selections like r12, r23, r34, r45 and r56; z6(t) of 6th IPTRM have 7 kinds: r12, r23, r34, r45, r56, r67 and r78. Obviously, in order to markedly enhance the longer path signal, the later half parts of z2(t), z4(t) and z6(t), are not shown at all. We focused more attention in the first two selections of 2nd ITRM, first three selections of 4th ITRM and first four selections of 6th ITRM. And in the consequently

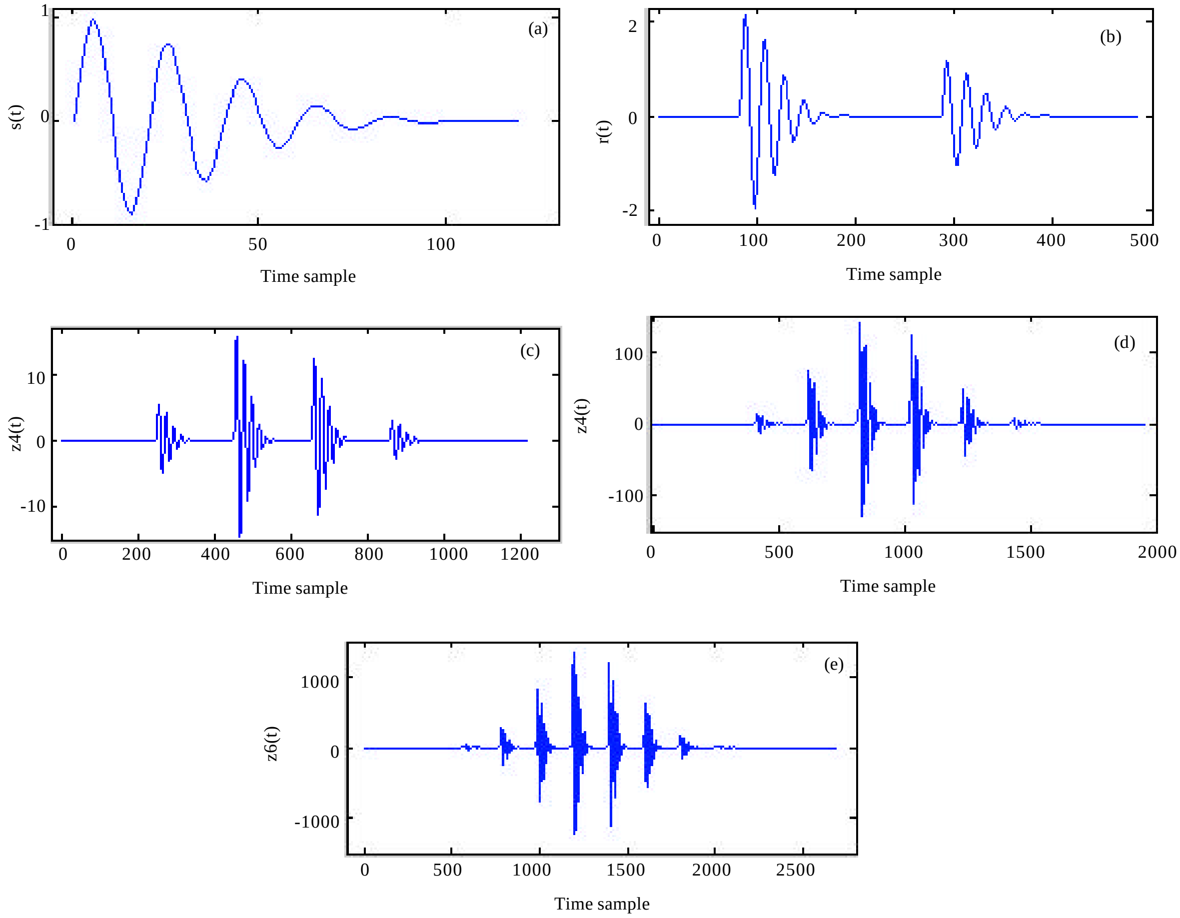

Fig. 2(a-e): Simulation results in 2nd, 4th, 6th IPTRM, (a) Transmitted signal s(t), (b) Originally received signal r(t), (c) Result of 2nd IPTRM, z2(t), (d) Result of 4th IPTRM, z4(t) and (e) Result of 6th IPTRM, z6(t)

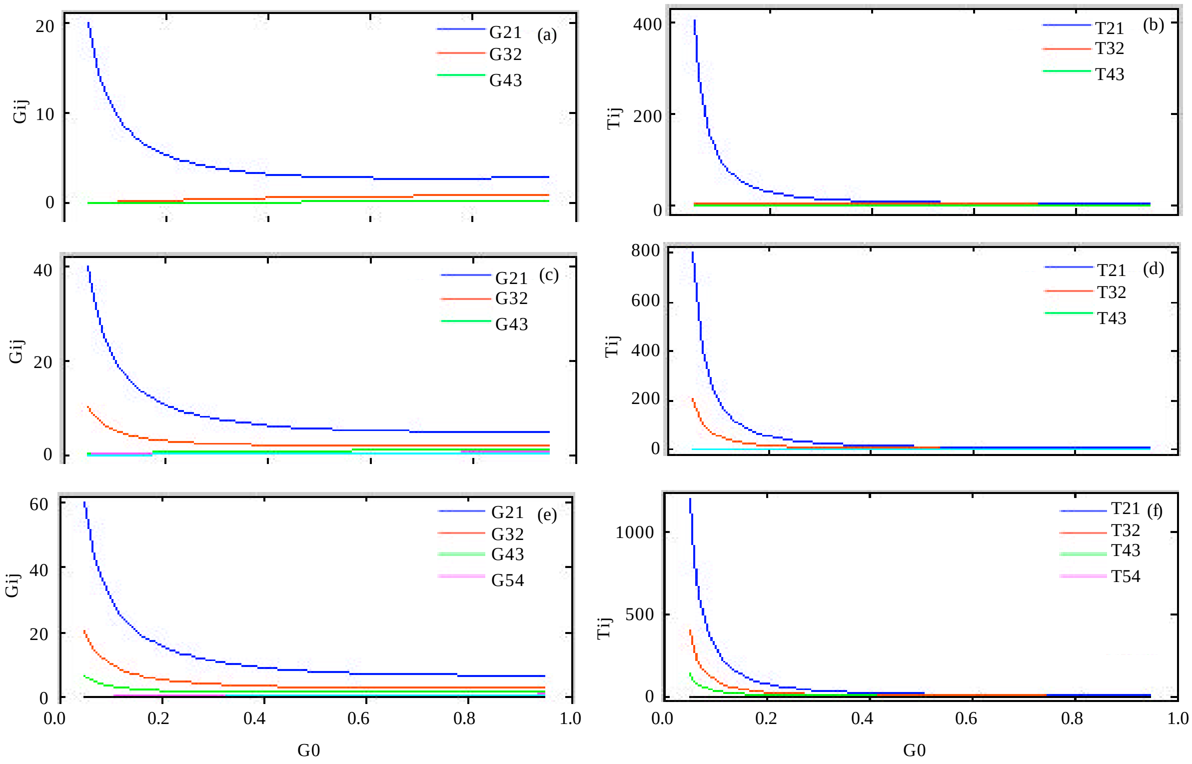

Fig. 3(a-f): Gij and Tij in 2nd, 4th and 6th IPTRM, (a) Gij in 2nd IPTRM, (b) Tij in 2nd IPTRM, (c) Gij in 4 th IPTRM, (d) Tij in 4th iterative PTRM, (e) Gij in 6th IPTRM and (f) Tij in 6th IPTRM

discussion, defined Gij, the Gain ratio, Tij, the Gain ratio times relative to the original Gain ratio G0 and Rsnrij, the SNR increment of IPTRM relative to the originally received signal's SNR snr0. For instance, G32 stands for the amplitude ratio of the later and former sub-wave in r23, T32 stands for G32/ G0, Rsnr32 stands for the difference of SNR23, the SNR in r23 and snr0.

Simulation of TVG and its times in IPTRM: Figure 3a-c reflect the characteristics in the aspect of time varying gain when the channel is completely matched. Figure 3a, c and e are shown how Gij changes with G0; Fig. 3b, d and f are shown how Tij changes with G0. From Fig. 3, Gain ratio Gij and its times Tij are all considered as a monotonically decreasing function of G0 which quickly gets steady. The smaller G0 is, the bigger difference between the two paths gains, the better the TVE can get. From Fig. 3a and b, when using 2nd IPTRM, whatever G0 is, r12 is optimal selection. From Fig. 3c-d, when using 4th IPTRM, whatever G0 is, r12 or r23 are better selections. From Fig. 3e-f, when using 6th IPTRM, whatever G0 is, r12, r23 and r43 are better selections. From Fig. 2, it is clear that the sub-waves gradually enlarge form the beginning on, but turn to shrink after the middle of the whole sequence of IPTRM outputs. So, it is reasonable to select the first half part of the sequence to study. Expanding this to the other times of IPTRM, assuming the times of iteration is k = 2n, then select 1st to (n+1)th sub-waves is possible to get enhanced.

Simulation of the de-noising in IPTRM: Figure 4 shows how SNR increment Rsnrij changes with snr0 when the channel is completely matched which reflects the characteristics of IPTRM in de-noising. From Fig. 4, whatever G0 and the number of iteration are, the Rsnrij of IPTRM increases monotonically with snr0. That is, the higher quality of the originally received signal is, the more SNR in IPTRM can promote. From Fig. 4a, Rsnr21 is higher than Rsnr32, but not much. Therefore, for de-noising, r12 is not much different from r23, but for TVE, r12 is much better than r23. So, r12 is the optimal selection in 2nd IPTRM. From Fig. 4b, Rsnr43 and Rsnr32 are better than the others, but Rsnr32 is better than Rsnr43 generally. So, as for de-noising, r23 and r34 are all good, but for TVE, r23 is much better than r34. So, r23 is the optimal selection in 4th IPTRM. Similarly, from Fig. 4c, r34

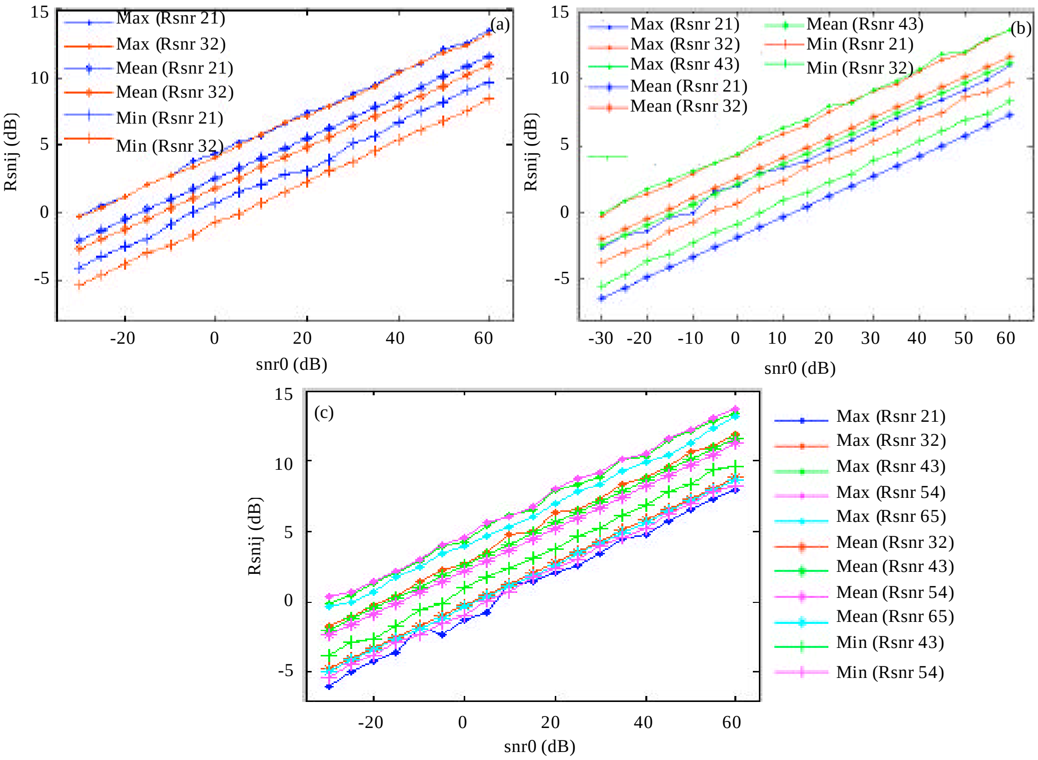

Fig. 4(a)-(c): The relation between Rsnr and snr0, (a) Rsnrij in 2nd IPTAM, (b) Rsnrij in 4th IPTAM, (c) Rsnrij in 6th IPTAM

is the optimal selection in 6th IPTRM. Expanding to the other number of iteration, assuming the number of iteration is k = 2n, the optimal selection is $r_{n(n+1)}$.

Selection of optimized G0: G0 has effect on the TVE and de-noising of IPTRM and should be selected properly. Fig. 3 has shown the relation between TVE and G0 and the smaller G0 is, the higher TVE can get. Figure 5 is shown the trend of SNR increment Rsnrij changing with G0. Rsnrij is a monotonically increasing function of G0 and gradually gets steady as a whole. When snr0 is above 0dB, Rsnr21 in z2, Rsnr32 in z4 and Rsnr43 in z6 are all bigger than 0dB and keep flat. That is to say, as for these optimal selections in different IPTRM, their capacities of de-noising are nearly not influenced by G0. However, the other non optimal selections are more sensitive to G0, the small G0 will aggravate the SNR in IPTRM on the contrary.

Therefore, totally considering the TVE and de-noising characteristics above, when using the optical selection, G0 should be small, because smaller G0 can make the Gij and Tij bigger while the de-noising function is well kept constant. The G0 in practical channel can't be changed, but the G0 in the estimated channel used in IPTRM can be changed manually and freely. This is a convenient way to reduce G0 to get better results.

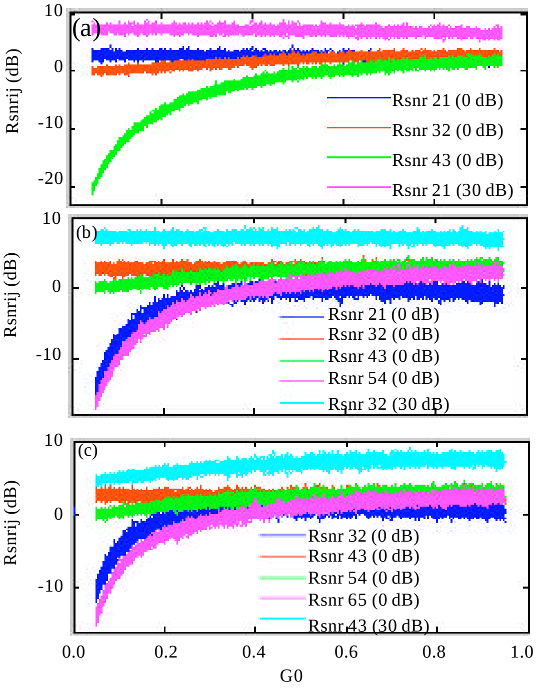

Fig. 5(a)-(c): Relation between Rsnr and G0, a1 = 0.1~12, (a) Rsnr changes with G0 in z2, (b) Rsnr changes with G0 in z4, (c) Rsnr changes with G0 in z6

CONCLUSION

Multipath fading of signal is tough problem often encountered in communication and measurement using sound, laser or radar. TVE is an important technology to deal with multipath fading. Its main idea is to give the larger gain to the signal passing the longer path, so that to make up for its energy losing. TRM's the function of self-focusing makes it effective in blind TVE. IPTRM much further strengths its TVE function by iteration, because being realized in software, it doesn't need any more extra hardware cost and complexity.

This study described and analyzed the principle of TVE of IPTRM for the multipath signal in mathematics, presented the formulas of Gain Ratio and its times in 2nd IPTRM and simulated the characteristics of IPTRM in both TVE and de-noising clearly. On the base of the analysis of IPTRM of the two paths condition, if the number of iteration is $k = 2n$, the optimal selection of the interesting part of the IPTRM output is the part including nth and (n+1)th sub-waves. This selection has the bigger time varying Gain ratio and the Gain ratio times. It also has the better de-noising capability under the condition when SNR of the originally received signal snr0 higher than 0dB, the bigger snr0 is, the higher the capability it has. G0 has remarkable effect on the Gain ratio and its times and has some effect on the de-noising capability. As for the optimal selection, the de-noising capability is rather robust to G0, hence, changing G0 in estimated channel manually can better the gain ratio and gain ration times without any decreasing the SNR promotion.

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