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Optimal One Bit Time Reversal For UWB Impulse Radio In Multi-User Wireless Communications

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***Abstract*—In this paper, with the purpose of further reducing the complexity of the system, while keeping its temporal and spatial focusing performance, we investigate the possibility of using optimal one bit time reversal (TR) system for impulse radio ultra wideband multi-user wireless communications. The results show that, by optimally selecting the number of used taps in the pre-filter the optimal one bit TR system can outperform the full one bit TR system. In some cases, the temporal and spatial focusing performance of the optimal one bit TR system appears to be compatible with that of the original TR system. This is a significant result as the overhead cost is much lower than it is required in the original TR system.

***Keywords*—Time reversal, optimal one bit, UWB, multi-user interference, inter symbol interference

I. INTRODUCTION

RECENT research works have shown great interests on the application of the time reversal (TR) technique to wireless communications ([1], [2], [3], [4], [5]). Due to the spatial focusing and temporal focusing properties of the TR, major problems in wireless communications such as inter symbol interference (ISI) and multi-user interference (MUI) can be alleviated. Moreover, by using TR, the complexity burden at the receiver side can be moved to the transmitter side which allows for a very simple receiver structure. As long as we can have good temporal focusing and spatial focusing performance, single tap receiver can be deployed and the need for a complex equalizer at the receiver can be alleviated [6]. With these properties, TR is very suitable for wireless sensor network where impulse radio ultra wideband (UWB) platform is a good example.

TR requires the knowledge of channel impulse response (IR) at the transmitter to operate. The principle is that if we use a pre-filter with the coefficients correspond to the time reversed version of the complex conjugate channel IRs, the transmit signal will trace through the same track it has experienced before. We then have both temporal focusing (in the delay domain) and spatial focusing (in the space domain) at the same time. In a time duplex division systems, the recorded channel IRs in the uplink can be used to estimate the channel IRs in the downlink. In general, TR needs more than one transmitting antenna in order to obtain good temporal and spatial focusing performance. Therefore, there is a trade off between the performance of TR and the complexity of the system, even though it is mostly still at the transmitter side.

The system complexity increases along with the number of transmitting antennas, the length of the pre-filters as well as the quantization steps used in the channel estimation process. The system complexity becomes a practical hurdle should TR be implemented on the impulse radio UWB platform. In an impulse radio UWB systems with a transmission rate up to Giga symbols per second, it is practically very difficult to deploy the pre-filter TR with a very fine quantization steps. Several attempts have been made to reduce the complexity of the TR system by using only the phase of the recorded channel IR, the so-called one bit TR, to construct the pre-filter ([7], [8], [9]). However, the temporal focusing performance of the one bit system can be shown to be sub-optimal. With the purpose of further reducing the complexity of the system, while keeping its temporal and spatial focusing performance, in this work we investigate the possibility of using optimal one bit TR system for impulse radio UWB multi-user wireless communications. We then try to find the optimum number of taps which should be used to design the pre-filter to obtain the best system performance

The paper is organized in the following way. Section II briefly describes the working principle of TR and its signal formulations. Section III presents the motivation of the optimal one bit TR and metrics to quantify its performance. Optimum number of used taps for the optimal one bit TR is also derived in the same section. In section IV, we present and compare the results obtained from a semi-analytical approach, simulation based approach and measurement based approach. Section V wraps up the paper by conclusion and remarks.

II. TIME REVERSAL TECHNIQUE AND SIGNAL FORMULATIONS

The original TR technique consists in pre-filtering the transmitted signal by convolving it with a time reversed replica of the complex channel impulse response. The mathematical formulation of the received signal of a single input single output (SISO) link using TR in the absence of noise can be described as follows

$$y_j(t) = s_j(t) \star f_{ij}(t) \star h_{ij}(t) = s_j(t) \star R_{ij}^{auto}(t) \qquad (1)$$

where $\star$ denotes convolution, * indicates the complex conjugate; $f_{ij}(t)$ is the pre-filter which in the case of the original TR $f_{ij}(t) = h(-t)^*$; $R_{ij}^{auto}(t)$ is the autocorrelation of the channel IR $h_{ij}(t)$ between the i^{th} transmitting antenna and the j^{th} receiving antenna; $s_j(t)$ is the transmitted signal intended for the j^{th} user (receiving antenna).

The received signal at the off-target point has the form

$$s_j(t) \star f_{ij}(t) \star h_{ik}(t) = s_j(t) \star R_{ikj}^{cross}(t) \qquad (2)$$

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TR for SISO system works in the same manner as the traditional Pre-Rake system [10]. Although TR-SISO offers a moderate spatial focusing advantage, it has been shown that no temporal focusing can be obtained if the delay spread is used as the performance indicator. When there are N_t transmitting antennas (MISO system), under ideal conditions the received signal becomes the sum of N_t IR autocorrelations. The received signals are not only coherently added in the temporal domain (at a certain delay) but also in the spatial domain (at a certain location). Thereby, spatio-temporal focusing can be obtained at the same time. Due to the spatial focusing, the interference can be reduced and due to the time compression, the ISI can be alleviated. In that case, the received signal in the absence of noise is given by

$$y_j(t) = s_j(t) \star \sum_{i=1}^{N_t} R_{ij}^{auto}(t) = s_j(t) \star h_j^{eq}(t) \qquad (3)$$

where $h^{eq}(t)$ or "*equivalent IR*" denotes the sum of the autocorrelation $R_{ij}^{auto}(t)$.

III. Optimal one bit TR for UWB impulse radio multi-user communications

UWB impulse radio is a technique that uses a very narrow pulse in the order of ns for transmission. The dense multipath components can be resolved which makes UWB impulse ratio a perfect candidate for TR applications. In impulse radio UWB system, as there is no carrier we only consider the channel IR with taps of real values.

Although combining TR with impulse radio UWB has shown a great potential there are still several hurdles which make the practical deployment of TR-UWB a challenger task. First of all, it is the required number of taps which should be estimated at the transmitter. Even though high complexity signal processing algorithms could be applied at the transmitter side, being able to estimated the downlink channel IR with fine quantization steps as well as fine tap recording resolution is very challenging. Moreover, the performance enhancement brought by using a larger number of taps in the pre-filter may not be enough to compensate for the cost of the preamble overhead required to estimate the taps themselves.

On top of that, the spectrum of the transmitted impulse radio signal could be altered if we use both the magnitude and the phase of the channel IR to design the TR pre-filter. This is not a desirable effect because UWB systems operate in the industrial scientific and medical (ISM) radio band and in order to operate, the UWB signal should meet certain regulations on the transmission spectrum.

The UWB signal spectrum regulation issue on TR-UWB is solved by using only the phase of the channel IR to construct the pre-filter as in [9]. But the main drawback of this scheme is that the temporal focusing performance is inferior to that of the original TR-UWB. Thereby, to compensate for the ISI the symbol rate of the one bit TR-UWB system must be reduced. However, because the transmitted power to each user is equally controlled in the one bit TR-IR systems, its MUI level is lower than that of the original TR system with the same setting [9].

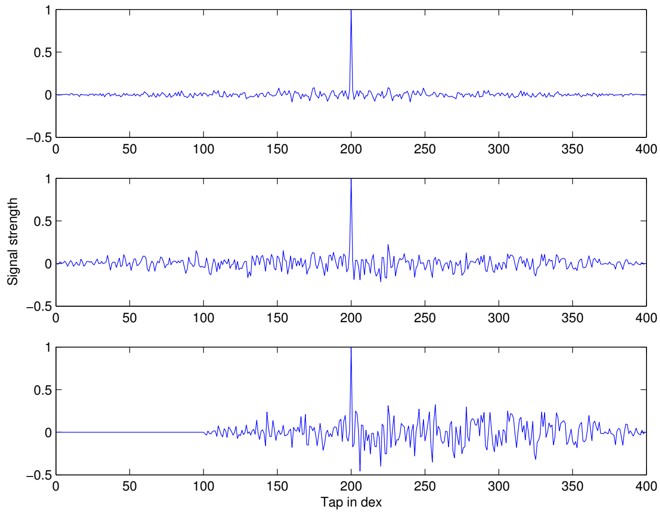

Fig. 1. Illustration on the equivalent channel IR of the original TR, one bit TR and optimal one bit TR systems

The properties of the equivalent IR of the one bit TR-IR system is follows

- The length of the equivalent IR is twice that of the original IR.
- The equivalent IR is not symmetric.
- Outside the main peak, the sidelobe level is almost the same for every tap.
- The pre-filter coefficients which corresponds to the taps of the channel with low energy have very limited contribution to the energy of the main peak. On the other hand, it increases the sidelobe energy level.

From these above observations one can intuitively deduce that, in the temporal domain the performance of the one bit TR system does not necessary improve when the number of pre-filter coefficients increases. This is because while the number of collected energy increases along with the number of pre-filter taps, the residual ISI level may also increase. Figure 1 shows an example of the equivalent channel IR of the original TR, the one bit TR and the optimal one bit TR system with four transmitting antennas.

In the spatial domain, the multi-user multiplexing performance of the one bit TR system might improve as the number of used taps in the pre-filter increases. However, as the PDP is often exponentially decayed, at certain number of taps, the desired energy collected by additional taps becomes negligible. Increasing the number of used taps above this threshold only marginally enhances the energy of the main peak as well as the MUI level. Thereby, the ratio between the desired received signal and the MUI becomes gradually saturated.

Therefore, being able to select an optimum number of the used taps in an optimal one bit TR system could improve the temporal focusing performance while maintaining the spatial focusing performance. On top of that, the complexity of the system can be significantly reduced. The structure of the pre-filter for the original, one bit and optimal one bit TR-UWB systems therefore can be formulated as follows

$$f(t) = \begin{cases} h(-t), & \text{Original TR;} \\ sign(h(-t)), & \text{1 bit TR;} \\ \begin{cases} sign(h(-t)), & t \leq P\Delta\tau; \\ 0, & t > P\Delta\tau \end{cases}, & \text{Optimal 1 bit TR.} \end{cases} \tag{4}$$

where P is the number of used taps in the pre-filter.

In wireless communication, the ISI effect occurs when the transmission rate is larger than the coherent bandwidth of the channel. Let us consider a discrete channel IR consisting of L taps and the interval between two consecutive transmitted symbols calculated as the number of channel IR taps is T, ($T \geq 1$). With a single tap TR receiver, the ISI level at the guard interval of T is calculated as

$$ISI_j(T) = P_o \left(\sum_{l=1}^{L-T} |h_j^{eq}(l)|^2 + \sum_{l=L+T}^{2L-1} |h_j^{eq}(l)|^2 \right) \tag{5}$$

where P_o is the transmit symbol power.

In a multi-user wireless communication, the spatial focusing capability of TR can be defined by how much the interference from other users can be mitigated. This interference comprises of the signals destined for other users other than the user of interest. Therefore, an inherent metric that can be used to quantify the capability of TR to focus the transmitted energy on a point of interest is the MUI level. Lower MUI level means a better focusing resolution and more users can be served. The MUI level at one particular user in a TR-UWB system with N_t transmitting antennas and N_u users can be calculated as

$$MUI_j = P_o \sum_{i=1}^{N_t} \sum_{k=1, k \neq j}^{N_u} R_{ikj}^{cross}(L) \tag{6}$$

In order to evaluate the overall performance of the single tap receiver TR systems which serve multi-user simultaneously we use the Signal to Interference ratio (SIR). The SIR is defined as the ratio of the intended received signal and the sum of the ISI and MUI levels. Thereby, the temporal focusing and spatial focusing performance of the TR system can be evaluated at the same time.

$$SIR_j(T) = \frac{P_o h_j^{eq}(L)^2}{ISI_j(T) + MUI_j} \tag{7}$$

In optimal one bit TR system, the number of used taps in the pre-filter P can be varied to obtain the optimum SIR value. In this case, at a particular guard interval T the $SIR_j(T)$ is a function of the used taps P and the optimum value of P can be found by the following criteria

$$P_{opt}(T) = \underset{P}{argmax}\, SIR_j(T) \tag{8}$$

IV. Results

A. Semi-analytical approach

Denoting the variance of the channel coefficient at the l^{th} tap of the IR as σ_l^2 and further assuming that the magnitude of each tap has Rayleigh distribution and uncorrelated scattering IRs we can calculate the mean received signal power level, the mean inter symbol interference power and the mean multi-user interference power level of the original, one bit and optimal one bit TR systems as in equations (9), (10), (11)

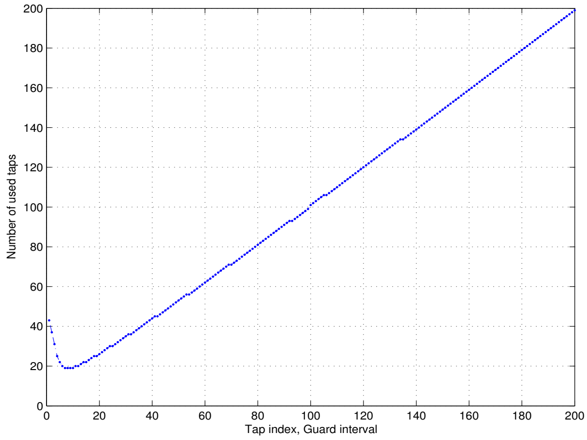

Fig. 2. Semi-analytical results of the optimum number of used taps for the Partial One bit TR systems

$$\begin{aligned} \overline{P_{S_O}} &= P_o \left(N_t \sum_{l=1}^{L} \sigma_l^4 + {N_t}^2 \left(\sum_{l=1}^{L} \sigma_l^2 \right)^2 \right) \\ \overline{P_{S_{1B}}} &= P_o {N_t}^2 \left(\sum_{l=1}^{L} \sigma_l \right)^2 \\ \overline{P_{S_{P1B}}} &= P_o {N_t}^2 \left(\sum_{l=1}^{P} \sigma_l \right)^2 \end{aligned} \tag{9}$$

$$\begin{aligned} \overline{MUI_O} &= P_o N_t (N_r - 1) \sum_{l=1}^{L} \sigma_l^4 \\ \overline{MUI_{1B}} &= P_o N_t (N_r - 1) \sum_{l=1}^{L} \sigma_l^2 \\ \overline{MUI_{P1B}} &= P_o N_t (N_r - 1) \sum_{l=1}^{P} \sigma_l^2 \end{aligned} \tag{11}$$

Using the exponential decay model for the variance of the IR taps [11]

$$\sigma_l^2 = exp\left(\frac{-(l-1)\Delta\tau}{\overline{\sigma_\tau}} \right) \tag{12}$$

where $\Delta\tau$ is the time spacing between the neighboring taps and $\overline{\sigma_\tau}$ is the mean RMS delay spread; it is possible to derive a semi-analytical results for the SIR values of the original, one bit and optimal one bit TR systems.

For optimal one bit TR-UWB, we can applied (9), (10), (11) and (12) in (7) to calculate the SIR values for one particular case and then find the optimum value of the number of used taps that gives the maximum SIR value (8). Figure 2 shows the optimum number of used taps for optimal one bit TR-UWB systems with different settings. To make it easy for the comparison of the semi-analytical results and the one obtained

$$\overline{ISI_O(T)} = 2N_tP_o\sum_{m=T}^{L}\sum_{l=1}^{L-m+1}\sigma_l^2\sigma_{l+m}^2$$

$$\overline{ISI_{1B}(T)} = \begin{cases} P_o\left(N_t\sum_{m=T}^{L}\sum_{l=m}^{L}\sigma_l^2\right), & T+P\geq L \text{ and } P<T;\\ P_oN_t\left(\sum_{m=T}^{L}\sum_{l=m}^{L}\sigma_l^2+\sum_{m=T}^{P}\sum_{l=1}^{P-m+1}\sigma_l^2\right), & T+P\geq L \text{ and } P\geq T\ ;\\ P_o\left(N_t\sum_{m=T}^{T+P}\sum_{l=m}^{T+P}\sigma_l^2\right), & T+P<L \text{ and } P<T;\\ P_oN_t\left(\sum_{m=T}^{T+P}\sum_{l=m}^{T+P}\sigma_l^2+\sum_{m=T}^{P}\sum_{l=1}^{P-m+1}\sigma_l^2\right), & T+P<L \text{ and } P\geq T\ ;\end{cases}$$

$$\overline{ISI_{P1B}(T)} = P_o\left(N_t\sum_{m=T}^{L}\sum_{l=1}^{L-m+1}\sigma_{l+m}^2+N_t\sum_{m=T}^{L}\sum_{l=1}^{L-m+1}\sigma_l^2\right) \qquad (10)$$

from Monte-Carlo simulations as well as the measurement data later on, we used L=200 taps and τ=0.33ns and $\overline{\sigma_\tau}$=12ns in the calculation. Note that the optimum values of the number of used taps are the same for different number of transmitting antennas, i.e. N_t=1..4, and different number of concurrent users, i.e. N_u=1..5. This manifests itself as the overlap of the curves in the same figure. It can be seen that the optimum number of used taps that gives the best SIR value is always smaller than the number of taps used in the original and one bit TR systems. The optimum number of taps at first decreases and then steadily increases as we extend the guard interval T. It then approaches the number of used taps in one bit TR system when the guard interval is equivalent to the number of taps of the channel IR, i.e. $L = 200$.

Figure 3 shows the semi-analytical SIR results for the original, one bit and optimal one bit TR systems with different transmitting antenna settings and number of users. As the guard interval advances, the SIR of the optimal one bit TR system always outperforms that of the one bit TR system. The SIR values of the optimal one bit TR system meet those of the one bit TR system when the guard interval is equivalent to the maximum estimated channel IR's length. At some guard interval, the SIR values of the optimal one bit system are even higher than those of the original TR system. It can be clearly seen that the ISI dominantly influences the SIR performance. On the other hand, the MUI level has little impact on the SIR values, manifests itself as a slight increase of at most 5dB in the SIR values as the number of concurrent users advances from 2 to 5.

B. Simulation approach

The UWB channel are modeled as NLOS in an office environment according to the 802.15.4a [12]. To simulate the multi-user MISO channels we assumed that the channels between transmitting antennas and between users are totally uncorrelated. Thereby, the channel IRs of a multi-user MISO system are independently generated. The parameters we used to simulated the UWB channel is tabulated in table I.

TABLE I
802.14A UWB STATISTICAL MODEL AND PARAMETERS

NLOS office Parameters	
Arrival rates	λ = 0.19, λ_{mean}= 3.1 λ_1 = 0.11, λ_2 = 2.09, β = 0.0096
Decay factors	γ=19.8, γ_0=11.2, Kγ=0, $\sigma_{cluster}$=3 γ_{rise}=15.21, γ_1=11.84, χ=0.78
Fading factors	mo=0.5, Km=0, σ_{mo}=0.25 σ_{Km}=0.25, std_shdw = 3.9;
Frequency dependent	κ=5.3, fc=4.5 GHz, fs=3 GHz
Number of IRs	100.000

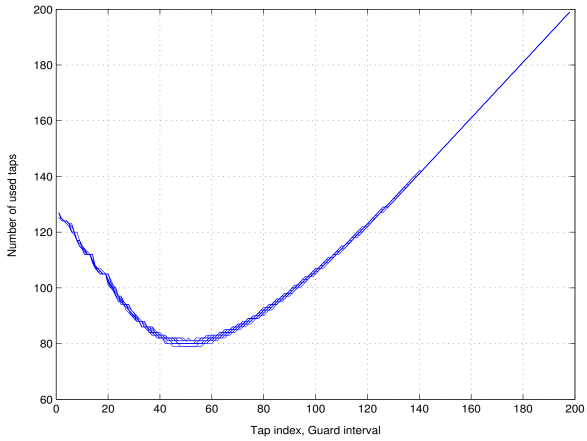

Fig. 4. Simulation results of the optimum number of used taps for the Partial One bit TR systems

Based on the generated channel IRs, we calculate the optimum number of used taps and the corresponding SIR values of the optimal one bit TR system. The SIR values of the original and one bit TR are also calculated for comparison purpose.

Figure 4 shows the optimum number of taps for optimal one bit TR-UWB systems. At first, this number goes down

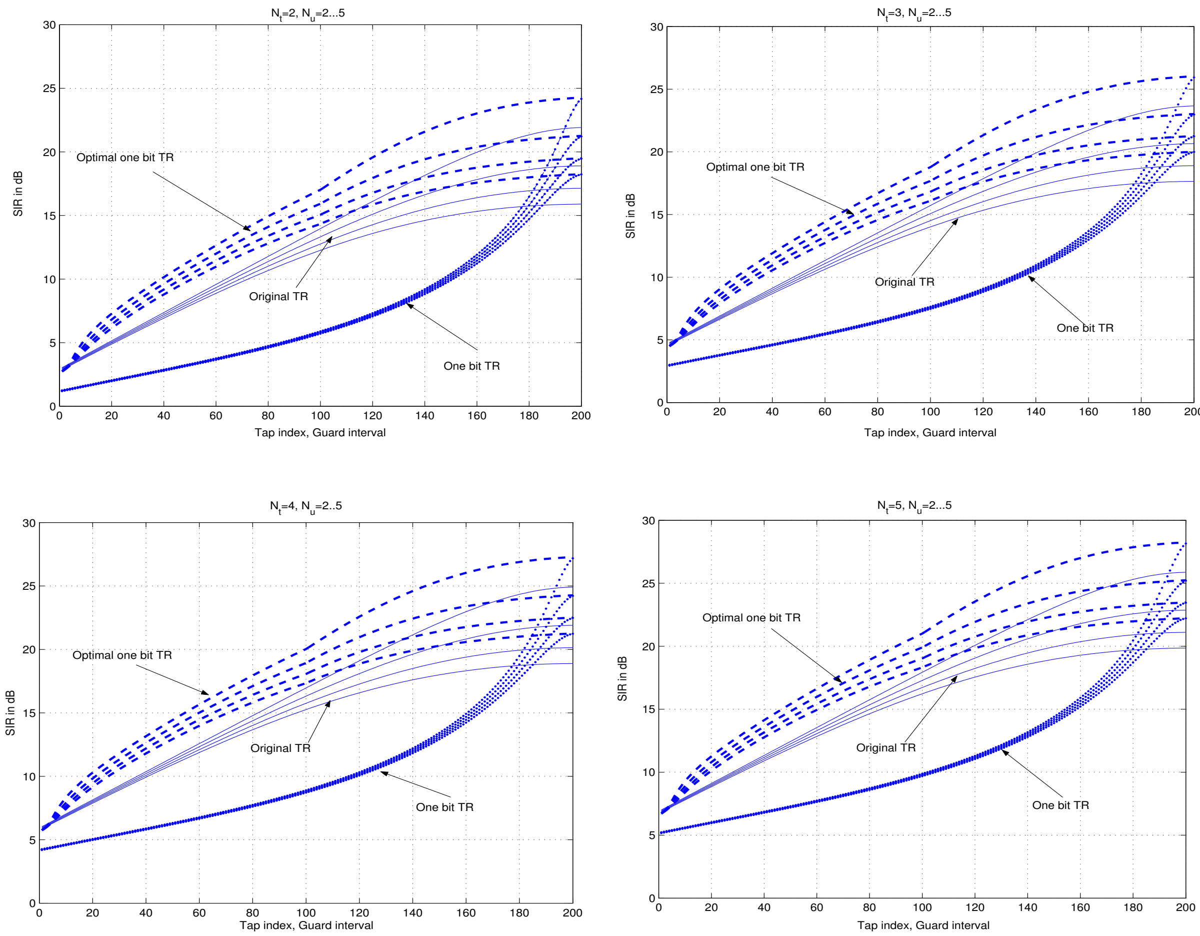

Fig. 3. Semi-analytical results of the SIR values for the traditional, One bit and Optimum Partial One bit TR system with different number of transmitting antennas and number of simultaneous users

until it reaches a minimum value. It then increases steadily along with the guard interval T. As in the semi-analytical results, the optimum number does not vary with the number of simultaneous users as well as the number of transmitting antennas. In general, the optimum number of used taps found by the simulation is always higher than which has been found by the semi-analytical approach. Nevertheless, the optimum number of taps obtained from the simulation is always smaller than the maximum number of taps used in the one bit TR-UWB system, i.e. L=200.

The SIR values calculated from the simulated channel IR of the TR-UWB system with different setting are plot in Figure 5. The range of the SIR values for most of the cases is in the same range with that obtained from the semi-analytical approach. For all system settings, the SIR values of the optimal one bit TR-UWB system are always higher than those of the one bit TR-UWB system.

It is interesting to observe that when the guard length T is around one half the length of the channel IR L, the SIR values of the one bit TR-UWB system become comparable to the SIR values of the original TR-UWB system. The number of used taps in this case is also around one half of L. With respect to the system complexity, it is a significant result. We only need to deploy half length pre-filters with one bit quantization taps to achieve the performance of an original TR-UWB system with full length pre-filter and very fine quantization steps.

The discrepancy between the semi-analytical results could be due to some limitations in the PDP modeling. For example, single cluster assumption in the PDP exponential decay model is not deployed in the model of the UWB channel.

C. Measurement based approach

To evaluate the performance of the proposed scheme in a real propagation environment, we used the measured channel data from recent measurement campaign [13]. To make it comparable with the semi-analytical and simulation results presented above we used 200 taps starting from the first arrival path, or the main peak of the measured IR in most case, as the effective length of the IR. The RMS delay spread of these measured channel IR is in the order of 10-12ns depending on the measured locations. Note that the RMS delay spread and the tap resolution of the measured channel IR are about those used in the analytical and simulation analysis.

In Figure 6 we show the optimum number of taps vs.

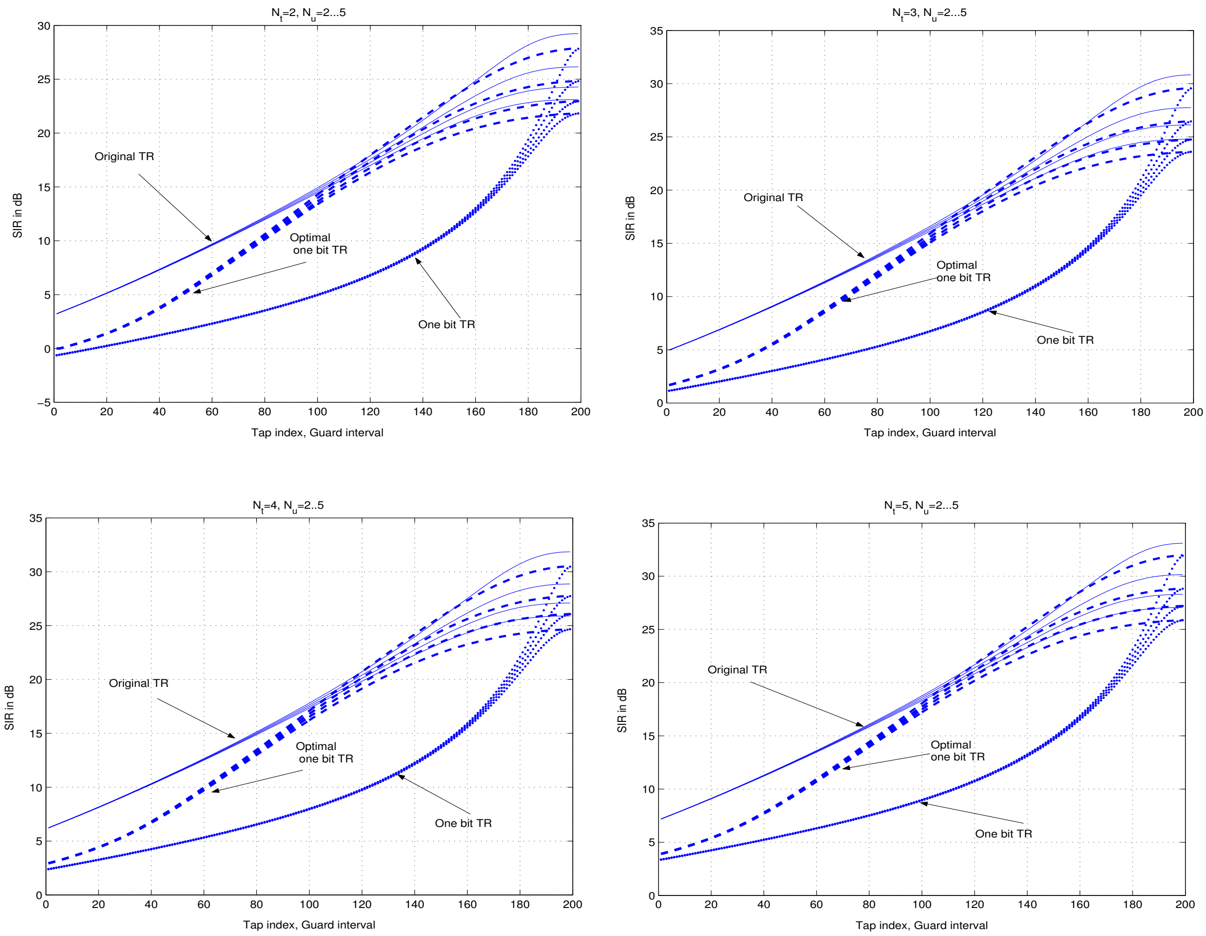

Fig. 5. Simulation results of the SIR values for the traditional, One bit and Optimum Partial One bit TR system with different number of transmitting antennas and number of simultaneous users

the guard interval T for the measured optimal one bit TR-UWB system. The optimum number of taps obtained by the analytical approach and simulation approach are also showed as references. The optimum number of taps obtained from measurement data closely follows that of the analytical result. This can be explained by the fact that the propagation is short range and therefore near LOS for most of the measured locations. It made the measured channel PDP be well modeled by the single exponential decay where the first arrival path is always the path with the highest energy. The optimum numbers of used taps obtain from measurement data are also unchanged when the number of transmitting antennas or the number of simultaneous users vary.

Figure 7 shows the SIR values for the original TR-UWB, one bit TR-UWB, optimal one bit TR-UWB with the number of used tap obtained from the semi-analytical result. Since the optimal numbers of used taps are almost the same for the measurement results and semi-analytical results, their SIR results are alike as expected. As the SIR value is not too much sensitive to the variation around its optimum value, we can use the semi-analytical results as a guideline for the design of the optimal one bit TR-UWB systems.

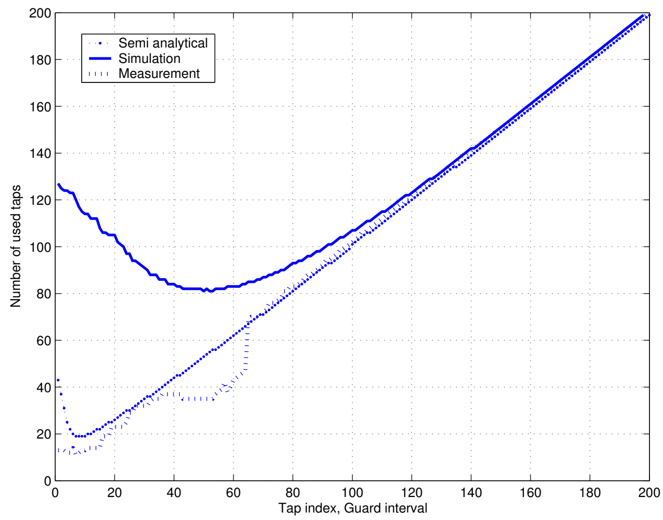

Fig. 6. Optimum number of used taps in TR-UWB system for measured channel IRs

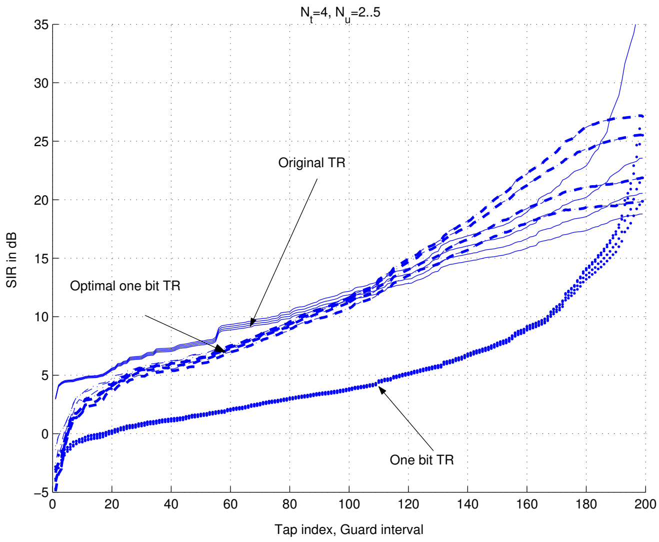

Fig. 7. SIR of the measured TR-UWB system with 4 transmitting antennas and up to 5 simultaneous users

As the guard interval advances, the SIR value of the optimal one bit TR-UWB is always better than that of the full one bit TR-UWB system. It is also shown that the ISI has greater influence on the SIRs than the MUI does. The SIR values of the optimal one bit TR-UWB system appear to be comparable with those of the original TR-UWB system. Again, this is a significant advantage as the optimal one bit system requires much lower preamble overhead.

V. Conclusion and Remarks

In this paper we proposed the use of optimal one bit TR technique for impulse radio UWB multi-user wireless communications. The optimum number of taps used in the pre-filter is derived. Semi-analytical, simulation and measurement based approaches are used to verify that, with less number of used taps, the optimal one bit system can outperform the full one bit system. This is obtained based on the fact that by optimally choosing the number of used taps, it is possible to reduce the ISI level significantly. Thereby, it leads to an improvement in the overall SIR values of the multi-users, ISI limited TR-UWB systems. The enhancement in the SIR level of the optimal one bit TR-UWB system as compare with the full one bit TR-UWB system can be as much as 10dB. This is a significant results as we can achieve better performance by while being able to reduce the system complexity.

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