An Energy Efficient Transmitted-Reference Scheme for Ultra Wideband Communications

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***Abstract*— Transmitted-Reference (TR) receivers represent a low complexity alternative to RAKE receivers, which are widely used in Ultra Wideband (UWB) communications. Known TR schemes are not very energy efficient since two pulses represent one bit value only. Therefore, we present a TR Pulse Interval Amplitude Modulation (PIAM) scheme which reduces the required energy per bit and a low complexity receiver structure for TR PIAM. We investigate the performance of TR 4PIAM analytically and by means of simulation and show that higher modulation alphabets can be adapted easily. Moreover, we show that there exists an optimal correlation length for transmission over multi-path channels.**

1. Introduction

The RAKE receiver [1] represents a widely used receiver structure for Ultra Wideband (UWB) systems which is composed of a correlator bank. Each correlator collects the energy from one multipath component of the channel by correlation with a template pulse form. This makes a large number of correlators necessary for robust transmissions. It has also to be considered that the transmitted pulse form is modified by transmit and receive antennas. Moreover, a channel estimation is needed when using a RAKE structure.

To circumvent the drawbacks of RAKE receivers, e.g. channel estimation or finding a suited template pulse form for correlation, transmitted-reference (TR) schemes are well suited. There, two pulses are transmitted, one pulse representing a reference pulse and the second pulse containing the information. TR UWB systems show some attractive properties [2], e.g., no explicit channel estimation is necessary since both reference and information pulse are transmitted through the same channel. Furthermore, TR systems are well suited for fast fading channels since the channel has to be constant over a frame with two pulses, only. TR-UWB receivers tend to behave like near-perfect RAKE receivers capturing a large percentage of the energy of multipath signals [3]. But the information rate drops by 50% since half of the pulses are reference pulses [4].
Therefore, TR-UWB systems seem to be well suited for applications where energy efficiency and low complexity are required and information rate is less important as, e.g., in wireless sensor networks. For TR pulse amplitude modulation (PAM) the receiver consists only of a correlator. But since every bit value is represented by two pulses, the transmitter is not very energy efficient. Therefore, we propose in this paper a TR pulse interval amplitude modulation (PIAM) scheme where two pulses represent at least two bit values. This reduces the required energy per bit value at the transmitter on cost of the receiver complexity. Nevertheless, the proposed receiver structure has still low complexity.

2. State of the art

In [5], [6], [7] and [8] a delay-hopped transmitted-reference (DHTR) scheme is presented for multi-user access. For modulation, TR PAM is used where the information is carried in the amplitude of the second pulse. To distinguish different users, the delay between reference and information pulse changes following a code division multiple access (CDMA) code known to transmitter and receiver. The presented receiver structure consists of a bank of pulse pair correlators and a subsequent delay hopping CDMA code word correlator.

Based on the DHTR scheme in [6] an improved signal processing model for the TR receiver is presented in [9]. However, the impact of the new receiver structure on the decoding performance is not shown.

Another approach which uses TR signaling for multiple-access in UWB is given in [10] and [11]. There, the multiple-pulse multiple-delay (MDMP) modulation scheme is introduced where the pulses are represented by mutually orthogonal chirp pulses.

The combination of TR signaling with binary block-coded pulse-position modulation for the single user case is presented in [12] and [13]. It is assumed that the reference pulse is an average of several previously received reference pulses which yields an almost noiseless template. The authors show that the system performance strongly depends on the noise cancellation in the received reference pulse. Furthermore, it is shown that the error probability decreases with increasing correlation time. But it is not considered that the performance decreases with to long correlation time and that there exists an optimal correlation length, which we will show in section 6.

For wireless sensor networks with asymmetric data channels where a sensor node has only transmit capabilities and has to be very energy efficient the above mentioned TR schemes are not well suited. Since all the above TR schemes assume binary signaling, two pulses represent only one bit value which is not energy efficient. Therefore, it would be desirable to represent more than one bit value with two pulses to reduce the energy which is needed to transmit one bit value.

TR as special case of pilot waveform assisted modulation (PWAM) with PAM and pulse position modulation (PPM) is investigated in [4]. In contrast to TR systems PWAM is not suited for fast fading channels since the channel has to be static for the time between two reference pulses (pilots).

In [2] a TR system with M-ary signal set is presented for the single user case. The receiver consists of a bank of pulse pair correlators where the reference pulse is delayed by a different lag in each correlator. By performing a joint decision of the correlator outputs based on the maximum likelihood criterion the error performance can be improved compared to TR PAM.

This scheme seems to be suited for the use in above mentioned energy efficient transmitters for asymmetric data channels. But the performance gain compared to TR PAM is realized at cost of a complex joint detection. This yields a very complex receiver structure. Therefore, we propose a very simple joint detection scheme which is based on the Transmitted-Reference Pulse Interval Amplitude Modulation (TR PIAM). This scheme is well suited for energy efficient transmitter and low complexity receiver. We will show that TR PIAM with our simple receiver structure outperforms TR PAM in the for UWB important low SNR regime.

3. Transmitted Reference Pulse Interval Amplitude Modulation

In contrast to most existing transmitted-reference schemes where information is contained only in the amplitude or only in the delay of two subsequent pulses, information in Transmitted-Reference Pulse Interval Amplitude Modulation (TR PIAM) systems is contained in the amplitude as well as in the delay between two subsequent pulses. For TR 4PIAM the transmit signal $s(t)$ is given by

$$s(t) = p(t) + s_1 \cdot p(t - T_I - \frac{|s_2 - s_1|}{2} \cdot T_D) \qquad (1)$$

$p(t)$ denotes the pulse form, $s_1, s_2 \in \{-1; 1\}$ are the bit values, T_I and T_D are the bit-independent and bit-dependent delays of the second pulse. With this scheme 4 different transmit signals can be described as shown in Fig. 1, each representing 2 bit values. A time hopping

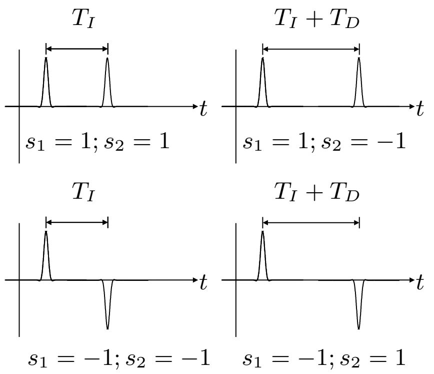

Fig. 1. Possible pulse constellations for TR 4PIAM

code can be adapted to the TR PIAM scheme easily. But due to simplicity of the description it is neglected here.

At the receiver side we consider a simple structure which consists of two correlators with different delays $T_1 = T_I$ and $T_2 = T_I + T_D$ as shown in Fig. 2. We assume that the delays are larger than the pulse duration, i.e. $T_1 > T_P$ and $T_2 > T_P$. Depending on the transmit signal the output signal of one correlator is the correlation of the reference signal with the information signal while the output signal of the other correlator is the correlation of the reference signal with noise.

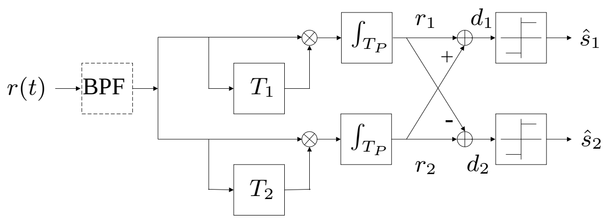

Fig. 2. Simple receiver structure for TR 4PIAM

The output signals r_1 and r_2 of the correlators are fed into two adders. Behind the adders the transmit signal is estimated as

$$\hat{s}_1 = \begin{cases} -1 & \text{if} \quad d_1 = r_1 + r_2 < 0 \\ 1 & \text{otherwise} \end{cases}$$

$$\hat{s}_2 = \begin{cases} -1 & \text{if} \quad d_2 = r_1 - r_2 < 0 \\ 1 & \text{otherwise} \end{cases}$$

using two slicers.

4. Analytical Performance Evaluation

Since the presented TR 4PIAM receiver consists of two correlators with subsequent adders it could be assumed that the error performance is the same as for TR PAM with one correlator as receiver. Therefore, we investigate signal and noise terms for the additive white Gaussian noise (AWGN) channel. The receive signal $r(t)$ for TR 4PIAM can be written as

$$r(t) = s(t) + n(t) \qquad (2)$$

with $s(t)$ as signal given in (1) and $n(t)$ as additive white gaussian noise (AWGN). With (2) and with $s_2' = \frac{|s_2 - s_1|}{2}$, the correlation over one pulse duration T_P at the receiver with lag T_1 yields

$$\begin{aligned} r_1 &= \int_{T_P} r(t) \cdot r(t - T_1) dt \qquad (3) \\ &= \int_{T_P} (s(t) + n(t)) \cdot (s(t - T_1) + n(t - T_1))\, dt \end{aligned}$$

If we only consider the non-zero components in (3) we get

$$\begin{aligned} r_1 &= \int_{T_P} n(t) \cdot n(t - T_1) + p(t) \cdot n(t - T_1) \\ &+ \ n(t) \cdot p(t - T_1) \\ &+ \ s_1 \cdot p(t - T_I - s_2' T_D) \cdot p(t - T_1) \\ &+ \ s_1 \cdot p(t - T_I - s_2' T_D) \cdot n(t - T_1) \\ &+ \ s_1 \cdot p((t - T_1) - T_I - s_2' T_D) \cdot n(t) dt \qquad (4) \end{aligned}$$

In (4), $r_{1s} = \int_{T_P} s_1 \cdot p(t - T_I - s_2' T_D) \cdot p(t - T_1) dt$ represents the term which carries the information while the other terms are noise. If we confine on the noise terms we get

$$
\begin{aligned}
r_{1n} \;=\; & \int_{T_1}^{T_1+T_P} n(t)\cdot n(t-T_1) + p(t)\cdot n(t-T_1) \\
+\; & n(t)\cdot p(t-T_1) \\
+\; & s_1\cdot p(t-T_I-s_2'T_D)\cdot n(t-T_1) \\
+\; & s_1\cdot p((t-T_1)-T_I-s_2'T_D)\cdot n(t)dt
\end{aligned} \tag{5}
$$

at the output of the first correlator. In the same way the noise term at the output of the second correlator with lag T_2 can be written as

$$
\begin{aligned}
r_{2n} \;=\; & \int_{T_2}^{T_2+T_P} n(t)\cdot n(t-T_2) + p(t)\cdot n(t-T_2) \\
+\; & n(t)\cdot p(t-T_2) \\
+\; & s_1\cdot p(t-T_I-s_2'T_D)\cdot n(t-T_2) \\
+\; & s_1\cdot p((t-T_2)-T_I-s_2'T_D)\cdot n(t)dt
\end{aligned} \tag{6}
$$

With (5) and (6), the noise component of d_1 can be derived as

$$
\begin{aligned}
d_{1n} \;=\; & \int_0^{T_P} n(t+T_1)\cdot n(t) + n(t+T_1)\cdot p(t) \\
+\; & s_1\cdot p((t+T_1)-T_I-s_2'T_D)\cdot n(t) \\
+\; & n(t+T_2)\cdot n(t) + n(t+T_2)\cdot p(t) \\
+\; & s_1\cdot p((t+T_2)-T_I-s_2'T_D)\cdot n(t) \\
+\; & p(t+T_1)\cdot n(t) \\
+\; & s_1\cdot p(t-T_I-s_2'T_D)\cdot n(t+T_1) \\
+\; & p(t+T_2)\cdot n(t) \\
+\; & s_1\cdot p(t-T_I-s_2'T_D)\cdot n(t+T_2)dt
\end{aligned} \tag{7}
$$

Since $T_1 > T_P$ and $T_2 > T_P$ the last four terms in (7) do not contribute to the correlation and d_{1n} can be written as

$$
\begin{aligned}
d_{1n} \;=\; & \int_0^{T_P} n(t+T_1)\cdot n(t) + n(t+T_1)\cdot p(t) \\
+\; & n(t+T_2)\cdot n(t) + n(t+T_2)\cdot p(t) \\
+\; & s_1\cdot p((t+T_1)-T_I-s_2'T_D)\cdot n(t) \\
+\; & s_1\cdot p((t+T_2)-T_I-s_2'T_D)\cdot n(t)dt
\end{aligned} \tag{8}
$$

In the same way the noise component d_{2n} of d_2 is given by

$$
\begin{aligned}
d_{2n} \;=\; & \int_0^{T_P} n(t+T_1)\cdot n(t) + n(t+T_1)\cdot p(t) \\
-\; & n(t+T_2)\cdot n(t) - n(t+T_2)\cdot p(t) \\
+\; & s_1\cdot p((t+T_1)-T_I-s_2'T_D)\cdot n(t) \\
-\; & s_1\cdot p((t+T_2)-T_I-s_2'T_D)\cdot n(t)dt
\end{aligned} \tag{9}
$$

If a signal $s(t)$ is transmitted where the second pulse is delayed by T_1, i.e. $s_2' = 0$, both the last term in (8) and the last term in (9) become 0. As well, if the second pulse of the transmit signal is delayed by T_2, i.e. $s_2' = 1$, both the second last term in (8) and the second last term in (9) become 0. With the noise components d_{1n} and d_{2n} and with $d_s = r_{1s}$ as signal component of d_1 and d_2, the signal-to-noise ratio SNR for TR 4PIAM is given by

$$
SNR_{\text{TR 4PIAM}} = \frac{|d_s|^2}{\text{var}(d_{1n})} + \frac{|d_s|^2}{\text{var}(d_{2n})} \approx \frac{|\int_0^{T_P} p^2(t)dt|^2}{\text{var}(d_{1n})} \tag{10}
$$

with var$(\cdot)$ as variance. If we compare a TR PAM correlation receiver with same energy per bit as for TR 4PIAM the transmit signal $s(t)$ can be written as

$$
s(t) = \frac{1}{\sqrt{2}}p(t) + \frac{1}{\sqrt{2}}s_1 p(t-T) \tag{11}
$$

where $p(t)$ denotes the pulse form and s_1 the bit value.

Analog to TR 4PIAM, the signal component d_s of r can be derived for TR PAM as

$$
d_s = \int_0^T \frac{1}{2}s_1 p^2(t)dt \tag{12}
$$

and the noise component d_n of r as

$$
d_n = \int_0^T \frac{1}{\sqrt{2}}p(t)n(t+T) + \frac{1}{\sqrt{2}}s_1 p(t)n(t) + n(t+T)n(t)dt \tag{13}
$$

With (12) and (13) the signal-to-noise ratio for TR PAM can be written as

$$
SNR_{\text{TR PAM}} = \frac{|d_s|^2}{\text{var}(d_n)} = \frac{|\int_0^{T_P} p^2(t)dt|^2}{4\cdot\text{var}(d_n)} \tag{14}
$$

Assuming $T_p > |T_1 - T_2|$, it can be shown by evaluation of

$$
4\cdot\text{var}(d_n) = 4\cdot\mathcal{E}\left\{d_n - \mathcal{E}\left\{d_n\right\}\right\}^2 \tag{15}
$$

with $\mathcal{E}\{\cdot\}$ denoting the expectation operator, that $4\cdot$ var(d_n) in (15) is larger than var(d_{1n}) in (10) for the same signal energy per bit. With it, $SNR_{\text{TR PAM}} < SNR_{\text{TR 4PIAM}}$ and therefore, the TR 4PIAM receiver will show a better error performance than the TR PAM receiver.

5. Higher modulation alphabets

If an application requires a lower transmit energy than it is possible with TR 4PIAM and allows a more complex receiver structure, the TR PIAM scheme can easily be extended to higher modulation schemes where two pulses represent more than two bit values. For the transmission of three bit values s_1, s_2 and s_3, four different time delays are necessary when using two different amplitude values ± 1. The transmit signal for TR 8PIAM is then given by

$$
s(t) = p(t) + s_1 p(t - T_I - (\frac{|s_3 - s_2|}{2} + |s_2 - s_1|)T_D)
$$

with the delays $T_1 = T_I$, $T_2 = T_I - T_D$, $T_3 = T_I - 2T_D$ and $T_4 = T_I - 3T_D$. The simple receiver structure for TR 4PIAM shown in Fig. 2 can easily be extended to a

TR 8PIAM receiver by adding two correlators, an adder and a slicer as shown in Fig 3.

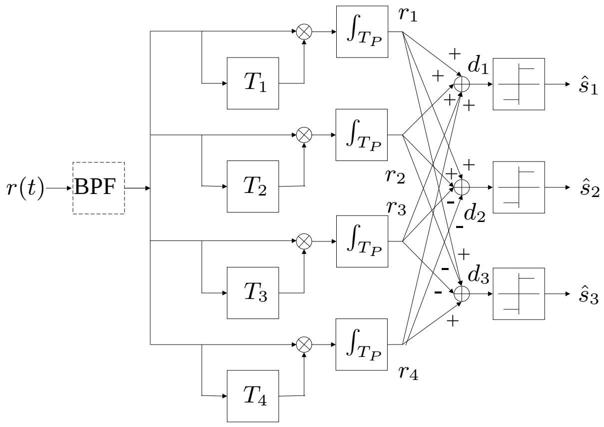

Fig. 3. Receiver structure for TR 8PIAM

The decision variables d_i, which are fed to the slicers, can be derived directly from the correlator outputs r_i as

$$\begin{aligned} d_1 &= r_1 + r_2 + r_3 + r_4 \\ d_2 &= r_1 + r_2 - r_3 - r_4 \\ d_3 &= r_1 - r_2 - r_3 + r_4 \end{aligned}$$

Using TR 16PIAM the transmit signal generating eight different delays can be written as

$$\begin{aligned} s(t) &= p(t) + s_1 p(t - T_I \\ &- (\frac{|s_4 - s_3|}{2} + |s_4 - s_2| + 2|s_4 - s_1|)T_D) \end{aligned}$$

The receiver structure for TR 16PIAM consists of eight correlators with different delays and four adders. The summation of the correlator outputs yields the decision variables

$$\begin{aligned} d_1 &= r_1 + r_2 + r_3 + r_4 + r_5 + r_6 + r_7 + r_8 \\ d_2 &= r_1 + r_2 - r_3 - r_4 - r_5 - r_6 + r_7 + r_8 \\ d_3 &= r_1 - r_2 + r_3 - r_4 - r_5 + r_6 - r_7 + r_8 \\ d_4 &= r_1 + r_2 + r_3 + r_4 - r_5 - r_6 - r_7 - r_8 \end{aligned}$$

6. Simulation Results

To verify the results achieved in section 4 we perform simulations where the TR PIAM schemes are compared with the TR PAM scheme. The bit error ratio (BER) curves are simulated for AWGN channels and for the IEEE 802.15 channel models 1 and 2 [14]. The first channel model is based on time domain channel measurements for line-of-sight (LOS) channels between 0 and 4 meters while the second one is based on non line-of-sight (NLOS) channels between 0 and 4 meters. Moreover, we assume perfect synchronization and a channel that is static over one TR symbol consisting of two consecutive pulses.

a) AWGN Channel: In Fig. 4 the BER curves are shown over signal-to-noise ratio E_b/N_0. E_b denotes the energy per bit and $N_0/2$ is the noise spectral power density. As expected from the considerations in section 4 the BER for TR 4PIAM is lower than the BER for TR PAM and performs about 1dB better. For low E_b/N_0 up to about 10dB the BER of TR PAM is worse than that of TR 8PIAM.

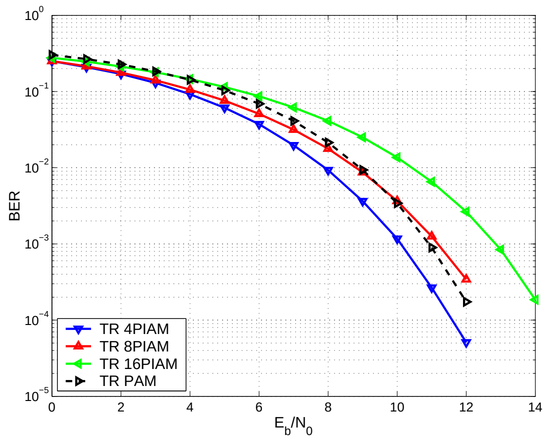

Fig. 4. Comparison of bit error ratios for AWGN channel

b) Multipath Channel: Since energy is spread over the multipath components in multipath channels, the correlation length in the receiver has severe impact on the performance. If the correlation length is too short, not enough energy is collected from the multipath components. But since the energy of the multipath components is decreasing with time, more and more noise energy is collected with increasing correlation length while less and less signal energy is collected. In Fig. 5 we show bit error ratios for TR 4PIAM for LOS and NLOS channels varying the correlation length. The signal-to-noise ratio per bit is set to $E_b/N_0 = 12$dB. The pulse bandwidth is chosen to be 1.2 GHz which corresponds to a pulse duration of $T_P \approx 834$ ps. As expected, it

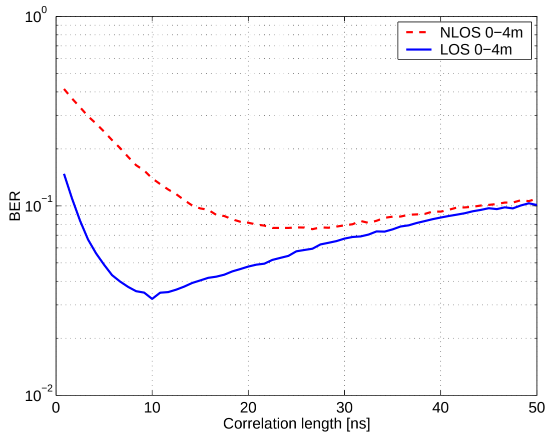

Fig. 5. Bit error ratios for TR 4PIAM with different correlation lengths ($E_b/N_0 = 12$dB)

can be seen that the error performance strongly depends on the correlation length. For LOS channels the optimal correlation length is about 10ns. The optimal correlation length for NLOS channels is with about 25ns obviously longer since the channel impulse response is decaying slower and the energy is spread over more multipath components. An interesting fact is that the energies of the multipath components up to the above mentioned optimal correlation lengths correspond to about 90% of the whole energies of all multipath components. It can be also seen that the BER remains almost constant for slight variations of the correlation length (about up to ± 2ns for LOS and ± 10ns for NLOS) around the optimum.

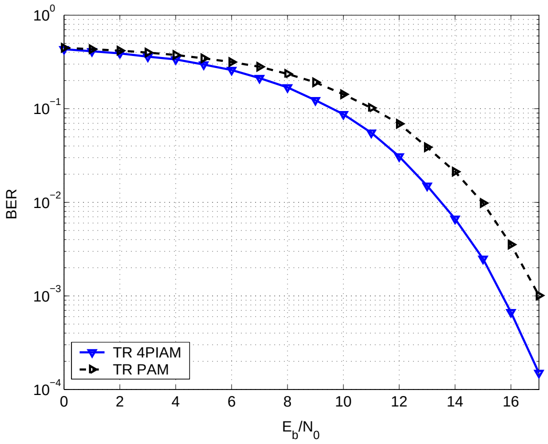

Fig. 6. Bit error ratios for LOS channels from 0-4 meters

The bit error ratios for LOS channels are presented in Fig. 6 using the optimum correlation length determined above. The pulse repetition time is chosen such that all multipath components of a pulse are received before the next pulse is transmitted, which corresponds to a best case consideration. Compared to the AWGN channel the performance is about 6 dB worse at $BER = 10^{-3}$. Nevertheless, the relation between different modulation schemes remains the same. Thus, TR 4PIAM performs here also about 1dB better than TR PAM. This is also true for the bit error ratios for NLOS channels, which are shown in Fig. 7. But the error performance is only slightly worse compared to the LOS channels results using the optimal correlation length.

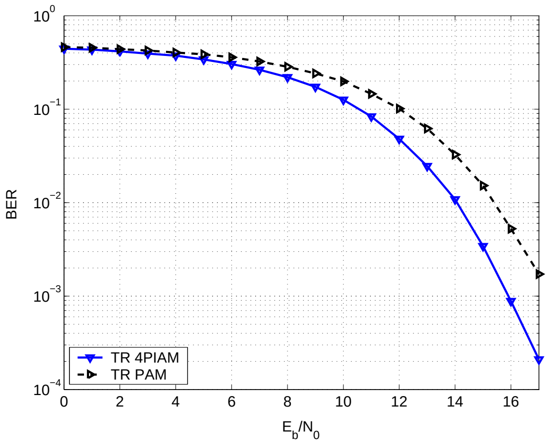

Fig. 7. Bit error ratios for NLOS channels from 0-4 meters

7. Conclusion

We presented a very simple receiver structure for the TR PIAM scheme that is well suited for the use in asymmetric data channels with energy efficient transmitter and low complexity receiver. There, two pulses represent at least two bit values. Moreover, we showed analytically that the SNR for the proposed TR 4PIAM receiver is lower than for TR PAM. By means of simulation we verified this result and showed that TR 4PIAM outperforms TR PAM not only in AWGN channels but also in LOS and NLOS multipath channels. In the low SNR regime also TR 8PIAM and TR 16PIAM show a good BER performance. These both modulation schemes are suited if the transmit energy per bit has to be reduced further. We also showed that there exists an optimal correlation length which depends on the multipath channel. But it could be shown that this optimal correlation length is achieved if about 90% of the energy of all multipath components is collected.

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