Synchronization-Free Data Detection for UWB Communications

Vincenzo Lottici[*], *Zhi Tian*[†] and *Geert Leus*[‡]

[*]Department of Information Engineering, University of Pisa, Pisa, Italy
[†]Dept. of Electrical & Computer Engineering, Michigan Technological University, Houghton, MI, USA
[‡]Faculty of Electrical Engineering, Delft University of Technology, Delft, The Netherlands
Emails: vincenzo.lottici@iet.unipi.it; ztian@mtu.edu; g.leus@tudelft.nl

Abstract— **The dense multipath scattering typical of ultra-wideband (UWB) wireless channels provides very large multipath diversity, but from the other side makes the receiver design a demanding task as far as channel estimation and timing recovery are concerned. The contribution of this paper is to derive a novel receiver structure based on the multiple symbols differential detection (MSDD) framework with particular emphasis on bypassing costly channel estimation and relaxing the stringent requirements imposed on timing recovery. The computational complexity of the proposed detection scheme, that becomes quite impractical as the data block size increases, is then circumvented by resorting to an efficient implementation based on the sphere decoding (SD) algorithm. Simulation results carried out in typical multipath propagation scenarios verify that appealing detection performance is achieved at affordable receiver complexity.**

I. Introduction

Conveying information over a stream of very low power density and ultrashort pulses, the UWB concept lends itself to efficiently meeting the stringent requirements of state-of-the-art low-cost short-range high-speed wireless communications. UWB radios come with many appealing features, such as fine timing resolution, robustness against multipath, potentiality for very high data rates and large user capacity, and coexistence with existing services via frequency-overlay operations [1]. The harsh multipath propagation conditions occurring in indoor environments, however, make the energy capture of the received waveform a very demanding task, especially in view of the limited receiver affordable complexity. The well-known Rake receiver has the potential of capturing a significant level of received energy. The cost to be paid that inhibits its choice is a large number of correlator-based fingers together with an intensive computational load involved in the estimation of channel parameters [2]. Viable alternative approaches for efficient energy capture without requiring any prior channel estimation have been recently proposed in the form of transmitted reference (TR) methods or differential detectors (DDs). In the former, the received waveform resulting from the "information-free" reference pulse(s) is used as noisy template in a simple correlation receiver for data detection [3], [6], [7]. In the latter, instead, differential encoding of information data allows to detect the current symbol using as noisy template the signal waveform received within the previous symbol interval [4], [5]. Then, the inherent drawbacks still being present in the above approaches, such as additional transmit power and decreased data rate caused by the reference pulses in TR and poor performance for multiple access environments in DD, have been circumvented with the multiple symbol differential detection (MSDD) scheme, as pursued in [8] and [9]. Herein, the channel invariance within the coherence time is exploited to jointly detect a block of differentially-encoded symbols experiencing the same unknown channel, without any knowledge of the multipath channel impulse response.

The aforementioned developments stand for promising energy-efficient receivers in comparison with traditional Rake processing, but the condition to be fulfilled is that accurate timing information be recovered from the received signal. Due to the unique structure of UWB signaling, timing synchronization means to identify at frame level where the first frame in each symbol starts, and then to find at the pulse level where a pulse is located within a frame. Properly designed schemes are usually called upon to meet the stringent accuracy requirements, that inevitably add to the overall receiver complexity; see [10] and references therein. Hence, the aim of achieving an even lower complexity receiver pushes toward a non-coherent receiver that avoids not only channel estimation, but also timing synchronization, while ensuring an efficient performance versus affordable computational load tradeoff.

Motivated by this need, this paper contributes to deriving a novel receiver structure based on the MSDD framework under the assumption that timing information is only partially acquired with a rough accuracy within the symbol interval. Viewing the mistiming effect as intersymbol interference (ISI) and explicitly dealing with it within the detection process, the correlation between consecutive received symbol waveforms induced by the ISI is exploited to jointly detect a burst of consecutive symbols included in the channel coherence time. The receiver structure is derived following the GLRT rule as optimization criterion, according to which the maximization of the likelihood function is performed over the unknown symbols and all the finite-energy received template waveforms. Then, the cost of high computational complexity going up exponentially in the burst length is avoided through an efficient implementation of the proposed detection rule based on a modified version of the sphere decoding (SD) method, as originally proposed in [8]. Simulation results are provided to corroborate the effectiveness of the proposed scheme in achieving considerable detection performance in typical multipath indoor propagation environments.

II. System Model

In UWB impulse radio signaling, each symbol is conveyed over a “block” of N_f frames with one pulse $u(t)$ per frame. The symbol, frame and pulse durations are denoted as T_s, T_f and T_u respectively, satisfying $T_s = N_f T_f$, $T_f \gg T_u$, and T_u being on the order of (sub-)nanoseconds. To enable concurrent channel access, each user employs user-specific pseudo-random time hopping (TH) codes $\{c_j\}_{j=0}^{N_f-1} \in [0, N_c-1]$ that time-shift pulse positions at multiples of the chip period T_c, with $N_c T_c < T_f$. Accordingly, the transmitted symbol-long waveform takes the form $u_s(t) = \sum_{j=0}^{N_f-1} u(t - jT_f - c_j T_c)$. The independent information-bearing symbols $a_i \in \{\pm 1\}$ are differentially encoded into channel symbols $b_i \in \{\pm 1\}$ through the rule $b_i = a_i b_{i-1}$. Adopting pulse amplitude modulation (PAM), the transmitted signal relevant to a burst of M information symbols is given by

$$x(t) = \sum_{i=0}^{M} b_i u_s(t - iT_s). \quad (1)$$

After traveling through a multipath channel assumed to be slow-fading, the received pulse becomes $p(t) = \sum_{l=0}^{L-1} \alpha_l u(t - \tau_l)$ of width T_p, where L is the total number of channel paths, each with gain α_l and delay τ_l. According to (1), the received signal in the interval $0 \le t \le (M+1)T_s$ can thus be written as

$$y(t) = \sum_{i=0}^{M} b_i p_s(t - iT_s - \tau) + w(t), \quad (2)$$

where $p_s(t) = \sum_{j=0}^{N_f-1} p(t - jT_f - c_j T_c)$ is the unknown received symbol-level waveform with non-zero support less than T_s (i.e., ISI-free condition is satisfied), whereas the additive noise $w(t)$ (modeled as white Gaussian process) accounts for the contribution of both the MAI and thermal noise.

III. Synchronization-Free Multiple Symbol Differential Detection

In this section, we will derive the structure of a synchronization-free multiple symbol differential detection scheme (SF-MSDD), whose aim is to recover M consecutive differentially-encoded information symbols $\mathbf{a} = [a_1, a_2, \cdots, a_M]^T$ based on the received signal $y(t)$ in the interval $0 \le t \le (M+1)T_s$. The following main assumptions are imposed: *i)* timing synchronization is only partially acquired, i.e., the timing offset is assumed to be within one symbol, $\tau \in [0, T_s)$; *ii)* the data block duration $(M+1)T_s$ is smaller than the channel coherence time so that thereon the channel is treated as being time-invariant; *iii)* the channel impulse response, consisting of parameters $\{\alpha_l, \tau_l\}$, is unknown and will not be explicitly estimated during detection.

Let us start on partitioning $p_s(t)$ into the two waveform segments

$$p_{s_0}(t) \triangleq \begin{cases} 0, & t \in [0, \tau) \\ p_s(t - \tau), & t \in [\tau, T_s) \end{cases}, \quad (3)$$

$$p_{s_1}(t) \triangleq \begin{cases} p_s(t + T_s - \tau), & t \in [0, \tau) \\ 0, & t \in [\tau, T_s) \end{cases}, \quad (4)$$

both of them being dependent on the timing offset τ. The above definitions and the differential encoding rule allow us to express the received waveform (2) as

$$y(t) = \sum_{i=0}^{M} \prod_{k=0}^{i} a_k q(t - iT_s) + \sum_{i=1}^{M+1} \prod_{k=0}^{i-1} a_k g(t - iT_s) + w(t), \quad (5)$$

where $q(t) \triangleq b_0 p_{s_0}(t)$ and $g(t) \triangleq b_0 p_{s_1}(t)$.

Given that $q(t)$ and $g(t)$ in (5) are not known, the detection of the information symbols $\mathbf{a}$ will be carried out following the GLRT rule. This means maximizing with respect to the trial $\tilde{\mathbf{a}} = [\tilde{a}_1, \tilde{a}_2, \cdots, \tilde{a}_M]^T$ and all the finite-energy functions $\tilde{q}(t)$ and $\tilde{g}(t)$ with support $[0, T_s]$ the log-likelihood metric (LLM)

$$\Lambda\left[y(t)\,|\tilde{\mathbf{a}}, \tilde{q}(t), \tilde{g}(t)\right] = 2\int_0^{(M+1)T_s} y(t)\tilde{s}(t)dt - \int_0^{(M+1)T_s} \tilde{s}^2(t)dt, \quad (6)$$

where the trial signal is

$$\tilde{s}(t) = \sum_{i=0}^{M} \prod_{k=0}^{i} \tilde{a}_k \tilde{q}(t - iT_s) + \sum_{i=1}^{M+1} \prod_{k=0}^{i-1} \tilde{a}_k \tilde{g}(t - iT_s). \quad (7)$$

Now, due to the finite support of $\tilde{q}(t)$ and $\tilde{g}(t)$ in $[0, T_s)$ it can be proved that (6) can be rewritten as

$$\Lambda\left[y(t)\,|\tilde{\mathbf{a}}, \tilde{q}(t), \tilde{g}(t)\right] = 2\int_0^{T_s}\left[\tilde{q}(t)z_1(t;\tilde{\mathbf{a}}) + \tilde{g}(t)z_2(t;\tilde{\mathbf{a}})\right]dt - \int_0^{T_s}\left[\tilde{q}^2(t) + \tilde{g}^2(t)\right]dt - 2\eta(\tilde{\mathbf{a}})\int_0^{T_s}\tilde{q}(t)\tilde{g}(t)dt, \quad (8)$$

where $z_1(t;\tilde{\mathbf{a}}) \triangleq \frac{1}{M+1}\sum_{i=0}^{M}\prod_{k=0}^{i}\tilde{a}_k y(t+iT_s), t \in [0, T_s)$, $z_2(t;\tilde{\mathbf{a}}) \triangleq \frac{1}{M+1}\sum_{i=1}^{M+1}\prod_{k=0}^{i-1}\tilde{a}_k y(t+iT_s), t \in [0, T_s)$ and $\eta(\tilde{\mathbf{a}}) \triangleq \frac{1}{M+1}\sum_{i=1}^{M}\tilde{a}_i$. Hence, the GLRT-based decision strategy on the information symbols $\mathbf{a}$ works as

$$\hat{\mathbf{a}} = \arg\max_{\tilde{\mathbf{a}}}\left\{\max_{\tilde{q}(t),\tilde{g}(t)}\left\{\Lambda\left[y(t)\,|\tilde{\mathbf{a}}, \tilde{q}(t), \tilde{g}(t)\right]\right\}\right\}. \quad (9)$$

In order to solve (9), we will first keep $\tilde{\mathbf{a}}$ fixed and compute the inner term $\Gamma\left[y(t)\,|\tilde{\mathbf{a}}\right] \triangleq \max_{\tilde{q}(t),\tilde{g}(t)}\left\{\Lambda\left[y(t)\,|\tilde{\mathbf{a}}, \tilde{q}(t), \tilde{g}(t)\right]\right\}$. To this end, resorting to variational techniques we obtain (up to an irrelevant multiplicative factor)

$$\Gamma\left[y(t)\,|\tilde{\mathbf{a}}\right] = \int_0^{T_s}\left[z_1^2(t;\tilde{\mathbf{a}}) + z_2^2(t;\tilde{\mathbf{a}})\right]dt, \quad (10)$$

where we assume for simplicity $\eta(\tilde{\mathbf{a}}) \ll 1$. Hence, the proposed SF-MSDD detection rule can be summarized as

$$\hat{\mathbf{a}} = \arg\max_{\tilde{\mathbf{a}}}\left\{\Gamma\left[y(t)\,|\tilde{\mathbf{a}}\right]\right\}. \quad (11)$$

A few remarks about the SF-MSDD defined in (10)-(11) are now in order.

1) The SF-MSDD circumvents the explicit estimation of both the channel parameters, even in the presence of an unknown UWB multipath channel, and the timing offset information. The metric to be maximized, indeed, lies on the energy of $z_1(t;\tilde{\mathbf{a}})$ and $z_2(t;\tilde{\mathbf{a}})$, which in turn are constructed solely from the received signal $y(t)$.
2) The fact that the information symbols take values in $\{\pm 1\}$ enables a further rearrangement of the metric (10) as

$$\bar{\Gamma}\left[y(t)\,|\tilde{\mathbf{a}}\right] = \sum_{i=1}^{M}\sum_{l=0}^{i-1}\prod_{k=1}^{i-l}\tilde{a}_{k+l}(Y_{l,i} + Y_{l+1,i+1}), \quad (12)$$

where the coefficients

$$Y_{i,j} \triangleq \frac{1}{M+1}\int_0^{T_s} y(t+iT_s)y(t+jT_s)dt \quad (13)$$

are generated by correlating symbol-long segments of the received signal $y(t)$.
3) The basic idea of the SF-MSDD is to jointly detect a block of M data symbols, as long as within such time interval within a time interval the channel response can be considered as time-invariant. As a result, it is expected that the detection accuracy improves as M increases. Searching for the maximum of the objective function via some exhaustive search method, however, requires high computational complexity going up exponentially in the number M of symbols to be jointly detected. Therefore, whenever performance has to be maintained with affordable complexity, efficient implementations of the SF-MSDD are inevitably called for.

IV. Sphere Decoding for SF-MSDD

The sphere decoding (SD) search algorithm, originally proposed for enumerating all the lattice points inside a sphere centered at the origin [11], can be conveniently applied to the SF-MSDD scheme developed so far to avoid the unfeasible computational complexity that an exhaustive method involves [8]. To this end, let us observe again that the information symbols take values in $\{\pm 1\}$. Hence, the maximum possible value of the objective function (12) is $\sum_{i=1}^{M}\sum_{l=0}^{i-1}|Y_{l,i} + Y_{l+1,i+1}|$, which is independent of $\tilde{\mathbf{a}}$. Accordingly, the SF-MSDD detection rule can be put in the alternative form

$$\hat{\mathbf{a}} = \arg\min_{\tilde{\mathbf{a}}}\left\{\Phi\left[y(t)\,|\tilde{\mathbf{a}}\right]\right\}, \quad (14)$$

where the new objective function (this time to be minimized) is

$$\Phi\left[y(t)\,|\tilde{\mathbf{a}}\right] = \sum_{i=1}^{M}\sum_{l=0}^{i-1}\vartheta_{l,i}\,|Y_{l,i} + Y_{l+1,i+1}|, \quad (15)$$

with $\vartheta_{l,i} \triangleq 1 - \sigma_{l,i}\prod_{k=1}^{i-l}\tilde{a}_{k+l}$ taking values in $\{0, 2\}$ depending on whether $\sigma_{l,i} \triangleq \mathsf{sign}\{Z_{l,i}\}$, with $Z_{l,i} \triangleq Y_{l,i} + Y_{l+1,i+1}$, has the same or opposite sign with respect to $\prod_{k=1}^{i-l}\tilde{a}_{k+l}$. The structure of the metric $\Phi\left[y(t)\,|\tilde{\mathbf{a}}\right]$, namely the sum of non-negative coefficients $|Z_{l,i}|$ each weighed by the *unknown* non-negative $\vartheta_{l,i}$, suggest to view it a sphere in the M-dimensional lattice of the vectors $\tilde{\mathbf{a}}$. This property combined with the fact that the i-th addend in (15), $1 \le i \le M$, depends only on preceding tentative symbols $\tilde{a}_1, \tilde{a}_2, \ldots, \tilde{a}_i$, allow us to apply the SF-MSDD decision rule within the SD framework. To show how we can proceed, let us assume that the initial radius $\delta^{(1)} > 0$ is chosen to be large enough so that the sphere defined by (15) contains the optimal $\hat{\mathbf{a}}$ obeying to the detection rule (14). At the generic m-th SD iteration, a necessary condition for any tentative estimate $\hat{\mathbf{a}}^{(m)}$ to lie inside the sphere of radius $\delta^{(m)} > 0$ is given by

$$\sum_{i=1}^{j}\sum_{l=0}^{i-1}\left[1-\sigma_{l,i}\prod_{k=1}^{i-l}\hat{a}_{k+l}^{(m)}\right]|Z_{l,i}| \leq \delta^{(m)}, \quad 1\leq j\leq M. \tag{16}$$

Note that the condition in (16) for $j=1$ contains $\hat{a}_1^{(m)}$ only, that concerning $j=2$ contain $\hat{a}_1^{(m)}$ and $\hat{a}_2^{(m)}$ only, and so on. Therefore, each iteration of the SD algorithm consists on checking the M conditions in (16) one by one, as detailed in the sequel.

Starting from the first condition, we can find the candidate set for $\hat{a}_1^{(m)}$ as

$$\mathcal{I}_1^{(m)} = \left\{\tilde{a}_1 \in \{\pm 1\} |\, [1-\sigma_{0,1}\tilde{a}_1]\,|Z_{0,1}| \leq \delta^{(m)}\right\}. \tag{17}$$

After the tentative $\hat{a}_1^{(m)}$ has been chosen from $\mathcal{I}_1^{(m)}$, it is substituted into the second condition in (16), which generates the candidate set for $\hat{a}_2^{(m)}$ as

$$\begin{aligned}\mathcal{I}_2^{(m)} = \Big\{\tilde{a}_2 \in \{\pm 1\} |\, &\left[1-\sigma_{0,1}\hat{a}_1^{(m)}\right]|Z_{0,1}| \\ &+\left[1-\sigma_{0,2}\hat{a}_1^{(m)}\tilde{a}_2\right]|Z_{0,2}| \\ &+[1-\sigma_{1,2}\tilde{a}_2]\,|Z_{1,2}| \leq \delta^{(m)}\Big\}.\end{aligned} \tag{18}$$

At the j-th step, the candidate set for $\hat{a}_j^{(m)}$ is derived as

$$\begin{aligned}\mathcal{I}_j^{(m)} = \Big\{\tilde{a}_j \in \{\pm 1\} |\, &\left[1-\sigma_{0,1}\hat{a}_1^{(m)}\right]|Z_{0,1}| \\ +\left[1-\sigma_{0,2}\hat{a}_1^{(m)}\hat{a}_2^{(m)}\right]&|Z_{0,2}| + \left[1-\sigma_{1,2}\hat{a}_2^{(m)}\right]|Z_{1,2}| + \\ &+\left[1-\sigma_{0,j}\hat{a}_1^{(m)}\hat{a}_2^{(m)}\cdots\tilde{a}_j)\right]|Z_{0,j}| \\ &+\left[1-\sigma_{1,j}\hat{a}_2^{(m)}\hat{a}_3^{(m)}\cdots\tilde{a}_j)\right]|Z_{1,j}|\cdots \\ &+[1-\sigma_{j-1,j}\tilde{a}_j]\,|Z_{j-1,j}| \leq \delta^{(m)}\Big\}.\end{aligned} \tag{19}$$

The steps continue till the last candidate set $\mathcal{I}_M^{(m)}$ is acquired for $\hat{a}_M^{(m)}$, which concludes the m-th SD iteration and yields a new tentative estimate $\hat{\mathbf{a}}^{(m)}$. Then, the radius $\delta^{(m)}$ and the optimal estimate $\hat{\mathbf{a}}_{\rm opt}$ are updated according to

$$\delta^{(m+1)} \leftarrow \sum_{i=1}^{M}\sum_{l=0}^{i-1}\left[1-\sigma_{l,i}\prod_{k=1}^{i-l}\hat{a}_{k+l}^{(m)}\right]|Z_{l,i}|, \tag{20}$$

$$\hat{\mathbf{a}}_{\rm opt} \leftarrow \hat{\mathbf{a}}^{(m)}, \tag{21}$$

respectively, which in turn enable the next $(m+1)$-th iteration.

The SD procedure goes on with a smaller and smaller sphere, with the candidate estimate $\hat{\mathbf{a}}^{(m)}$ found in the previous iteration lying on its surface. At the last iteration, after all the points within the sphere at a given iteration have been checked, the detection process stops, yielding the optimal solution $\hat{\mathbf{a}}_{\rm opt}$ for which the objective function attains the minimum value $\Phi\left[y(t)\,|\hat{\mathbf{a}}_{\rm opt}\right]$.

V. Performance Results

The BER robustness of the SD-based SF-MSDD receiver is evaluated through computer simulations for a dense-multipath single-user scenario. The conventional Rake receiver under perfect channel state information (IRake) and the one-shot differential detector (IDD) are taken as performance benchmarks under the assumption of ideally timing recovery.

We focus on a peer-to-peer link where a single active user transmits consecutive bursts of M data symbols during which the transmission channel (assumed to be time invariant) is generated randomly according to [12]. According to this propagation model, the multipath components arrive in clusters with amplitude modeled as independent double-sided Rayleigh distributed random variables having mean square values exponentially decaying with a cluster delay, as well as with a ray delay within a cluster with decay factors chosen as 30 ns and 5 ns. The clusters and the rays within each cluster have arrival times modeled as Poisson variables with arrival rates, namely 0.5 ns^{-1}, and 2 ns^{-1}. The monocycle $u(t)$ has been selected as the second derivative of a Gaussian shape with normalized unit energy and pulse width equal to 1.0 ns. The frame and chip interval are $T_f = 100$ ns and $T_c = 1.0$ ns, respectively, $N_f = 10$ is the number of frames in each information symbol, and the TH codes are randomly picked up in the interval $[0, 90]$, the modulation format is binary PAM, whereas the timing offset of the desired user is equally distributed within the symbol interval with the exclusion of the edge intervals around $\tau = 0$ and $\tau = T_s$.

Figure 2 depicts the BER performance of the SF-MSDD for the block sizes $M = 5, 10, 15, 20, 30$, in the case of $Z_{l,i}$ being taken as real-valued coefficients (soft SD). As expected, SF-MSDD performance gets better and better as the block size M increases, and improves a lot compared to the differential detector under mistiming (DD). To be specific, at BER$= 10^{-2}$ the the SF-MSDD with $M = 10$ equals the performance of IDD, but setting $M = 30$ offers a 4.5 dB gain even combined with the advantage of being independent of timing synchronization. On the other side, the IRake outperforms the SF-MSDD by approximately 10 dB at the considerable price of requiring accurate timing and channel estimation. The performance of the SF-MSDD with one-bit hard-quantized coefficients $Z_{l,i}$ is illustrated in Figure 1 (hard SD). The results indicate that the BER degradation with respect to the soft version is limited to 2-3 dB in the range of practical interest and for adequate burst length, namely $M \geq 15$, in spite of the considerable reduction in computational complexity due to the adoption of integer-based arithmetic only. Finally, the average complexity of the SD-MSDD algorithm (quantified by the average number of required floating-point additions per block) turns out to be several orders lower than that of an exhaustive search method (results not shown due to space limitation), and approximately polynomial in the data block size.

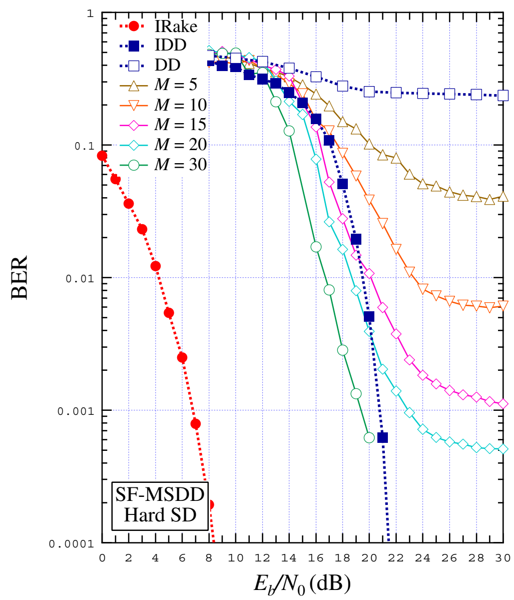

Fig. 1. BER of hard-SD-based SF-MSDD for various M.

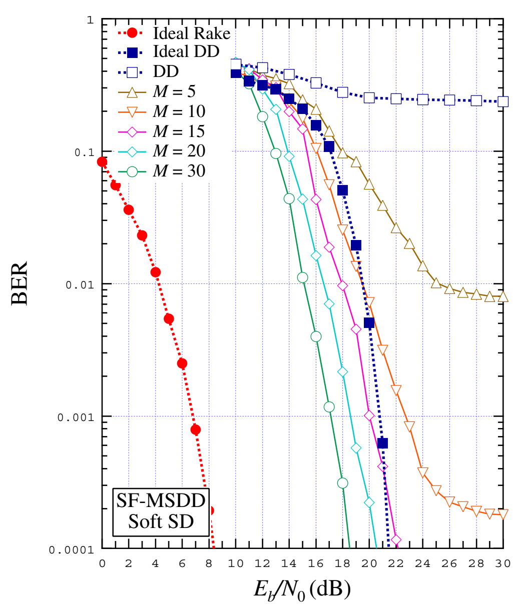

Fig. 2. BER of soft-SD-based SF-MSDD for various M.

VI. Concluding Remarks

A sphere decoding approach to multiple symbols differential detection has been derived for UWB communications with particular emphasis put on relaxing the stringent requirements on timing synchronization. The proposed scheme offers a number of attractive features concerning both performance and complexity: *i*) improved joint symbol detection over traditional one-shot differential schemes with substantial independence of timing knowledge; *ii*) simple receiver structure by avoiding demanding tap-by-tap channel estimation; *iii*) high power efficiency by circumventing transmission of pilot symbols; and, *iv*) efficient implementation of the detector by introducing a SD-based algorithm enabling affordable computational complexity even for large blocks. Simulation results corroborate the effectiveness of the proposed detection scheme in achieving considerable detection performance when adopted for decoding UWB transmissions.

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