Compressive Sensing Multi-User Detection for Multicarrier Systems in sporadic Machine Type Communication

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***Abstract*—Massive Machine Type Communication is seen as one major driver for the research of new physical layer technologies for future communication systems. To handle massive access, the main challenges are avoiding control signaling overhead, low complexity data processing per sensor, supporting of diverse but rather low data rates and a flexible and scalable access. To address all these challenges, we propose a combination of compressed sensing based detection known as Compressed Sensing-based Multi User Detection (CS-MUD) with multicarrier access schemes. We name this novel combination Multicarrier CS-MUD (MCSM). Previous investigations on CS-MUD facilitates massive direct random access by exploiting the signal sparsity caused by sporadic sensor activity. The new combined scheme MCSM with its flexibility in accessing time-frequency resources additionally allows for either reducing the number of subcarriers or shortening the multicarrier symbol duration, i.e., we gain a high spectral efficiency. Simulation results are given to show the performance of the proposed scheme.**

***Index Terms*—CS-MUD, multicarrier, sporadic transmission, machine to machine communication.**

I. Introduction

Predictions for the Internet of Things see billions of machine type devices accessing future wireless networks as soon as 2020. As a consequence, a huge increase in machine-to-machine traffic poses novel challenges in the design of wireless systems to efficiently handle massive access [1]. In addition to the strong increase of supported devices future wireless systems also have to handle a huge variety of new traffic profiles that are mainly characterized by the requirements of low data rates, low latency and highly reliable communication. To keep the massive number of devices with small payloads manageable control signaling overhead has to be kept as small as possible. Current access reservation protocols have the problem of additional delays before the data transmission starts. Towards aggregation of a massive amount of Machine Type Communication (MTC) we require a fast and, thus, a direct random access. Furthermore, MTC devices are expected to be sporadically active only, which leads to an uplink communication, where out of a large number of devices only a fraction is transmitting data at a given time. This sporadic traffic characteristic leads to sparse multiuser signals at the aggregation point [2], [3].

To address the challenges mentioned above, we propose a paradigm shift towards combining the need for a flexible and highly reliable air interface with direct medium access and low control signaling overhead in the design of new PHY-layer technologies. To this end, several authors [2], [3], [4], [5] proposed a novel PHY-layer signal processing schemes named Compressed Sensing-based Multi User Detection (CS-MUD). The idea is to use recent advantages of compressive sensing [6], and thus exploit the sparsity introduced by sporadic transmission of MTC in the received multiuser signal. With CS-MUD we are able to detect whether a sensor is active (activity detection) as well as which data the sensor has transmitted (data detection). The capability of CS-MUD to perform joint activity and data detection facilitates a reliable detection of direct random access. So far investigations of CS-MUD have been focused on coded access schemes (e.g. DS-CDMA) where a massive number of sensors are separated via coding applied in time domain only. To improve the flexibility and scalability of accessing both time and frequency resources, we propose to apply the CS-MUD technology for multicarrier transmissions [7], which we name MCSM. As an example we can use orthogonal multicarrier schemes in combination with CDMA formerly introduced as MC/OFDM-CDMA [8], [9].

The main contribution of this paper is as follows: We show that CS-MUD with the application of multicarrier schemes will also exploit the sparsity in the multiuser signal that either results in a reduced number of assigned subcarriers per sensor or, alternatively, leads to a reduced multicarrier symbol duration. That means MCSM increases spectral efficiency. Interestingly, we also show that for the delay spread assumed in LTE as a typical mobile communication channel the used subcarriers per sensor node can be located within coherence bandwidth while still facilitating data rates per user up to 1.5kbit/s being suitable for many Machine Type Communications. As a consequence, we can use non-coherent differential modulation schemes. Therefore, we are able to ease or even avoid channel estimation, and hence significantly reducing control signaling overhead and processing complexity required to handle massive MTC.

Moreover, we show how to extend the proposed MCSM scheme of a single time-frequency block that is accessed by sensor nodes to multiple of these blocks.

Simulation results are given showing the increased spectral

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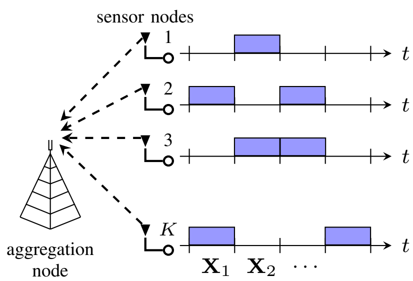

Fig. 1. Machine to machine uplink scenario with K nodes transmitting frames of length L to a central aggregation point.

efficiency of the proposed MCSM scheme.

The paper is organized as follows. In Sec. II the system model of a general MCSM scheme is presented. Here the processing of individual sensor nodes and of the aggregation point is presented. Also, the design parameters for a flexible configuration of the overall system are given. Additionally, the idea of using multiple blocks to further increase the bandwidth efficiency is presented. Sec. III shows numerical results of an overloaded and overlapped system, and provides an analysis on the bit error rate of this novel scheme as well as a system load analysis.

Notations: In this paper, upper case bold characters $\mathbf{X}$ denote matrices, whereas lower case bold characters $\mathbf{h}$ denote vectors.

II. System Model

Throughout this paper, the following system, also depicted in Fig. 1 is assumed. A set of K nodes sporadically accesses the wireless channel to transmit data to a central aggregation point. The sporadic nature of the transmission is captured with via a simple Bernoulli traffic model parametrized by the node activity probability p_a, which we assume to be the same for all nodes. With this model a node transmits at the current frame with probability p_a and it is silent with $1 - p_\text{a}$. Also, we assume that the activity is very small with $p_\text{a} \ll 1$, so that the overall system has a sporadic nature. First, the processing in one block is introduced, where multiple sensor nodes in one block are sporadically transmitting data in the frequency domain. Additionally, we show how several MCSM system can be combined such that more users can supported within a given bandwidth.

A. Multicarrier-CS-MUD block

The basic idea of our approach is to exploit the sparse structure of a multiuser signal to reduce the number of subcarriers in a multicarrier system. Consequently, for data detection we apply extended Compressed Sensing (CS) algorithms at the aggregation point. Moreover, due to the lower number of subcarriers used, we can allocate these within the coherence bandwidth of the channel of each sensor node. Thus, each sensor node experiences flat fading across all used subcarriers. This motivates the use of non-coherent modulation schemes.

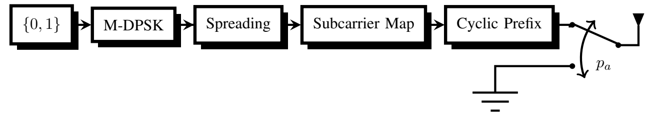

Fig. 2. Model for transmit signal generation at node.

As a result we are able to ease or completely avoid channel estimation. Later we show that we can support a data rate per sensor node up to 1.5kbit/s within a coherence bandwidth assuming a delay spread given by Long Term Evolution (LTE) parameters.

1) Processing at Sensor Nodes: Subsequently, we describe the generation of the transmit signal for an arbitrary sensor node which we denote as node $k = 1, \ldots, K$, where K is the number of overall sensor nodes. To facilitate non-coherent detection, active sensor nodes modulate their data using a differential $M-$PSK. After modulation, the active nodes spread their modulated symbols to a chip sequence $\mathbf{s}_k \in \mathbb{C}^{N_\text{c}}$ of length N_c. The chips are randomly drawn samples from the unit circle such as $s_i(\mathcal{U}) \sim \exp[2\pi\mathcal{U}]$ with $\mathcal{U}$ being a uniform distribution on the interval $[0, 1]$. After spreading, all active nodes map their chip sequences of length N_c to a block of N_s subcarriers, given a total number of subcarriers N_DFT. The processing at a sensor node is summarized in Fig. 2. In contrast to that, incative nodes just remain silent without transmitting any data. We assume that all K sensor nodes will occupy the same subcarriers yielding a block load of $\beta = \frac{K}{N_\text{s}}$. Moreover, we aim to assign more than K nodes to N_s subcarriers yielding an overloaded system with a load $\beta > 1$ with $K > N_\text{s}$. In general, the multicarrier scheme is not fixed to Cyclic Prefix (CP) based Orthogonal Frequency Division Multiplexing (OFDM). Also, the mapping of subcarriers is not necessarily localized or distributed. To simplify the description, we focus on a localized subcarrier mapping onto N_s consecutive orthogonal subcarriers and we use a CP of length N_CP.

2) Base-Station Processing: In the following we assume that all subcarriers are located within the coherence bandwidth of the channel of each sensor node. After receiving the uplink signal the base-station removes the the CP and performs a DFT of length $N_\text{DFT} = N_\text{s}$. Note that the DFT length is not necessarily $N_\text{DFT} = N_\text{s}$. The received signal $\mathbf{Y} \in \mathbb{C}^{N_\text{s} \times L}$ in frequency domain can be written as

$$\mathbf{Y} = \mathbf{SHX} + \mathbf{N} \quad . \tag{1}$$

Here the matrix $\mathbf{X} \in \mathcal{A}_0^{K \times L}$ is the multiuser signal where each column vector captures one multiuser symbol containing data from K sensor nodes. The kth row of $\mathbf{X}$ contains L consecutive time symbols transmitted by the kth node. Note that due to the sporadic sensor activity p_a, not all sensors are active for a frame. We assume frame activity $p_\text{a} \ll 1$, thus if a sensor is not active the corresponding row in $\mathbf{X}$ can be modeled as containing L consecutive zeros. Hence, the multiuser matrix $\mathbf{X}$ is sparse. If a sensor is active, the symbols are drawn from the set $\mathcal{A}$. In order to include the inactivity

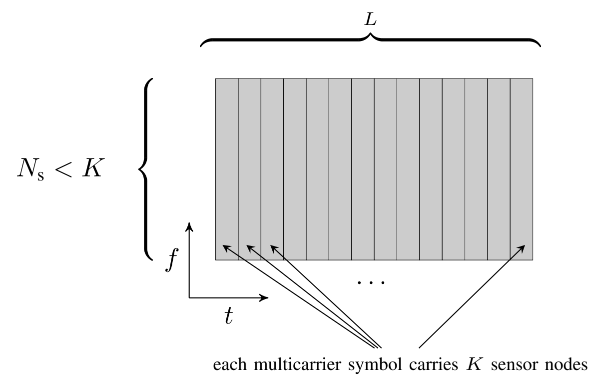

Fig. 3. One MCSM resource block of a frame with L symbols in time frequency grid with K sensor nodes mapped to N_s subcarriers. One gray bar is one multicarrier symbol containing the influences of K sensor nodes with dimension $N_s \times 1$

we use the augmented alphabet $\mathcal{A}_0 = \mathcal{A} \cup 0$ at the detector. Note that this is just a detection model, in fact inactive nodes do not transmit anything and remain silent.

The matrix $\mathbf{H} \in \mathbb{C}^{K \times K}$ is a diagonal matrix containing the corresponding sensor node and subcarrier specific channel taps and is generated as

$$\mathbf{H} = \text{diag}\{\mathbf{h}\} \tag{2}$$

with the vector $\mathbf{h} = [h_1, \ldots, h_k, \ldots, h_K]^{\mathrm{T}}$ of length K, as flat fading coefficients for each sensor node k. Note that, the assumption of single tap channels is only valid if N_s coincides with the coherence bandwidth of the underlying wireless channel. Otherwise, we have to deal with frequency selective sub-bands which significantly complicates estimation of the sensor node data. Here the matrix $\mathbf{S} \in \mathbb{C}^{N_s \times K}$ reflects the spreading of each sensor node to a frequency resource. $\mathbf{N} \sim \mathcal{N}(0, \sigma_{\mathrm{N}}^2)$ is the additive white Gaussian noise (AWGN) matrix. Fig. 3 shows one MCSM resource block containing L data frames of K sensor nodes in N_s subcarriers. Note that due to (1) the receiver has to detect KL unknown symbols by using $N_s L$ observations in the frequency domain. Since $\mathbf{X}$ is sparse, CS theory shows that we can choose $N_s L \leq KL$ and are still able to reliably detect KL unknowns. That means we can support an overloaded system with $\beta = \frac{K}{N_s} > 1$. In other words, the use of CS in the context of multicarrier facilitates high spectral efficiency.

With a total bandwidth denoted as $B = \Delta f N_s$, the load of an MCSM can be written as $\beta = \frac{K \Delta f}{B}$. For a classical system, $\beta \leq 1$ has to be satisfied, which is not the case using MCSM. The gain of having $\beta > 1$ allows for very flexible system design in the following sense.

1) *Increasing K, keeping B and Δf constant:* Without changing any parameter of the multicarrier configuration, the spectral efficiency is incresed by adding additional nodes.
2) *Decreasing B, keeping K and Δf constant:* By assigning less subcarriers N_s, without changing any parameters of the multicarrier configurtation, we can increase the spectral efficiency.
3) *Increasing Δf, keeping B and K constant:* Here the configuration of the multicarrier system changes such that we have a smaller symbol duration T_s and a lower number of subcarriers.

Herein, we focus on the first item such that we keep the number of subcarriers constant by gaining spectral efficiency from increasing the number of sensor nodes K.

B. Multiple Multicarrier-CS-MUD blocks

By extending the idea in Sec. II-A with more blocks $b = 1, \ldots, N_b$, we can parallelize these systems to a larger system. Furthermore, if these subsystems allow an overlapping in frequency domain, the number of measurements will further decrease, and also the number of overall used subcarriers will decrease.

1) Processing at Sensor Nodes: In the next step we show how to allocate the MCSM blocks to a total system bandwidth. We assume that we have in total N_b blocks of N_s consecutive subcarriers each, where each block carries K_b nodes. The mapping of the N_b blocks to the overall bandwidth is a system specific design parameter. By placing these blocks consecutively in a non-overlapping manner yielding $N_{\text{max}} = N_b N_s$ subcarriers in total. This is the simplest form of such a mapping. However, we will see that due to exploiting sparsity we enable a mapping of these blocks in an overlapping manner, such that N_o subcarriers of each block are used not exclusive to one block any more. With this mapping we occupy

$$N_{\text{max}} = \underbrace{N_b N_s}_{\text{number of needed resources}} - \underbrace{(N_b - 1)N_o}_{\text{resource saving}} \tag{3}$$

subcarriers in total, where the overlap is a free parameter to gain spectral efficiency by allowing interference between blocks.

2) Base-Station Processing: The same processing as in Section II-A at the base station is done over all N_b blocks at once, which changes the dimensions at the receiver. This allows resolving of the interference occurring between overlapping blocks at the detector. Successive processing of consecutive blocks is also possible, but is not considered here as it is sub-optimal. After removing the CP at the base station, the overall extended received signal $\underline{\mathbf{Y}} \in \mathbb{C}^{N_{\text{max}} \times L}$ is converted into frequency domain via an N_{DFT} point DFT yielding

$$\underline{\mathbf{Y}} = \underline{\mathbf{S}}\,\underline{\mathbf{H}}\,\underline{\mathbf{X}} + \underline{\mathbf{N}} \quad . \tag{4}$$

The matrix $\underline{\mathbf{X}} \in \mathcal{A}_0^{(N_b \cdot K_b) \times L}$ is now extended to contain all sensor nodes of all blocks b. The dimension is $(N_b \cdot K_b) \times L$, where K_b is the number of sensor nodes in block b. We still have the property that the k_b^{th} row contains differentially modulated signals from the k_b^{th} node and zeros if the node is inactive. The channel matrix $\underline{\mathbf{H}} \in \mathbb{C}^{(N_b \cdot K_b) \times (N_b \cdot K_b)}$ is an extended diagonal matrix containing sub-band specific channel taps per sensor node.

$$\underline{\mathbf{H}} = \text{diag}\{[\mathbf{h}_1^{\mathrm{T}}, \ldots, \mathbf{h}_b^{\mathrm{T}}, \ldots, \mathbf{h}_{N_b}^{\mathrm{T}}]^{\mathrm{T}}\} \tag{5}$$

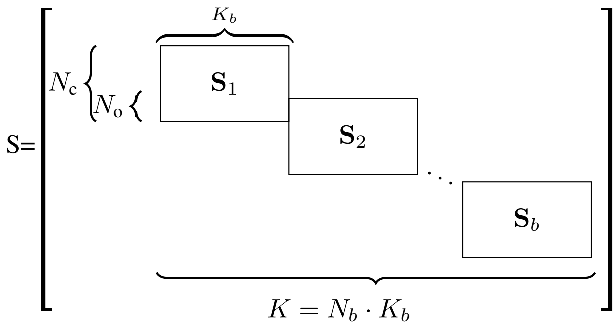

Fig. 4. Illustration for setting up the system matrix at the detector. Each sub-matrices $\mathbf{S}_1, \dots, \mathbf{S}_b$ represent one block of MCSM as explained in II-A

where each vector $\mathbf{h}_b$ of length K_b containing the corresponding channel tabs. $\underline{\mathbf{N}} \sim \mathcal{CN}(0, \sigma_{\mathrm{N}}^2)$ is the AWGN matrix.

Here the extended matrix $\underline{\mathbf{S}} \in \mathbb{C}^{N_{\max} \times N_{\mathrm{b}} \cdot K_b}$ reflects the spreading and overlapping in frequency domain, where $K = N_{\mathrm{b}} \cdot K_b$ are the overall number of sensor nodes. The matrix $\underline{\mathbf{S}}$ is nearly a block diagonal matrix composed of the individual matrices for the subsystems in the blocks $\mathbf{S}_b, 1 \leq b \leq N_{\mathrm{b}}$, where each subsystem can be interpreted as one single MCSM system given in Section II-A. Note that by choosing $N_{\mathrm{b}} = 1$ this system is a single block MCSM system. As depicted on Fig. 4, the first N_{o} rows of subsystem $\mathbf{S}_b$ overlap with the last N_{o} rows of the subsystem $\mathbf{S}_{b-1}$. If no overlapping is used, i.e., $N_{\mathrm{o}} = 0$, we have N_{b} parallel MCSM systems, with the same load β as in section II-A. The system in (4) constitutes a so called Multiple Measurement Vector Compressed Sensing (MMV-CS) system, where the activity of the nodes in $\underline{\mathbf{X}}$ denotes the sparsity pattern which is exploited for reconstruction.

C. Design Parameters

In this section, we show system parameters, if we assume LTE specific parameters for the transmission such as a delay spread of $\tau_d = 16.66\mu s$ for the wireless channel [10]. This assumption coincides the LTE assumptions for the maximaum delay spread if a long cyclic-prefix is used. I.e., this is a conservative assumption which may be relaxed in most of the cases. With τ_d, we have a coherence bandwidth of $B_c = 1/\tau_d \approx$ 60kHz. We have to ensure, that N_{b} consecutive subcarriers coincide the coherence bandwidth such that frequency selective channels are avoided within one block. To make sure that this assumption is valid, we work with subsystems of bandwidth of $B_b = B_c/4 =$ 15kHz. Additionally, we have to chose N_{c} sufficiently large since the spreading factor must not be too low for CS-MUS to perform sufficiently well [5], [2]. Thus, we choose $N_{\mathrm{c}} = N_{\mathrm{s}} = 20$ and thus have $\Delta f = \frac{B_s}{N_{\mathrm{s}}} =$ 0.75kHz. This assumption determines the length of the time domain symbol as $T_{\mathrm{s}} = 1.33$ms. Consequently, our per node data rate is $R_k = \frac{\mathrm{ld}(M)}{T_{\mathrm{s}} + T_{\mathrm{g}}}$, with a guard time T_{g} which is assumed to be equal with τ_d. Note that only active nodes achieve the stated data rate, inactive nodes are silent and do not transmit any data. Assuming D-QPSK as modulation scheme we have a data rate $R_k \approx 1.5$kbit/s for all k, which is clearly reasonable for future low data rate M2M applications.

We see that our example bases on the assumption of the delay spread of the wireless channel. If the delay spread increases, we have to adapt the system parameters and finally obtain a lower data rate. However, we see that the dependency is linear such that a factor of two in delay spread would decrease our data rate by a factor of two.

III. Performance Analysis

Subsequently, we consider the performance of this approach. Therefore, the greedy Group Orthogonal Matching Pursuit (GOMP) detector, which exploits block-information, is used to detect the sensor nodes at the aggregation point [11]. According to the assumptions made in section II-C, we consider a system composed of $N_{\mathrm{b}} = 20$ subsystems, where each subsystem contains $N_{\mathrm{s}} = 20$ orthogonal subcarriers with a subcarrier spacing of $\Delta f = 0.75$kHz. The length of the analog channel impulse response is assumed to be $t_h = 16.66\mu s$ related to LTE with extended CP length as the worst case scenario. The activity probability per node is $p_{\mathrm{a}} = 0.2$. Active nodes transmit a frame of $L = 50$ symbols. To measure the performance of our scheme, we consider the bit error rate and the system load measured in nodes per subcarrier as

$$\beta = \frac{N_{\mathrm{b}} K_b}{N_{\mathrm{b}} N_{\mathrm{s}} - (N_{\mathrm{b}} - 1) N_{\mathrm{o}}}. \tag{6}$$

Also, we can define the bandwidth saving given by

$$B_{\text{save}} = \frac{(N_{\mathrm{b}} - 1) N_{\mathrm{o}}}{N_{\mathrm{b}} N_{\mathrm{s}}}. \tag{7}$$

Fig. 5 plots the BER curves for a system involving $K_b = 40$ nodes per block for different overlapping sizes $N_{\mathrm{o}} = 0, \dots, 8$. As usual, the BER rates are measured on bit level with the exception, that wrong activity detection may lead to double bit errors. In this setup, we see that increasing the block overlap only leads to small performance losses. However, the efficiency can be increased by this method up to $\beta = 3.23$ nodes per subcarrier, using an overlapping of N_{o}. In this example, we save $19 N_{\mathrm{o}}$ subcarriers by this method, leading to a decreased bandwidth of $19 \cdot 8 \cdot \Delta f = 114$kHz using $N_{\mathrm{o}} = 8$ overlapped subcarriers. The absolute saving of the overall bandwidth is $B_{\text{save}} = 38\%$, which now can be used to allocate more sensor nodes in the system or to relax the subcarrier spacing Δf.

It is also possible to overload the system further by increasing the block load to $K_b = 60$ nodes per block. The BER curves for this setting are shown on Fig. 6. We observe that the BER performance is slightly worse than in the previous setting. However, by increasing the block overlap, we can achieve a system load of $\beta = 4.83$ nodes per subcarrier. It should be mentioned that this system serves $K = 1200$ nodes with a data rate of $R_k \approx 1.5$kbit/s per node without performing any channel estimation.

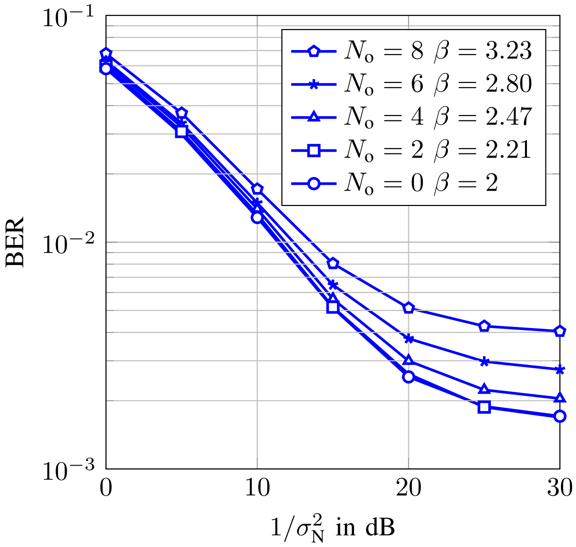

Fig. 5. $K = 40, N_\mathrm{b} = N_\mathrm{s} = 20$, saving $(N_\mathrm{b} - 1)N_\mathrm{o} = 19N_\mathrm{o}$ subcarriers

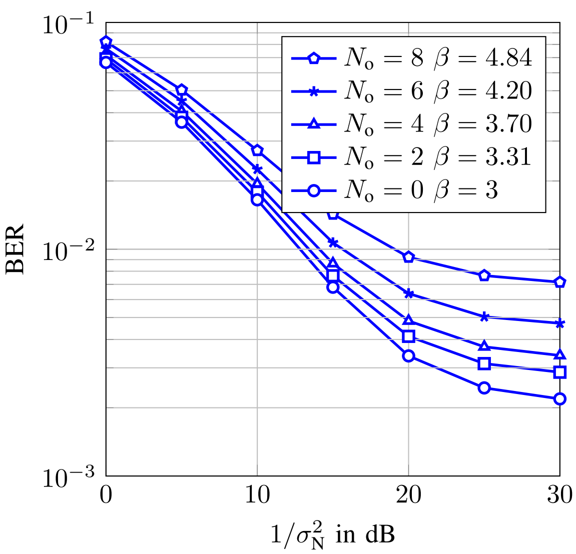

Fig. 6. $K = 60, N_\mathrm{b} = N_s = 20$, saving $(N_\mathrm{b} - 1)N_\mathrm{o} = 19N_\mathrm{o}$ subcarriers

IV. Conclusion

In this paper we proposed the novel scheme of Multicarrier CS-MUD (MCSM) that is a application of Compressed Sensing-based Multi User Detection (CS-MUD) with multicarrier access schemes. In addition to the well known properties of CS-MUD to efficiently handle massive Machine Type Communication (MTC) the new scheme MCSM enables flexibility and scalability in accessing overloaded time-frequency resources. Furthermore, we can allocate subcarriers within the coherence bandwidth of the channel of each sensor node only, and thus we can reduce processing complexity tremendously by easing channel estimation and equalization. Additionally, we extended the Multicarrier CS-MUD system to a multi-block system, which further reduces the required bandwidth by increasing the overall load.

Acknowledgment

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