A Novel Sparse Transmission Scheme for Efficient Mobile Radio Communications

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***Abstract*—Applications like multi user and distributed MIMO can benefit from a sparse transmission scheme due to a reduced inter-cell and inter-cluster interference. In this paper, the so-called start stop bit method, which presents a new type of transmission with sparse resource usage is studied. Several enhancements are analyzed such as i) transmitting multiple stop bit sequences, ii) adding sparse stop bit areas representing artificial fractional time frequency shifts, iii) adding a given MCS over the stop bit areas, and iv) compressing the permutation matrix needed for multiple stop bit sequences. Bit error rate curves of the proposed transmission scheme are analyzed and suitable parameter sets are provided that lead to the highest throughput per set of resource elements for a given sparsity level in comparison with a conventional OFDMA system.**

***Index Terms*—6G, dMIMO, start stop bit method**

I. Introduction

Increasing the capacity and coverage for mobile radio communications is a key goal of the next generation technologies. In 6G systems, the main drivers are applications like extended reality, digital twins, or artificial intelligence-related traffic. Since its introduction in LTE Rel. 11 [1], joint transmission coordinated multipoint (JT CoMP) or distributed MIMO (dMIMO) systems theoretically promise large performance enhancements, but the achieved system level simulation gains are still moderate. Research results from projects like Fantastic5G [2] identified inter-cluster interference (ICI) as one of the main reasons for these observed discrepancies. In that sense, sparsity may help with the high ICI as the amount of interfered/interfering resources is minimized, which, to our knowledge, has not been yet studied. The start stop bit method, proposed in [3], tries to maximize the sparsity during data transmission, thereby minimizing the ICI. This could become a key enabler for practical 6G dMIMO systems.

The basic start stop bit method is realized by encoding the information bits of a message into the relative position of a start and a stop bit in the radio resource grid. Thereby, the start bit position is pre-defined, and thus, the stop bit is the only resource element (RE) carrying power. By running a counter over the resource elements and correctly detecting the stop bit position, the information bits can be decoded at the receiver side. This transmission scheme provides a very sparse set of precoding matrices in time and frequency, which reduces the processing complexity as well as the related power consumption for JT-CoMP precoding [3]. Moreover, it reuses many of the building blocks of the MIMO-OFDMA framework to facilitate its introduction into 6G. Pulse position modulation (PPM) [4], ultra wideband (UWB) modulation [5], and subcarrier index modulation (SC-IM) [6] maybe regarded as prior art to this technique [3]. However, the start stop bit method differs from previous ideas due to its mapping of information into bit sequences related to a counter spanning over the REs. The counter first runs over the frequency and then over the time domain, but it can be extended over other domains, such as the modulation and coding scheme (MCS). The latter avoids the need for a very large frequency bandwidth as in UWB modulation [5]. SC-IM [6] is an index modulation technique, which conveys information bits implicitly by the index of a single or multiple subcarriers. Similar ideas exist with antenna indexes in spatial modulation (SM) or also with code indexing modulation (CIM) [6][7]. The start stop bit method by design tends to be sparser than other methods like SC-IM as a very low number of stop bits mapped in few REs are used instead of requiring some amount of all possible ON/OFF subcarrier combinations. Moreover, the SC-IM does not ensure that adjacent subcarriers and time domain symbols are empty, which is possible for the stop bit detection.

This paper develops on the top of the work in [3] providing a first in-depth analysis of the start stop bit method. Moreover, a number of enhancements to the basic start stop bit method are proposed to improve throughput gain while keeping a highly sparse transmission. The proposed enhancements are: i) transmitting multiple parallel stop bit sequences in the same allocated resource grid area; ii) allowing artificial fractional time frequency shifts by adding sparse stop bit areas; iii) adding a given MCS over the stop bit areas; and iv) compressing the permutation matrix needed for multiple parallel stop bit sequences. Different performance metrics are mathematically analyzed and related simulation results are provided.

The paper is organized as follows: Section II describes the concept of the start stop bit method and the various extensions. Additional considerations about data encoding, power boosting, and error handling are discussed in Section III. Then, in Section IV, further analysis and Link Level Simulations (LLSs) are used to evaluate the performance of the mechanism. Finally, Section V concludes the paper.

II. The Start Stop Bit Method

The basic concept of the start stop bit method was first introduced in [3]. The following sections describe this transmission technique and all the proposed extensions together with the main Key Performance Indicators (KPIs) to be analyzed.

A. Sparsity and Throughput Gain

The primary objective of the start stop bit method is to achieve a high system sparsity while obtaining a high throughput. Therefore, the most important KPIs employed to analyze the method are the sparsity ρ and the throughput gain Γ_{thr}. The sparsity (ρ) describes the ratio of free REs compared to available REs and, thus, the opposite of the resource usage. The throughput gain (Γ_{thr}) describes the ratio between the data rate efficiency of the start stop bit transmission and the data rate efficiency achieved in a conventional OFDMA system. Both KPIs exhibit a high trade-off, whereby increasing the sparsity leads to lower throughput and vice versa.

B. Basic Concept

The start stop bit method modifies the mechanism of transmission in a conventional OFDMA system. Instead of directly transmitting the entire bit sequence across adjacent subcarriers, only one stop bit is sent per bit sequence of length N_c^{bit}. A predefined start RE triggers a counter in the receiver, which increments over the available frequency and time resources. The counter continues until the stop bit is detected, and at that point, the receiver determines the bit sequence directly from the counter value. The stop bit is identified as the only active RE, meaning it carries power.

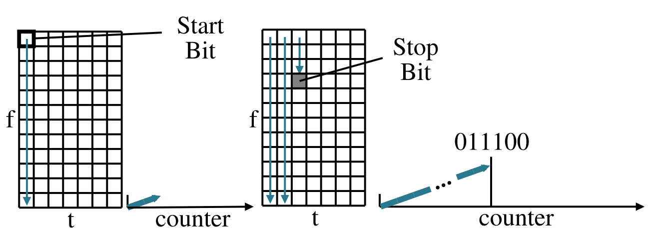

Fig. 1. Basic concept of data transmission in the start stop bit method.

Fig. 1 illustrates the start stop bit method in the resource grid. On the left, the start bit position triggers the counter, which first runs across the frequency domain, as indicated by the arrow. On the right, the counter reaches the stop bit, halting the counter and decoding the bit sequence. In this example, the stop bit position is at the 28th RE in the grid and therefore encodes the bit sequence '011100'. This results in a sparse transmission, with only one active RE per counter length, whereby the number of REs reserved for the counter directly correlates with the number of bits encoded into the position of the stop bit ($N_{\text{c}}^{\text{bit}}$) and is given by

$$L_{\text{ss}} = 2^{N_{\text{c}}^{\text{bit}}}. \tag{1}$$

Thus, the sparsity for the basic start stop bit method can be calculated by

$$\rho = 1 - \left(\frac{1}{2^{N_{\text{c}}^{\text{bit}}}}\right). \tag{2}$$

To compute the throughput gain, the number of bits encoded into one start stop bit cycle is compared to the bits transmitted across all REs of the same cycle (L_{ss}) in a conventional system. The latter is determined using the number of information bits per RE ($N_{\text{MCS,con}}^{\text{bit}}$) encoded in the MCS. The throughput gain is given by

$$\Gamma_{\text{thr}} = \frac{N_{\text{c}}^{\text{bit}}}{L_{\text{ss}} \cdot N_{\text{MCS,con}}^{\text{bit}}}. \tag{3}$$

The formulas indicate that the number of information bits encoded into the stop bit position ($N_{\text{c}}^{\text{bit}}$) should not be too high, as the start-stop bit cycle length (L_{ss}) increases exponentially with $N_{\text{c}}^{\text{bit}}$. Eqs. (2) and (3) highlight the trade-off between the two KPIs for sparsity and throughput gain, whereby increasing the information bits for the stop bit position results in greater sparsity but reduces the throughput gain.

Example: For a bit sequence of $N_{\text{c}}^{\text{bit}} = 6\,\text{bits}$, a start stop bit cycle length of $L_{\text{ss}} = 2^{N_{\text{c}}^{\text{bit}}} = 64$ is used. Therefore, the sparsity is given by $\rho = 1 - 1/64 = 98.4\,\%$ and the throughput gain by $\Gamma_{\text{thr}} = 6\text{ bit} \cdot (2\text{ bit/RE} \cdot 64\text{ REs})^{-1} = 0.05$, whereby a conventional system with QPSK is assumed, meaning that 2 bits are encoded per RE.

This example demonstrates that while the basic start stop bit method offers a highly sparse system, its throughput is lower compared to conventional data transmission. To address this, enhancements to the method are described below, which increase throughput while preserving a high sparsity.

C. Extension of the Counter Dimension by the Modulation and Coding Scheme

The first approach to enhance the throughput of the start stop bit method is to use the MCS as an additional dimension for the counter.

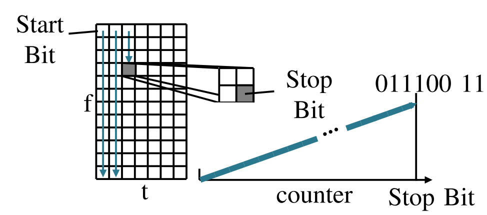

Fig. 2. Enhancement of the counter dimension by the MCS.

Fig. 2 illustrates a counter for an MCS encoding $N_{\text{MCS,sb}}^{\text{bit}} = 2\,\text{bits}$, such as in a QPSK scheme. The information bits encoded in the stop bit are now derived from two sources. First, the position of the stop bit, which encodes $N_{\text{c}}^{\text{bit}}$ bits, and the transmitted constellation point, which encodes an additional $N_{\text{MCS,sb}}^{\text{bit}}$ bits. This is visualized in Fig. 2, where the bit sequence from Fig. 1 is extended by two additional information bits encoded through the MCS. The sparsity (2) remains unchanged, but the throughput gain is increased to

$$\Gamma_{\text{thr}} = \frac{N_{\text{c}}^{\text{bit}} + N_{\text{MCS,sb}}^{\text{bit}}}{2^{N_{\text{c}}^{\text{bit}}} \cdot N_{\text{MCS,con}}^{\text{bit}}}. \tag{4}$$

Example: With the inclusion of the MCS, the length of the start stop bit cycle $L_{\text{ss}} = 64$ as well as the sparsity $\rho = 98.4\,\%$ remain. However, the throughput gain is increased to $\Gamma_{\text{thr}} = (6+2)$ bit $\cdot\, (2\ ^{\text{bit}}/_{\text{RE}} \cdot 64\ \text{REs})^{-1} = 0.06$ when comparing to a conventional QPSK system.

D. Multiple Parallel Stop Bits

To allow the throughput of the start stop bit method to converge closer to the one of the conventional system, multiple parallel stop bits, each with $N_{\text{sb}}^{\text{bit}}$ bits, can be transmitted within a single counter length. This increases the number of stop bits to M. Fig. 3 illustrates the extended method with parallel stop bits (SB) detected at different counter values. To reconstruct the original message, these sequences must be mapped to their correct positions in the original message, using an additional permutation matrix that aligns them within the message stream. This matrix maintains a sparse transmission pattern, allocating a total of L_{P} REs, with only $M-1$ of them being active. Each row ($m = 1, ..., M-1$) contains M elements and encodes the position for the m^{th} received stop bit sequence in the message. The size of the permutation matrix is therefore $L_{\text{P}} = M \cdot (M-1)$, as the position of the last sequence can be deduced from the other positions. The position is hereby transmitted in the same way as the stop bit sequence itself, whereby the k^{th} position in the message is represented by activating the k^{th} RE in the row and nulling the other REs into the permutation matrix.

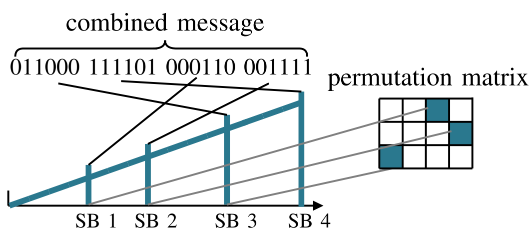

Fig. 3. Concept of ordering the parallel stop bits (SB) with the help of the permutation matrix.

In the example depicted in Fig. 3, the first row ($m = 1$) has the active RE at $k = 3$ and, thus, indicates that the first received stop bit sequence belongs to the 3[rd] position of the message. Similarly, the second stop bit belongs to the 4[th] position of the message, etc. The last position can be deduced from the others and, hence, is redundant information that is not transmitted. As the size of the permutation matrix (L_{P}) scales exponentially with M, the permutation matrix needs to be compressed. A possible compression method may consist of encoding the position of the stop bit not only into the position k of the active RE but also in the MCS of this RE.

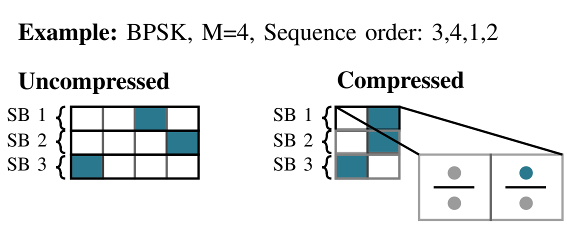

Fig. 4. Compression of the permutation matrix by using the MCS.

Fig. 4 illustrates an example of the compression of the permutation matrix with a BPSK system and $M = 4$. However, this can be transferred to any number of parallel stop bits and MCS. For the transmission of each position of one stop bit, $l_{\text{P}} = \lceil M/2^{N_{\text{MCS,P}}^{\text{bit}}} \rceil$ REs are needed, whereby $N_{\text{MCS,P}}^{\text{bit}}$ is the number of bits encoded on each RE of the permutation matrix. In the example of Fig. 4, two REs are reserved per stop bit position. The position is extracted by counting over the constellation points of the two adjacent REs. For the first position, the first RE is empty, meaning that the encoded position must be bigger than 2. In the second RE, the first constellation point is selected, meaning that the first stop bit is positioned at the 3rd position in the message. With this compression method, the permutation matrix size L_{P} can be reduced to

$$L_{\text{P}} = (M-1) \cdot \left\lceil \frac{M}{2^{N_{\text{MCS,P}}}} \right\rceil . \tag{5}$$

In some cases, the counter length has to be increased to solve the ambiguity of two counters with the same stop bit position by using a rule, e.g., by continuing counting at the next RE. In general, it leads to a total start stop bit cycle length of

$$L_{\text{ss}} = 2^{N_{\text{c}}^{\text{bit}}} + (M-1) + L_{\text{P}}. \tag{6}$$

As only $M-1$ REs are active for the transmission of the permutation matrix, the sparsity is given as

$$\rho = 1 - \left(\frac{M + (M-1)}{L_{\text{ss}}} \right), \tag{7}$$

while the throughput gain is given by

$$\Gamma_{\text{thr}} = \frac{(N_{\text{c}}^{\text{bit}} + N_{\text{MCS,sb}}^{\text{bit}}) \cdot M}{L_{\text{ss}} \cdot N_{\text{MCS,con}}^{\text{bit}}}. \tag{8}$$

Example: If $M = 10$ parallel sequences are utilized, each containing $N_{\text{sb}}^{\text{bit}} = 8$ bits of information, the total length of the start stop bit cycle is $L_{\text{ss}} = 64 + 9 + 9 \cdot 3 = 100$ given that the permutation matrix compression is realized with QPSK. Therefore, the resulting sparsity is $\rho = 81.0\,\%$, and the throughput gain is given by $\Gamma_{\text{thr}} = (8 \cdot 10)$ bit $\cdot\, (2\ ^{\text{bit}}/_{\text{RE}} \cdot 100\ \text{REs})^{-1} = 0.4$. This shows that a high number of parallel sequences helps to drastically increase the throughput.

E. Time and Frequency Shifts

As demonstrated in the examples above, the throughput of the start stop bit method can be improved by using several parallel stop bits. Nevertheless, there remains a noticeable gap to the conventional throughput. To address this issue, an additional enhancement was proposed in [3], utilizing fractional time and frequency shifts. This results in a further dimension of the counter space. The RE carrying the stop bit is hereby shifted in time by a fraction of the OFDM symbol length (δt) and in frequency by a fraction of the subcarrier spacing (δf). The different time and frequency shift options, i.e., different combinations of δt and δf, can be utilized to encode further information bits, whereby each combination encodes a bit sequence. Therefore, if, e.g., 16 time and 16 frequency shifts can be realized, there are 256 combinations leading to 8 bits encoded into each shift. Each of the time and frequency shifts creates a unique amplitude pattern on the adjacent REs, which the demodulator can identify. However, this amplitude modulation is created due to the fact that the shift causes inter-carrier and inter-symbol interference, which not only appears at the direct neighbor REs, but also on other REs. As a countermeasure for this unintentional interference, this paper proposes artificial time and frequency shifts. Thereby, the effect of the time and frequency shifts, namely an amplitude modulation on the adjacent REs of the stop bit, is created artificially without affecting any other REs. The concept can be seen in Fig. 5.

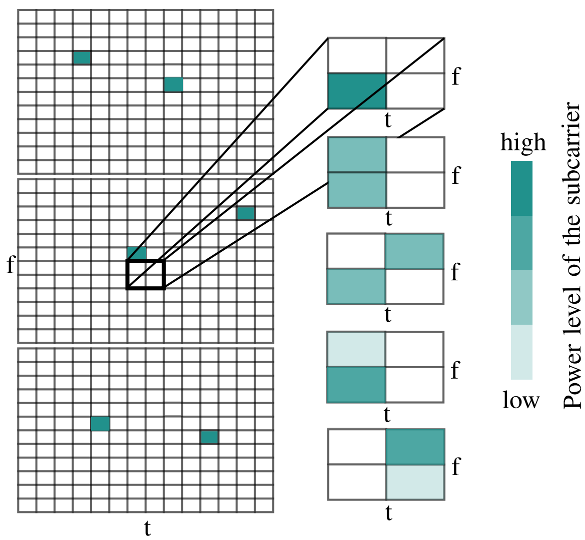

Fig. 5. Artificial time and frequency shifts to encode further information bits.

Adjacent to each stop bit, a stop bit area is positioned to reserve additional REs in time and frequency for the artificial shifts. The number of additional REs (L_{add}) of an area, here in our example is equal to 4, but it can be set to any other value. On those REs, the amplitude modulation is realized, whereby each amplitude pattern directly refers to a bit sequence. The amplitude patterns are constructed sparsely, with at most two active REs, while the other REs are nulled. The different shift possibilities are predefined in a look-up table, which is generated based on maximizing the sparsity while simultaneously maximizing the minimum distance between two neighboring entries. Additionally to a single area encoding the artificial time and frequency shift, also several areas, all encoding a different shift, can be used. Here, L_{areas} defines the total number of areas that are used. In order to avoid that parallel stop bits are positioned in the shift areas of another stop bit, the start stop bit cycle length is increased by the area size. Then, the counter skips the REs of the stop bit area, i.e., the counter continues with the first RE after the area. This leads to a start stop bit cycle length of

$$L_{\text{ss}} = 2^{N_{\text{c}}^{\text{bit}}} + (M-1) + M \cdot L_{\text{add}} \cdot L_{\text{areas}} + L_{\text{P}}. \quad (9)$$

Moreover, the sparsity is now given as

$$\rho = 1 - \left(\frac{M + M - 1 + M \cdot L_{\text{act}} \cdot L_{\text{areas}}}{L_{\text{ss}}} \right), \quad (10)$$

whereby L_{act} denotes the number of active REs per shift, which is at most two by construction in this example. The information bits encoded into each stop bit are composed of four different components. First, the position of the stop bit encodes information bits ($N_{\text{c}}^{\text{bit}}$). Then, the MCS used for the stop bit itself encodes further information bits ($N_{\text{MCS,sb}}^{\text{bit}}$). Moreover, the shift on the additional REs encodes information bits ($N_{\text{shift}}^{\text{bit}}$), and lastly, the additional REs can also transmit an independent MCS that encodes information bits ($N_{\text{MCS,shift}}^{\text{bit}}$). Thus, the total amount of bits encoded into each stop bit area can be calculated as

$$N_{\text{sb}}^{\text{bit}} = N_{\text{c}} + N_{\text{MCS,sb}} + (N_{\text{shift}} + N_{\text{MCS,shift}}) \cdot L_{\text{areas}}. \quad (11)$$

Lastly, the throughput gain can be determined as

$$\Gamma_{\text{thr}} = \frac{N_{\text{sb}}^{\text{bit}} \cdot M}{L_{\text{ss}} \cdot N_{\text{MCS,con}}^{\text{bit}}}. \quad (12)$$

Example: If for the same example from before, one shift area ($L_{\text{areas}} = 1$) with $L_{\text{add}} = 4$ REs is used and in total 64 different shifts can be detected, the number of bits per stop bit is given by $N_{\text{sb}}^{\text{bit}} = 6\,\text{bit} + 2\,\text{bit} + 6\,\text{bit} + 2\,\text{bit} = 16\,\text{bit}$, if for both the stop bit and the shift area QPSK is used as the MCS. The start stop bit length is then given by $L_{\text{ss}} = 100 + 40 = 140$, leading to a sparsity of $\rho = 72.14\,\%$ if $L_{act} = 2$ is used, and a throughput gain of $\Gamma_{\text{thr}} = 0.57$, which again improves the throughput of the start stop bit method.

III. Power, Encoding, and Error Handling Aspects

A. Power Boosting of Active REs

In an OFDM system, the transmit signal is always scaled to an average power $\overline{P} = 1$ before the transmission. In a conventional transmission, this scaling is already included in the constellation points as they are constructed to have an average power of 1. However, as the sparsity with the start stop bit method is very high, this scaling to the average power boosts the active REs. The power boost directly represents the ratio of the total number of REs for one start stop bit cycle against the sum power of the active REs in the cycle as

$$P_{\text{boost}} = \frac{L_{\text{ss}}}{M + (L_{\text{areas}} \cdot M) + (M-1)}. \quad (13)$$

This power boost allows the stop bit, permutation matrix, and shift bit detection to be less susceptible to noise.

B. Information Encoding and Decoding

The encoding and decoding process of the start stop bit method is different compared to the conventional method. First, the SINR is identified per UE, which defines the MCS. The next step then includes splitting the message into sequences of $N_{\text{sb}}^{\text{bit}}$ bit, whereby each sequence will be encoded into one stop bit. Afterward, the positions of the REs for the stop bit areas are determined in the resource grid. Then, the shift look-up table is used to extract the amplitude pattern that encodes the bits for the shift, which is then modulated on the adjacent REs of the stop bit. Next, the permutation matrix is constructed and modulated onto the subcarriers, whereby the matrix is placed at the end of each start stop bit cycle. After those steps, the typical OFDM transmission is realized. At the receiver side, the steps are repeated in reverse order, whereby the detection of the stop bits and permutation matrix is crucial for the performance of the proposed method. One way of detecting a stop bit is by inspecting all REs in each start stop bit cycle in a frequency first order, observing if the received power of a RE exceeds a predefined threshold. However, the additional REs placed adjacent to the stop bit RE can also be used as information to further improve the detection of the stop bits.

C. Error Rates

Another metric to measure the performance of the start stop bit method compared to the conventional system, besides the sparsity and throughput gain, is the Bit Error Rate (BER). There are several errors that contribute to the BER in the start stop bit method:

- **a *Stop* bit is misdetected:** Error propagates into future *stop* bit positions and a minimum of $N_{\text{sb}}^{\text{bit}}$ bit errors occur.
- **a permutation matrix entry is misdetected:** At most 2 $N_{\text{sb}}^{\text{bit}}$ bit errors can occur for a misdetection.
- **MCS is misdetected in a RE:** A total of $N_{\text{MCS}}^{\text{bit}}$ bit errors can occur per misdetection.
- **a shift is misdetected:** A total of $N_{\text{shift}}^{\text{bit}}$ bit errors can occur per misdetection.

The first two sources of errors drastically affect the BER because the misdetection of a stop bit or the misdetection of the positions of the stop bits by the permutation matrix directly causes the whole stop bit information to be wrong. However, if one entry of the permutation matrix is wrongly detected, this can mostly be recognized and corrected as every stop bit position can occur at most once. Nevertheless, detecting and decoding the stop bits and the permutation matrix needs to be be as robust as possible to ensure BERs that are comparable to conventional OFDM systems.

IV. Analysis of the Start Stop Bit Method

The analysis of the start stop bit method is divided into two parts. First, the sparsity and throughput gain are analyzed using the mathematical formulas from Section II. Afterward, a LLS is used to analyze the BERs of the start stop bit method and compare them to the BERs of a conventional system.

A. Analysis of Sparsity and Throughput Gain

Fig. 6 shows the throughput gain with the compressed permutation matrix for a conventional BPSK system using multiple parallel stop bits without additional shift areas. The maximum throughput gain is $\Gamma_{\text{thr}} = 0.72$, achieved with $M = 8$ parallel sequences for $N_c^{\text{bit}} = 5$. Local maxima occur with different numbers of parallel sequences, where all the MCSs are optimally utilized to encode the sequence positions. This means that the permutation matrix length, as calculated in (5), is optimal since smaller M values result in the same permutation matrix overhead. For instance, using $M = 9$ with BPSK, the matrix consumes 5 REs per position to encode 9 sequences, but it could also encode $M = 10$ sequences without using additional REs. Increasing the number of parallel sequences beyond $M = 8$ causes the throughput gain to decrease. This happens because the REs allocated for the permutation matrix grow quadratically with M. However, by increasing N_c^{bit}, the impact of this overhead diminishes as the ratio of REs for the permutation matrix to those for the counter in the start stop bit cycle decreases.

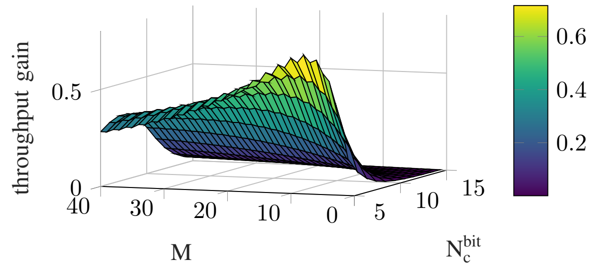

Fig. 6. Throughput gain with compressed permutation matrix, multiple stop bits, and no additional shift areas compared to a BPSK conventional system.

Fig. 7 illustrates the sparsity of the start stop bit method with the compressed permutation matrix. It shows that sparsity decreases as N_c^{bit} decreases, regardless of M. Additionally, the trade-off between sparsity and throughput gain is evident as the sparsity is very low when the throughput gain is high and conversely.

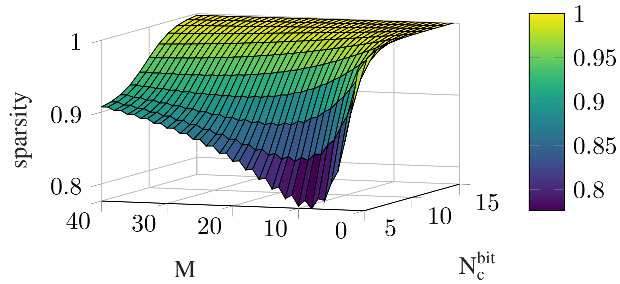

Fig. 7. Sparsity with compressed permutation matrix, multiple stop bits, and no additional shift areas.

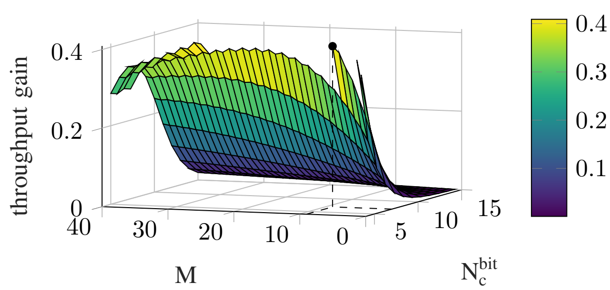

Fig. 8. Throughput gain for the compressed permutation matrix and sparsity lower bound of $\rho > 90\%$ with maximum at $M = 9$ and $N_c^{\text{bit}} = 7$.

To maintain a sparsity above a specific level, it must be lower-bounded. Fig. 8 shows the data from Fig. 6, focusing on combinations of M and N_c^{bit} where $\rho > 90\%$. Using this constraint, the maximum throughput gain is $\Gamma_{\text{thr}} = 0.41$. For this example, the optimal parameters for maximizing throughput gain while keeping sparsity above 90% are $N_{\text{c}}^{\text{bit}} = 7$ and $M = 9$. Thus, while the conventional system offers more than twice the data rate of the start-stop bit method, the latter achieves this with only 10% of the REs being utilized.

B. Link Level Analysis

To evaluate the performance of the start stop bit method, a LLS is used to simulate both the start stop bit and conventional transmission for a single-user AWGN channel with one transmission point. The simulation includes the implementation of the conventional OFDM transmission and the start stop bit method, following the encoding and decoding steps from Section III-B. It uses 20 MHz bandwidth, 15 kHz subcarrier spacing, 1200 subcarriers, and an FFT size of 2048.

The system parameters for the start stop bit method are optimized for each SNR value due to its impact on the error rates. Therefore, different parameter constellations are chosen to maximize throughput while maintaining at least 75% sparsity and meet predefined error rate limits. Table I summarizes the KPIs for these parameters.

TABLE I
SUMMARY OF THE THROUGHPUT GAIN AND SPARSITY FOR DIFFERENT PARAMETER CONSTELLATIONS

SNR	0 dB	3 dB	6 dB	9 dB
$\boldsymbol{\Gamma}_{\text{thr}}$	0.2	0.43	0.75	1.12
$\boldsymbol{\rho}$	0.96	0.91	0.84	0.76

Fig. 9 shows the BER for the optimized parameters. Therefore, the different curves represent the different parameter constellations that achieve the sparsity and throughput gains displayed in Table I.

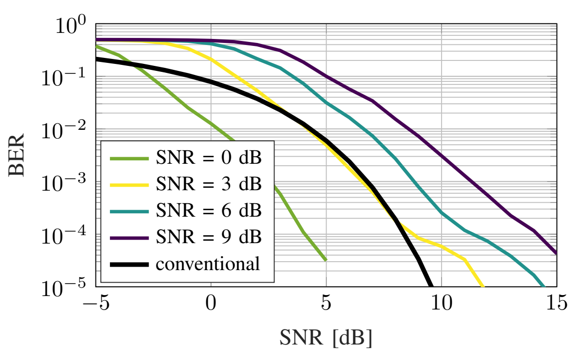

Fig. 9. BER of the start stop bit method compared to the conventional BPSK system with a sparsity limitation of $\rho > 0.75$.

The first notable effect occurs at low SNRs, where the BER for different parameter constellations approaches 50%. This results from the high noise relative to the received power, makes stop bit detection unreliable and, therefore, producing random bit sequences. Such conditions are unsuitable for real communication systems as error-free stop-bit detection needs to be ensured. However, e.g., for the optimization with SNR = 0 dB, the BER is mostly smaller compared to the BER of a conventional system using BPSK. For the chosen parameter constellations for this SNR, the throughput is only 20% of the one achieved by a conventional transmission, but the sparsity is 96%, meaning that only 4% of the REs are active. Conversely, the parameters for the 9 dB scenario generate higher BERs compared to the conventional transmission, but achieve a throughput gain of 1.12 and a sparsity of 76%. This means that a throughput gain can be achieved if the higher BERs can be handled. These parameter constellations offer different benefits for various applications. If high sparsity is crucial, parameters with greater sparsity and lower throughput gain may be preferred. On the other hand, for applications prioritizing throughput gain, alternative constellations with higher throughput but less sparsity may be more suitable.

V. Conclusion and Outlook

This paper presents the first comprehensive performance analysis of the start stop bit method. The conducted study highlights the trade-off between sparsity and throughput, whereby a high sparsity reduces processing complexity and interference, but also might lower the throughput. Notably, the analysis shows that the method achieves around 41% of the conventional system throughput with 90% sparsity. For some other parameter configurations, the BERs are higher than in conventional systems, but the start stop bit method can achieve higher throughput than a conventional transmission. For instance, it is possible to obtain 12% throughput gain by a slight sparsity reduction to 76%. These first studies provide promising insights in the potential of this new method. Further work is needed to address the high BER issue, while keeping throughput gains and high levels of sparsity, for instance, by means of coding and error correction techniques on the top of our proposed approaches.

VI. Acknowledgments

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