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Joint Multi-User Detection with Weighting Factors for Unsourced Multiple Access

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Abstract

Multi-user detection techniques are currently being studied as highly promising technologies for improving the performance of unsourced multiple access systems. In this paper, we propose joint multi-user detection schemes with weighting factors for unsourced multiple access. First, we introduce bidirectional weighting factors in the extrinsic information passing process between the multi-user detector based on belief propagation (BP) and the LDPC decoder. Second, we incorporate bidirectional weighting factors in the message passing process between the MAC nodes and the user variable nodes in BP-based multi-user detector. The proposed schemes select the optimal weighting factors through simulations. The simulation results demonstrate that the proposed schemes exhibit significant performance improvements in terms of block error rate (BLER) compared to traditional schemes.

Keywords

Communication, Sparse IDMA, Multi-User Detection, Belief Propagation

1. Introduction

Next-generation wireless communication systems face significant challenges in ensuring extensive capacity to support massive machine-type communication [1]. Multiple access technology plays an important role in wireless communication: it increases the capacity of the channel and allows different users to access the system simultaneously [2]. However, the traditional multiple access technologies cannot meet the requirements of future sixth generation (6G) systems in terms of ultra-high reliability, extremely low latency, and massive connectivity [3].

Unsourced random access is a promising multiple access technology for 6G

[4]. In [5], uncoordinated and unsourced multiple access communication is proposed as a novel formulation for current uplink data transfers, which is closely related to coded random access and many access channel [6]. In the unsourced multiple access channel (MAC) problem, a wireless communication system is composed of K_{tot} users, out of which only a small group of K_{a} users are active at any given time [7], each active device wishes to transmit a B-bit message to a central base station (BS), and the BS is tasked with recovering the collection of B-bit messages communicated by the active devices without regard to the identities of the senders.

Uncoordinated and unsourced multiple access communication breakthroughs the conventional capacity-oriented optimization approach [8]. While ensuring access reliability, it significantly enhances spectrum efficiency and user capacity, aligning with the explosive data growth and massive connectivity demands of mobile communication systems. Compared to coordinated non-orthogonal multiple access technology [9], it has stronger overload resistance and eliminates the signaling overhead and latency generated during the collaboration process, thus meeting the requirements of 6G.

Among the existing unsourced multiple access coding schemes, a sparse version of interleave-division multiple access (IDMA) which control multi-user interference by keeping the transmissions sparse has excellent performance [10]. IDMA is a new proposed multiple access technique in present and next generation wireless communication [11]. In this new scheme, users are distinguished by different chip-level interleaving methods instead of by different signatures as in a conventional code-division multiple access (CDMA) scheme [12]. The sparsity in spare IDMA is useful in ensuring low computational complexity of optimal soft-input soft-output demodulation and efficient performance of massage passing decoding when the number of users is large and message block length is small [10]. However, in [10], the sparse IDMA encoding scheme relies on the joint iteration of the BP-based multi-user detector and LDPC decoder, which is not hard-ware friendly due to its high complexity.

BP algorithm is defined on factor graph [13], which has been originally proposed for the probabilistic inference problem which is the problem to calculate the marginal probabilities of the interested variables [14]. The use of BP-based iterative receivers in multiple access systems is a important breakthrough [15]. Iterative receivers can be classified into two groups. In one group an iterative receiver performs multi-user detection (MUD) with conventional non-iterative detectors [16], and the detector uses decisions fed back from the decoders to subtracts the multiple access interference [17]. In this paper, we focus on the other group of BP-based iterative receivers, which perform MUD with iterative detectors and decisions in the detector are directly utilized to mitigate the multiple-access interference. The generalized version of the standard BP algorithm by assigning weights to the edges of the Tanner graph has been proven to exhibit excellent performance [18].

In this paper, weighting factors are utilized to improve the performance of BP-based iterative MUD and decoding for sparse IDMA scheme. The novelty and contribution of this paper are summarized as follows:

- Weighted extrinsic information passing process. By adding bidirectional weighting factors in the extrinsic information transfer process between the multi-user detector and the LDPC decoder, the joint multi-user detection scheme can be improved from two perspectives: improving performance and reducing complexity. From the first perspective, the improved joint multi-user detection scheme outperforms traditional schemes in terms of BLER performance with the same number of iterations. From the second perspective, the improved joint multi-user detection scheme can achieve considerable performance even when the number of inner iterations of multi-user detector and outer iterations of receiver are less than traditional schemes.
- Weighted message passing in multi-user detector. Based on the weighted extrinsic information passing process, we further incorporate bidirectional weighting factors in the message passing process between the MAC nodes and the user variable nodes in multi-user detector. By this means, the performance of the joint multi user detection scheme can be further improved.
- Optimizing weighting factors by simulations. We obtained the optimal values of the weighting factors through simulations using the controlled variable method, where we fixed the signal-to-noise ratio (SNR) and all other conditions and only varied the values of the corresponding weighting factors.

2. System Model

The system architecture of sparse IDMA [10] scheme is presented in **Figure 1**. Sparse IDMA adds random irregular repetition within superposition coding structure and reduces collision among symbols with zero-padding [19]. The preamble determines the interleaver and the repetition pattern of each user's codewords [19]. In sparse IDMA, the encoding process is identical for every active user and independent of user identity.

In the transmission process, user k out of K_{a} active users randomly selects a certain slot for transmission, and then there are K_{a}^{t} users sparsely superposing their data within the slot t. Let T be the maximal number of users that can simultaneously transmit in the same slot without incurring error. In [20], Or Ordentlich donated by $E_{1,k}$ be the event that more than $T-1$ other active users transmitted within the same time slot as user k and donated by

$$\Pr(E_{1,k}) = 1 - \Pr(\text{Binomial}(K_a - 1, \frac{1}{V} < T) \triangleq \varepsilon_1 \tag{1}$$

be the probability of event $E_{1,k}$ occurring, where V represents the total number of time slots. Given the values of V and ε_1, the value of T can be determined. In this paper, we set $\varepsilon_1 = 0.05$ in our simulations. In the receiver, if $K_{\mathrm{a}}^{t} \le T$, the decoding process is performed; otherwise, the decoding process is not executed.

The transmitter contains two components: a compressed sensing (CS) encoder

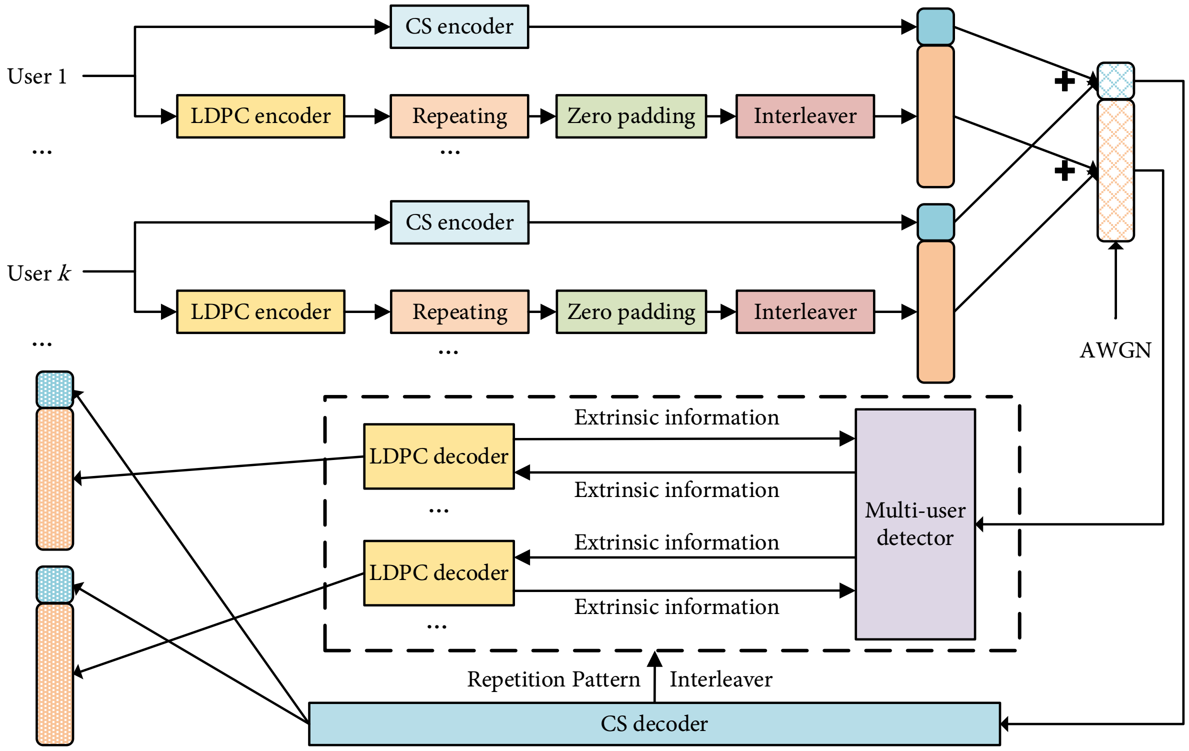

Figure 1. System architecture of sparse IDMA scheme.

for the preamble message, and a multi-user channel encoder for the binary-input real-adder multiple access channel [10]. Every active user has B bits of information to send, which includes preamble and data. The preamble portion is encoded by CS encoder. The data portion undergoes sequential processes of LDPC encoding, repetition, zero padding, interleaving, and modulation to obtain the transmitted data. Stitch the signals of the two parts, the transmitted signal $\mathbf{x}_k$ is obtained.

In the receiver, for any given slot t, the received signal is

$$\mathbf{y}_t = \sum_{k=1}^{K_a^t} \mathbf{x}_k + \mathbf{n}, \tag{2}$$

where $\mathbf{n}$ is additive white Gaussian noise (AWGN). The receiver has two components. The CS decoder recovers the preamble message to acquire the repetition patterns and interleavers for K_a^t users. The data portion $\mathbf{y}_{t,\text{data}}$ is recovered by joint decoder, which has two components: multi-user detector and protograph LDPC decoder. The Extrinsic information obtained from the iterative multi-user detector is sent to the single user LDPC decoders for decoding, and the decoding results are then sent to the multi user detector for detection. This iterative process is repeated until all user data packets are decoded or the maximum number of external iterations is reached.

3. Proposed Schemes

We introduce weighted joint multi-user detection schemes in this section.

3.1. Weighted Extrinsic Information Passing Process

Given the data portion $\mathbf{y}_{t,\text{data}}$ of the received signal, the joint BP-based decoder proceeds iteratively passing messages along the edges of a Tanner graph that represents the coding scheme. Such a Tanner graph, along with the associated messages passed during the decoding process appears in **Figure 2**. Here user k repeats its coded symbols twice, whereas user $k+1$ repeats its coded symbols once.

Taking into account the addition of a weighting factors in the process of extrinsic information transfer between the multi-user detector and the LDPC decoder, we propose I-WJMUD scheme. In the process of extrinsic information transfer from the multi-user detector to the LDPC decoder, we have added a weighting factor $w_{\text{DET}\to\text{DEC}}$. In the reverse direction, we have added a weighting factor $w_{\text{DEC}\to\text{DET}}$.

3.2. Weighted Message Passing in Multi-User Detector

In addition to incorporating weighting factors during the external iteration process, we also introduce bidirectional weighting factors in the message passing process between the variable nodes and MAC nodes within the multi-user detector. By this means, we proposed II-WJMUD scheme. Given an edge of e between a variable node and a MAC node, let v_e and $+_e$ be the variable node and MAC node connected to *e*, respectively. Let $\xi(v_e)$ denote the set of edges that connect the variable node v_e to MAC nodes. Let $\varsigma(+_e)$ be the set of edges connected to MAC node $+_e$.

Let $m^k_{+\to v}(e)$ be the messages passed from MAC node to variable node of user k along edge *e*. It can be written as

$$m^k_{+\to v}(e) = \log\frac{P(c_{k,i}=0\mid y_{t,\text{data}})}{P(c_{k,i}=1\mid y_{t,\text{data}})} + w_{\text{DET},v\to+}\times\sum_{f\in\varsigma(+_e)\backslash e} m^k_{v\to+}(f), \tag{3}$$

where $c_{k,i}$ is coded bit of user *k*, the second item is initialized to 0 for the first multi-user detection iteration, and $w_{\text{DET},v\to+}$ is the weighting factor we introduce

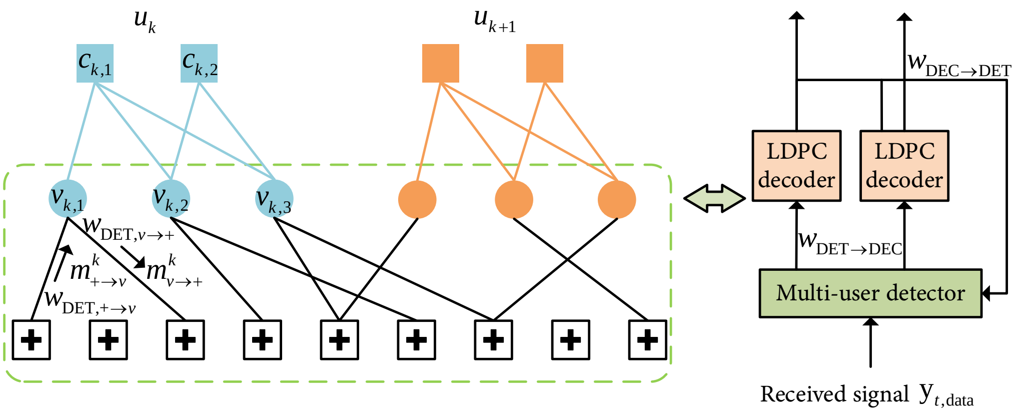

Figure 2. This figure illustrates the Tanner graph structure and associated messages passing process of the proposed schemes. The nodes marked *v*, *c* and + represent variable nodes, check nodes and MAC nodes, respectively.

in the process of passing the message from user variable node to MAC node.

Messages passed from variable node of user k to MAC node along edge e can be written as

$$m^k_{v\to+}(e) = w_{\mathrm{DET},+\to v} \times \sum_{f\in\xi(v_e)\setminus e} m^k_{+\to v}(f), \tag{4}$$

where $w_{\mathrm{DET},+\to v}$ is the weighting factor we add to the message passed from MAC node to user variable node in the multi-user detector.

3.3. Optimizing Weighting Factors

In our schemes, we add weighting factors $w_{\mathrm{DET}\to\mathrm{DEC}}$, $w_{\mathrm{DEC}\to\mathrm{DET}}$, $w_{\mathrm{DET},+\to v}$, and $w_{\mathrm{DET},v\to+}$ to traditional BP-based joint multi-user detection (T-JMUD) scheme to improve performance and reduce complexity. The optimal values of the weighting factors are obtained through simulations using the controlled variable method.

Figure 3 shows the simulation results of the relationship between BLER values and changes in weighting factors. It can be seen that when only $w_{\mathrm{DET}\to\mathrm{DEC}}$ is added, the minimum value of BLER occurs at $w_{\mathrm{DET}\to\mathrm{DEC}} = 0.5$. By fixing the value of $w_{\mathrm{DET}\to\mathrm{DEC}}$ to 0.5, we add $w_{\mathrm{DEC}\to\mathrm{DET}}$ and obtain a curve that shows the variations of BLER with respect to the value of $w_{\mathrm{DEC}\to\mathrm{DET}}$. It can be observed that the minimum BLER value is obtained when $w_{\mathrm{DEC}\to\mathrm{DET}} = 0.6$. In conclusion,

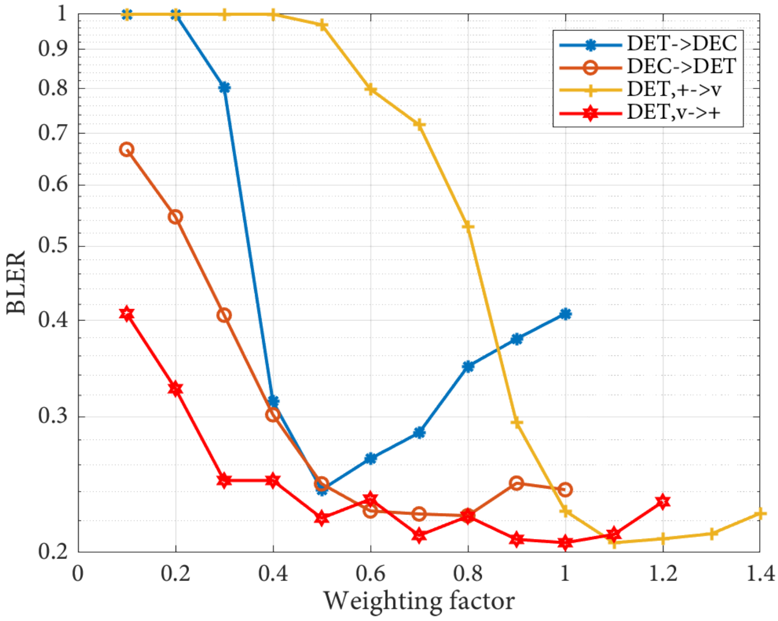

Figure 3. Variations of BLER with changes in weighting factors. The blue line represents the variations of BLER with the changes in the value of $w_{\mathrm{DET}\to\mathrm{DEC}}$. The orange line represents the variations of BLER with the changes in the value of $w_{\mathrm{DEC}\to\mathrm{DET}}$ with $w_{\mathrm{DET}\to\mathrm{DEC}}$ fixed. The yellow line represents the variations of BLER with the changes in the value of $w_{\mathrm{DET},+\to v}$ with fixed $w_{\mathrm{DET}\to\mathrm{DEC}}$ and $w_{\mathrm{DEC}\to\mathrm{DET}}$. The red line represents the variations of BLER with the changes in the value of $w_{\mathrm{DET},v\to+}$ with fixed $w_{\mathrm{DET}\to\mathrm{DEC}}$, $w_{\mathrm{DEC}\to\mathrm{DET}}$, and $w_{\mathrm{DET},+\to v}$.

we have determined that I-WJMUD achieves optimal performance when $w_{\mathrm{DET}\to\mathrm{DEC}} = 0.5$ and $w_{\mathrm{DEC}\to\mathrm{DET}} = 0.6$.

Based on I-WJMUD, we add $w_{\mathrm{DET},+\to v}$ and observe a curve depicting the variations of BLER performance with respect to $w_{\mathrm{DET},+\to v}$. It can be seen that the minimum BLER value is achieved when $w_{\mathrm{DET},+\to v} = 1.1$. With the value of $w_{\mathrm{DET},+\to v}$ fixed at 1.1, we add $w_{\mathrm{DET},v\to +}$ and obtain a curve depicting the variations of BLER performance with respect to $w_{\mathrm{DET},v\to +}$. It can be observed that the minimum BLER value is achieved when $w_{\mathrm{DET},v\to +} = 1.0$. In summary, II-WJMUD achieves achieves optimal performance when $w_{\mathrm{DET}\to\mathrm{DEC}} = 0.5$, $w_{\mathrm{DEC}\to\mathrm{DET}} = 0.6$, $w_{\mathrm{DET},+\to v} = 1.1$, and $w_{\mathrm{DET},v\to +} = 1.0$.

4. Simulation

In this section, we evaluate the performance of I-WJMUD, II-WJMUD and T-JMUD by Monte-Carlo simulation. The simulation parameter settings are shown in **Table 1**.

In the transmitter, user data is generated by creating random binary messages. These messages are encoded using the protograph LDPC scheme defined in the 5G standard, modulated using BPSK, repeated according to repetition patterns, interleaved using random interleavers and superimposed to obtain transmitted signals. AWGN channel is used for signal transmission. To ensure reliable estimates of BLER performance, we conducted simulations with a requirement of detecting 500 block errors or simulating at least 1000 frames for each SNR.

We study the BLER performance of different detection schemes when K_{a} is 50, 100, and 150. The results of $K_{\mathrm{a}} = 50$ are shown in **Figure 4**. At low SNRs, the values of BLER of I-WJMUD and II-WJMUD are half that of T-JMUD. I-WJMUD and II-WJMUD can achieve $\mathrm{BLER} = 10^{-2}$ at $\mathrm{SNR} = 3.6$ dB yet T-JMUD reaches the same performance at $\mathrm{SNR} = 4.3$ dB, obtain a gain of about 0.7 dB. I-WJMUD and II-WJMUD can reach $\mathrm{BLER} = 10^{-3}$ at $\mathrm{SNR} = 5$ dB,

Table 1. Simulation parameters.

Parameters	Values		
Number of active users K_{a}	50	100	150
Collision threshold T	4	6	9
Transmitted bits per user	90	90	90
LDPC code rate	1/3	1/3	1/3
Length of time slot	1350	1350	1350
Repetition pattern	$\frac{1}{4}x^3 + \frac{3}{4}x^2$	x^2	$\frac{7}{9}x^2 + \frac{2}{9}x$
External iterations	4	4	4
Iterations of detector	15	15	15
Iterations of LDPC decoder	20	20	20

while T-JMUD do not. When $\text{SNR} > 3$ dB, I-WJMUD and II-WJMUD outperform T-JMUD as much as an order of magnitude. There is not much difference in BLER performance between I-WJMUD and II-WJMUD, but II-WJMUD is still slightly better than I-WJMUD.

Figure 5 illustrates the BLER performance of different detection schemes when $K_a = 100$. For all SNRs, I-WJMUD and II-WJMUD significantly outperform T-JMUD. I-WJMUD and II-WJMUD can achieve $\text{BLER} = 10^{-2}$ at $\text{SNR} = 4.1$

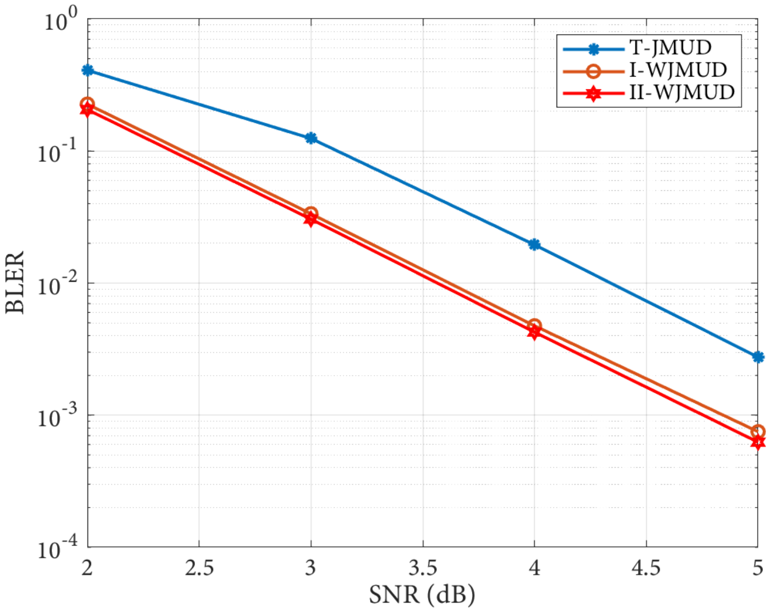

Figure 4. BLER performance of the proposed schemes and the traditional one when $K_a = 50$.

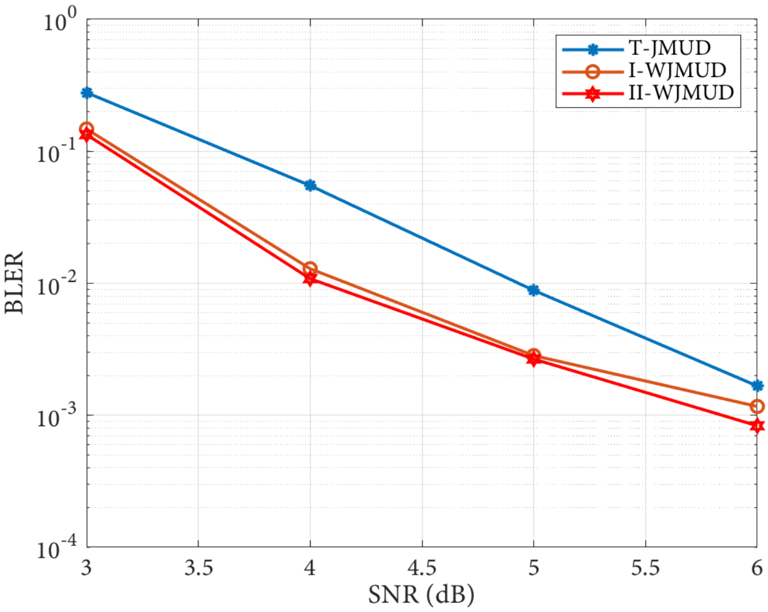

Figure 5. BLER performance of the proposed schemes and the traditional one when $K_a = 100$.

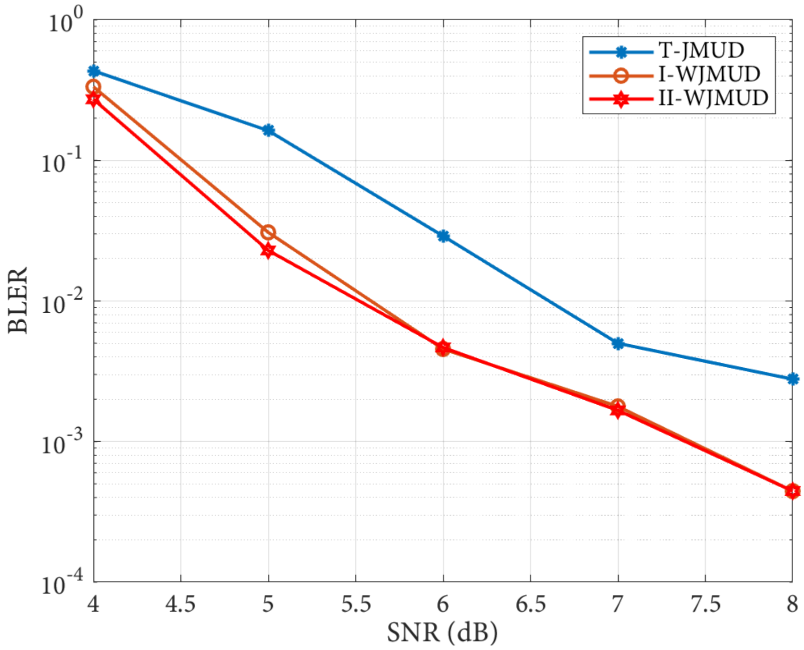

Figure 6. BLER performance of the proposed schemes and the traditional one when $K_a = 150$.

dB yet T-JMUD reaches the same performance at $\text{SNR} = 5$ dB, obtain a gain of approximately 0.9 dB. In addition, compared to I-WJMUD, II-WJMUD exhibits slight improvement in BLER performance for all SNRs. II-WJMUD can achieve $\text{BLER} = 10^{-3}$ at $\text{SNR} = 6$ dB, while I-WJMUD and T-JMUD do not.

The comparison of BLER performance for different detection methods when $K_a = 150$ is shown in **Figure 6**. When $\text{SNR} = 4$ dB, I-WJMUD and II-WJMUD have roughly the same BLER as T-JMUD, while at high SNRs, I-WJMUD and II-WJMUD outperform T-JMUD significantly. I-WJMUD and II-WJMUD can achieve $\text{BLER} = 10^{-3}$ at $\text{SNR} = 8$ dB, while T-JMUD does not. In addition, compared to I-WJMUD, II-WJMUD exhibits slight improvement at low SNRs, while at high SNRs, II-WJMUD performs similarly to I-WJMUD.

5. Conclusion

In this paper, we propose weighted joint BP-based multi-user detection schemes for unsourced multiple access by assigning weighting factors. Weighting factors are added in both directions of the extrinsic information transfer process between the multi-user detector and the LDPC decoder. Additionally, weighting factors are also added in both directions of the message passing process between the MAC nodes in the multi-user detector and the user variable nodes. The proposed schemes can outperform the traditional joint multi-user detection scheme in two aspects: achieving better performance with the same iterations and reducing the complexity under the condition of the achieving the comparable performance. In the future work, deep learning is a promising method to obtain optimal weighting factors.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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