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Generalized message passing detection of SCMA systems based on dynamic factor graph for better and flexible performance-complexity tradeoff

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Abstract Multiuser detection based on the message passing algorithm (MPA) has been considered for sparse code multiple access (SCMA) systems. Recently, some complexity-reduced MPA detectors have been proposed, among which the MPA detector based on dynamic factor graph (DFG-MPA) has been shown to outperform other MPA detectors with comparable complexities. However, all these MPA detectors are somehow not very flexible in terms of performance-complexity tradeoff, i.e., the granularities of computational complexity reduction are relatively large. In this paper, a generalized scheme of DFG-MPA, termed as GDFG-MPA, is proposed to make a better and more flexible performance-complexity tradeoff. The proposed scheme features two aspects: (1) instead of banning a message update forever, a banned message update at some iteration is allowed to be updated at later iterations; (2) different numbers of message updates are banned from updating at different iterations. Optimization of GDFG-MPA can be made by allocating banned message updates among iterations. Numerical results have demonstrated that compared to DFG-MPA the proposed GDFG-MPA can achieve much better performance at the same computational complexity or achieve the same performance with much lower complexity. Moreover, the proposed GDFG-MPA is more flexible in tuning the performance and complexity tradeoff.

Keywords sparse code multiple access (SCMA), multiuser detection, message passing algorithm (MPA), factor graph, computational complexity

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1 Introduction

The performance-complexity tradeoff has always been one of the central topics in the receiver design of communication systems. Recently, to support massive connection, non-orthongonal multiple access (NOMA) schemes and the associated multiuser detection methods have attracted a lot of research interests. As a novel NOMA scheme for the 5G systems [1–4], sparse code multiple access (SCMA) [5] features its multi-dimensional sparse codebooks [6–11], which enables it to achieve shaping gain and use message passing algorithm (MPA) as the multiuser detector [12, 13]. It is shown that the MPA detector is able to obtain nearly optimal performance with a feasible computational complexity. However, the MPA detector exhibits a computational complexity exponential in the number of superimposed users on resource nodes (RNs). This makes the MPA detector less attractive for systems with a lot of users. To overcome this difficulty, various complexity-reduced MPA detectors have recently been proposed to offer a tradeoff between performance and complexity. This paper is interested in developing modified MPA detectors with better and more flexible performance-complexity tradeoffs.

Different approaches have been attempted to reduce the computational complexity [14–18] of the MPA multiuser detector for SCMA systems. In [14, 15], serial schedules are proposed to speed up the convergence rate of the MPA detector. The basic idea is to use earlier updated messages in the updates of later

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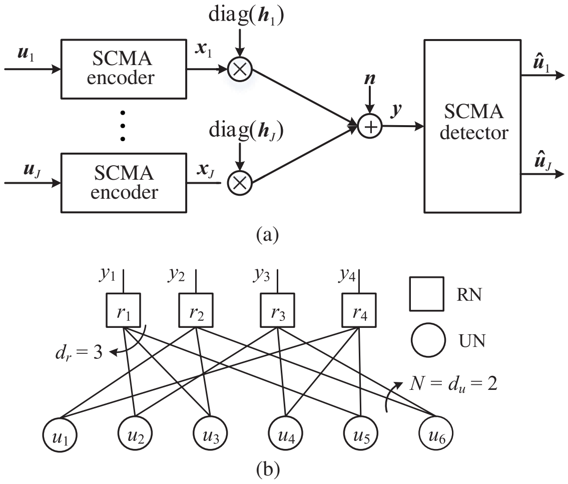

Figure 1 (a) An uplink SCMA system; (b) the factor graph of an uplink SCMA system with $K = 4$ and $J = 6$.

messages at the same iteration, thus accelerating the convergence speed. Simulation results have shown that optimized serial schedules can halve the number of iterations or even more. However, due to the serial nature, such serial schemes may not meet the low latency requirements in delay sensitive applications. Hence, it is necessary to design low complexity parallel MPA multiuser detection schemes. In [16], an MPA detector based on partial marginalization was proposed. In this scheme, after a few iterations, t symbols are selected and determined in advance. Then in the rest of the iterations, computations are not required for these t symbols in order to reduce the computational complexity. Motivated by the idea of sphere decoding (SD), a complexity-reduced MPA, called SD-MPA, is proposed in [17], which works by only considering superposed constellation points within a sphere centered at the received signal. In [18], a low complexity MPA detector based on dynamic factor graph (DFG) is proposed, which reduces the complexity by progressively prohibiting the updates of a fixed number of reliable messages from some iteration onwards. This procedure can be equivalently viewed as dynamically modifying the underlying SCMA factor graph, thus termed as dynamic factor graph based message passing (MP) detection. It is shown in [18] that DFG-MPA provides a much better tradeoff between performance and complexity than both PM-MPA and SD-MPA.

Although DFG-MPA outperforms the other complexity-reduced MPA detection schemes in terms of performance and complexity tradeoff, it suffers from a non-negligible bit error rate (BER) performance loss compared to the original MPA. To mitigate the performance loss while maintaining its low complexity, a generalized scheme of DFG-MPA (GDFG-MPA) is proposed in this paper. Two modifications are made to narrow the performance gap: firstly, instead of banning the message update of a directional edge from some iteration onwards, a message without updating at some iteration is allowed to be updated at later iterations in the proposed scheme. Moreover, different numbers, rather than a fixed number, of messages are allowed to be banned from updating at different iterations. Under this scheme, optimization of DFG-MPA is possible and can be carried out by allocating different numbers of banned messages at different iterations. Simulation results show that compared with the original DFG-MPA, the generalized DFG-MPA can achieve a better tradeoff between BER performance and computational complexity.

2 Background

2.1 System model

Consider an uplink SCMA system with one base station and J users, whose codewords are multiplexed over K shared orthogonal resources as shown in Figure 1(a). The system overloading factor is given by $\lambda = J/K$ $(J > K)$. An SCMA encoder is defined as a mapping from input bits to a multi-dimensional codeword. The codewords of different users are non-orthogonally superimposed on the same set of orthogonal resources in a sparse spread spectrum manner. More specifically, a predefined user codebook with size M features a sparse pattern with only N $(N < K)$ non-zero elements, which maps each $\log_2(M)$-bit data block to a K-dimensional codeword. To ease the description of MP detection, a factor graph is used to describe the occupation relationship between users and resources in an SCMA system. For example, Figure 1(b) shows an SCMA system with $K = 4$ resources, $J = 6$ users and $N = 2$, where squares and circles represent RNs and user nodes (UNs), respectively. In the SCMA factor graph representation, user u_j is connected to resource r_k if and only if r_k is used as one of the N non-zero elements in the codewords of u_j. Usually, we assume a regular factor graph with constant RN degree, d_r, and UN degrees, d_u. In Figure 1(b), we have $d_r = 3$ and $d_u = N = 2$.

According to Figure 1(a), the received signal for the SCMA system is given by

$$\boldsymbol{y} = \sum_{j=1}^{J} \operatorname{diag}(\boldsymbol{h}_j)\, \boldsymbol{x}_j + \boldsymbol{n}, \tag{1}$$

where the $\boldsymbol{x}_j = (x_{1,j}, \ldots, x_{K,j})^{\mathrm{T}}$ is a K-dimension complex codeword from user j's codebook, $\boldsymbol{h}_j = (h_{1,j}, \ldots, h_{K,j})^{\mathrm{T}}$ is the channel coefficient vector of user j, diag($\boldsymbol{h}_j$) is a diagonal matrix with its diagonal being $\boldsymbol{h}_j$, and $\boldsymbol{n} \sim \mathcal{CN}(0, N_0\boldsymbol{I})$ is the complex additive white Gaussian noise (AWGN).

2.2 MPA-based multiuser detection

In consideration of the sparse property of the users' codebooks, MPA can be applied to the factor graph representation of an SCMA system to approximate the calculation of a posteriori probabilities of codewords given the received signal $\boldsymbol{y}$. An MPA-based multiuser detector works by iteratively updating the extrinsic messages delivered along the edges in the SCMA factor graph. In the SCMA factor graph, there are two types of messages: message from RN r_k to UN u_j, $M_{r_k \to u_j}(\boldsymbol{x}_j)$, and message from UN u_j to RN r_k, $M_{u_j \to r_k}(\boldsymbol{x}_j)$. Denote as ξ_k and ζ_j the sets of neighbors of r_k and u_j, respectively. The expressions for updating these two types of messages are given by

$$M^t_{r_k \to u_j}(\boldsymbol{x}_j) = \sum_{\sim \boldsymbol{x}_j} \left\{ \frac{1}{\pi N_0} \exp\left(-\frac{1}{N_0} \left\| y_k - \sum_{l \in \xi_k} h_{k,l} x_{k,l} \right\|^2 \right) \times \prod_{m \in \xi_k \setminus \{j\}} M^{t-1}_{u_m \to r_k}(\boldsymbol{x}_m) \right\}, \tag{2}$$

and

$$M^t_{u_j \to r_k}(\boldsymbol{x}_j) = \prod_{n \in \zeta_j \setminus \{k\}} M^t_{r_n \to u_j}(\boldsymbol{x}_j), \tag{3}$$

where the superscipt t denotes the iteration number, and $\sum_{\sim \boldsymbol{x}_j}$ is the summary notation, representing a sum over all codeword combinations with user-j's codeword being $\boldsymbol{x}_j$. At the maximum iteration $t_{\max}$, the soft decision output can be calculated as

$$Q(\boldsymbol{x}_j) = \prod_{k \in \zeta_j} M^{t_{\max}}_{r_k \to u_j}(\boldsymbol{x}_j). \tag{4}$$

Then, hard decision can be made according to the values of $Q(\boldsymbol{x}_j)$. The codeword with the maximum soft decision value is chosen as the hard decision output.

3 Dynamic factor graph based MP detection and its generalization

3.1 DFG-MPA detection

From (2) and (3), it is easily seen that the message updates from RNs to UNs dominate the computational complexity. To effectively reduce the complexity while maintaining acceptable performance, only partial message updates from RNs to UNs are prohibited during the iterative detection process, leading to the DFG-MPA scheme. In DFG-MPA, the edges in the factor graph are divided into two types: bidirectional edges, which require message updates in both directions, and unidirectional edges[1)], which are only allowed to do UN-to-RN message updates. Following the notations in [18], let $\boldsymbol{B}_s(t)$ and $\boldsymbol{B}_d(t)$ denote the set of bidirectional edges and the set of unidirectional edges, respectively, at the t-th iteration. Then, the relationship between $\boldsymbol{B}_s(t)$ and $\boldsymbol{B}_d(t)$ can be written as

$$|\boldsymbol{B}_s(t)| + |\boldsymbol{B}_d(t)| = K d_r. \tag{5}$$

1) In [18], bidirectional and unidirectional edges are referred to as solid and dashed branches, respectively.

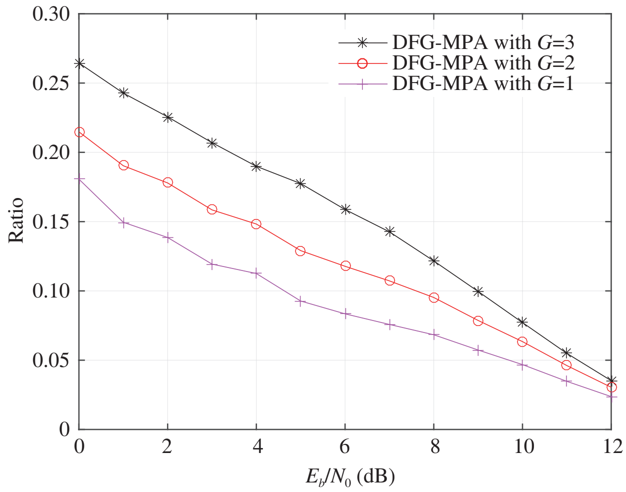

Figure 2 (Color online) Ratio of unreliable banned RN-to-UN messages at iteration 2 with DFG-MPA.

In the DFG-MPA scheme, some bidirectional edges are turned into unidirectional ones according to their belief values, which are defined as

$$\varphi_{k,j}(t) = \frac{\max_{c\in\{1,\ldots,M\}} M^{(t-1)}_{r_k\to u_j}(\boldsymbol{x}^{(c)}_j)}{\max_{n\in\{1,\ldots,M\}\backslash c} M^{(t-1)}_{r_k\to u_j}(\boldsymbol{x}^{(n)}_j)}, \tag{6}$$

where $\boldsymbol{x}^{(c)}_j$ and $\boldsymbol{x}^{(n)}_j$ are c-th codeword and n-th codeword of codebook $\mathcal{X}_j = \{\boldsymbol{x}^1, \ldots, \boldsymbol{x}^M\}$.

At the start of iteration t ($t \geqslant 2$), the belief values of all bidirectional edges are calculated by (6), and the G bidirectional edges with the highest belief values are turned into unidirectional edges, whose RN-to-UN messages are banned from updating in the current and all later iterations.

3.2 Weaknesses of DFG-MPA and generalized DFG-MPA

Compared with the original MPA, DFG-MPA can effectively reduce the computational complexity at the cost of noticeable BER performance degradation. One possible reason for performance degradation is that RN-to-UN messages along unidirectional edges may be unreliable, i.e., their hard decisions do not agree with the true values. Figure 2 illustrates the ratio of unreliable banned RN-to-UN messages against E_b/N_0 at iteration 2 with DFG-MPA. It is seen that at the same E_b/N_0 the larger G is the larger the ratio of unreliable messages. Moreover, with the increase of E_b/N_0 the ratio of unreliable messages decreases. However, even with a small value of $G = 1$ and a large $E_b/N_0 = 10$ dB, there are still about 5% unreliable banned messages. These unreliable messages will not be updated any more and there is no chance of correcting them. These unreliable messages will deteriorate the performance of the SCMA system. Another weakness of the original DFG-MPA is that its optimization space is limited: once G is fixed, the algorithm is determined.

To remedy the two weaknesses of the original DFG-MPA, two modifications are made, resulting in a generalized DFG-MPA (GDFG-MPA). Firstly, at the beginning of each iteration, all unidirectional edges are turned back to bidirectional edges and then the belief values of all the bidirectional edges are calculated, among which a new set of unidirectional edges will be selected. This modification gives a unidirectional edge a chance to become a bidirectional edge and thus allows an unreliable message to be updated at a later iteration. Notice that an RN-to-UN message banned from updating generally collects less extrinsic information and thus has a smaller belief value compared to update messages, which implies that banned messages will have a good chance to be updated at later iterations. A second modification is to allow to allocate different numbers of banned message updates at different iterations. The heuristic behind this modification is that the reliability levels of messages increase with iteration. Thus, allocating more banned message updates at later iterations rather than earlier iterations may reduce the chance of banning message updates for unreliable messages. $E_d(t)$ denotes the number of banned message updates at iteration t. Then $\boldsymbol{E}_d = [E_d(1), E_d(2), \ldots, E_d(t_{\max})]$ lists the number of banned RN-to-UN message updates at each iteration. The total number of banned RN-to-UN message updates is denoted by $|\boldsymbol{E}_d| = \sum_{t=1}^{t_{\max}} E_d(t)$.

An additional benefit brought along with the second modification is that GDFG-MPA provides a much finer granularity of complexity reduction than the original DFG-MPA. This can be explained as follows. Notice that starting from the second iteration DFG-MPA progressively bans additional G RN-to-UN message updates, or equivalently, $(t-1)G$ RN-to-UN messages[2] are banned from updating at iteration t $(t = 2, 3, \dots, t_{\max})$. Then, given $t_{\max}$, the total number of banned message updates can only be of the form $\frac{1}{2}(t_{\max} - 1)t_{\max}G$, which dominates the complexity reduction. For example, when $t_{\max} = 6$, the total number of banned message updates in DFG-MPA can only be multiples of 15. However, with GDFG-MPA the total number of banned message updates can be any positive integer. This implies that GDFG-MPA is more flexible in managing the complexity reduction than the original DFG-MPA.

3.3 Optimization of GDFG-MPA

Now, we consider the optimization of $\boldsymbol{E}_d$, i.e., the allocation of banned message updates at each iteration. As mentioned above, messages are getting more and more reliable with the increase of iteration number. This implies that banning a message update at a later iteration will generally impair the detection performance less than banning a message update at an earlier iteration. This intuition motivates us to allocate more banned message updates at later iterations in order to achieve a better tradeoff between complexity and performance. Following this understanding, we will progressively optimize the allocation of the numbers of banned message updates from $E_d(t_{\max})$ to $E_d(1)$ using a greedy strategy. More specifically, the value $E_d(t)$ is determined to be the maximum number of banned message updates such that the resulting performance is better than a target performance, i.e., $\gamma < T \times \gamma^*$, where γ and γ^* are BERs after and before banning $E_d(t)$ message updates, respectively, and T is the threshold and takes value from $(1, +\infty)$. The smaller T is, the less the performance degradation will be. Extensive simulations show that T can be chosen in the range of $[1.1, 1.3]$ to achieve good BER performances. In the following simulations, we set $T = 1.25$.

The algorithm for the optimization of $\boldsymbol{E}_d$ is summarized in Algorithm 1. Notice that the optimization of $\boldsymbol{E}_d$ is carried out offline. Once an optimized $\boldsymbol{E}_d$ is obtained, it will be used for all transmissions and no extra computation is needed.

Algorithm 1 Optimization of the allocation of banned message updates, $\boldsymbol{E}_d$

Inputs: The total number of edges in the factor graph, E; the total number of banned message updates, S; the maximum iteration, $t_{\max}$; the threshold T.

Output: The allocation of banned message updates, $\boldsymbol{E}_d$.

1: Initialization:
2: $\boldsymbol{E}_d \Leftarrow [0, \dots, 0]_{1\times t_{\max}}, t \Leftarrow t_{\max}$;
3: **while** $|\boldsymbol{E}_d| < S$ **do**
4:     Simulate the SCMA performance using GDFG-MPA with $\boldsymbol{E}_d$ and get BER γ^*;
5:     $e \Leftarrow \min(E, S - |\boldsymbol{E}_d|)$;
6:     $E_d(t) \Leftarrow e$;
7:     Simulate the SCMA performance using GDFG-MPA with $\boldsymbol{E}_d$ and get BER γ;
8:     **if** $\gamma > T \times \gamma^*$ **then**
9:         $E_d(t) \Leftarrow E_d(t) - 1$ and go to step 8;
10:     **end if**
11:     $t \Leftarrow t - 1$;
12: **end while**

3.4 Computational complexity analysis

The original MPA requires the computations of RN-to-UN and UN-to-RN message updates using (2) and (3) respectively. Compared to the original MPA, both DFG-MPA and GDFG-MPA need an extra computation of belief values and their ordering. However, this extra computation is marginal compared to that of RN-to-UN messages and thus is not counted here for simplicity. Notice that the computational savings of DFG-MPA and GDFG-MPA come from the banned RN-to-UN message updates. As all 3 MPA schemes employ (2) and (3) for message updates, their computational complexity analysis can be unified and tabulated in Table 1. Note that the exponents in (2) can be done once before iteration and stored in memory to save computational complexity.

2) Clearly, $(t-1)G \leqslant Kd_r$. If $(t_{\max} - 1)G > Kd_r$ the total number of banned message updates in the following should be changed accordingly.

Table 1 Complexity analysis of different detectors[a)]

Schemes	GDFG-MPA/DFG-MPA/original MPA
Multiplications	$C^{\mathrm{a}} M^{d_r}(d_r-1)+t_{\max} J d_u M(d_u-2)+K M^{d_r}(d_r+2)$
Additions	$C(M^{d_r}-M)+K M^{d_r} d_r$
Exponents	$K d_r M^{d_r}$

a) C is the total number of RN-to-UN message updates; for the original MPA, DFG-MPA, and GDFG-MPA, C is equal to $t_{\max} K d_r$, $\sum_{t=1}^{t_{\max}} |\boldsymbol{B}_s(t)|$, $(t_{\max} K d_r - |\boldsymbol{E}_d|)$, respectively.

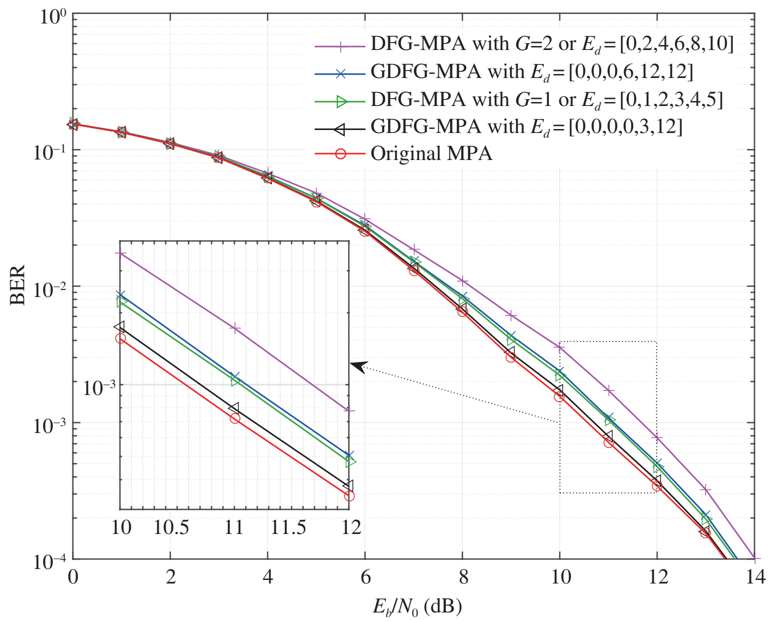

Figure 3 (Color online) BER performance of different detection schemes.

As Algorithm 1 is only carried out once to generate optimized $\boldsymbol{E}_d$ and thus can be done off-line, its computational complexity is not a serious issue. In fact, a simple analysis shows that even in the worst case the complexity of Algorithm 1 involves at most $(E+1)t_{\max}$ simulations of the SCMA system. In practice, only a few simulations of the SCMA system are needed. For example, for $S = 30$, $T = 1.25$, and $t_{\max} = 6$, only 6 simulations of the SCMA system are carried out.

4 Numerical results

In this section, numerical results are provided to compare GDFG-MPA with MPA and DFG-MPA in terms of performance and computational complexity. Assume an uplink SCMA system used over an AWGN channel with $K = 4$, $J = 6$, $M = 4$, $d_r = 3$, $d_u = 2$, $N = 2$, and $t_{\max} = 6$.

Figure 3 depicts the BER performance of MPA, DFG-MPA, and GDFG-MPA. From Figure 3, we observe that GDFG-MPA with $\boldsymbol{E}_d = [0,0,0,0,3,12]$ performs closely to MPA with only about 0.1 dB loss at BER $= 10^{-3}$, while it has a gain of 0.35 dB over DFG-MPA with $G = 1$ or equivalently $\boldsymbol{E}_d = [0,1,2,3,4,5]$. Notice that GDFG-MPA with $\boldsymbol{E}_d = [0,0,0,0,3,12]$ and DFG-MPA with $G = 1$ have similar computational complexities, as both schemes have banned 15 RN-to-UN message updates totally. Similarly, GDFG-MPA with $\boldsymbol{E}_d = [0,0,0,6,12,12]$ outperforms DFG-MPA with $G = 2$ by about 0.55 dB, while both shemes banned totally 30 RN-to-UN message updates and thus have similar complexities. These results show that GDFG-MPA can outperform DFG-MPA at the same computational complexity. Interestingly, we can observe that the BER performance of GDFG-MPA with $\boldsymbol{E}_d = [0,0,0,6,12,12]$ is very close to that of DFG-MPA with $G = 1$. However, GDFG-MPA with $\boldsymbol{E}_d = [0,0,0,6,12,12]$ banned totally 30 RN-to-UN message updates, which is twice that of DFG-MPA with $G = 1$. This result means that GDFG-MPA can achieve the same performance as DFG-MPA with a much lower complexity.

Figure 4 provides a detailed analysis of the performance-complexity tradeoff for DFG-MPA and GDFG-MPA. As explained in Subsection 3.4 and Table 1, the complexity reduction of both schemes depends on

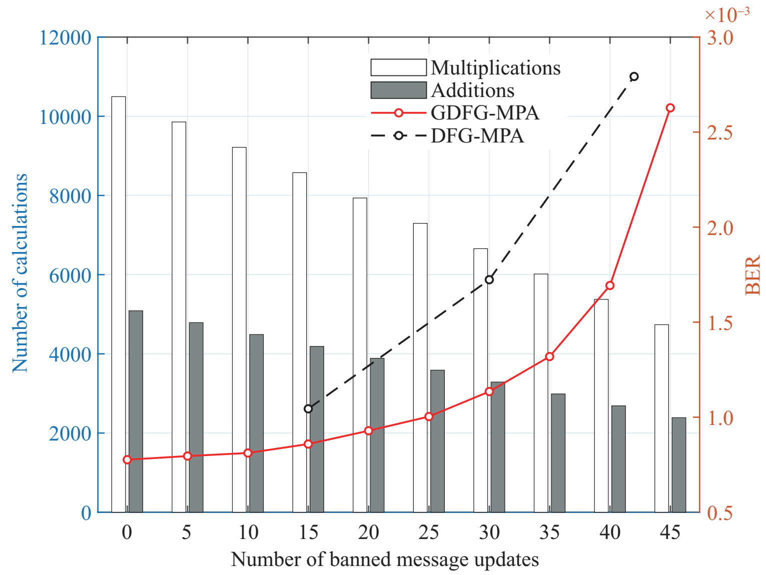

Figure 4 (Color online) Performance-complexity tradeoff for DFG-MPA and GDFG-MPA ($E_b/N_0 = 11$ dB).

the number of banned message updates. Thus, both schemes exhibit the same complexity behavior against the number of banned message updates, for which multiplications and additions are represented as white and gray bars, respectively, in Figure 4. Figure 4 also shows that for a given number of banned message updates GDFG-MPA has better BER performance than DFG-MPA. Moreover, Figure 4 shows that the granularity of complexity reduction with DFG-MPA is about 15 banned message updates, while with GDFG-MPA the number of banned message updates can be adjusted at a step of one message update. For clear illustration, a granularity of 5 message updates is used in Figure 4. In summary, GDFG-MPA provides a better and more flexible performance-complexity tradeoff compared to DFG-MPA.

5 Conclusion

A generalization of DFG-MPA, called GDFG-MPA, has been proposed for the SCMA system in order to make a better and more flexible performance-complexity tradeoff. GDFG-MPA features updating of unreliable banned messages and allocation of these updates among iterations. Simulation results were provided to demonstrate the advantages of GDFG-MPA over DFG-MPA.

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