Cross-Layer Collision-Tolerant MAC with Message Passing Detection

Jingxian Wu and Guoqing Zhou
Department of Electrical Engineering,
University of Arkansas, Fayetteville, AR 72701, USA.

Abstract— **A cross-layer collision-tolerant (CT) media access control (MAC) scheme is proposed in this paper. In the MAC layer, each user transmits multiple weighted replicas of a packet at randomly selected data slots in a frame, and the indices of the selected slots are transmitted in a special collision-free position slot at the beginning of each frame. Collisions of the data slots in the MAC layer are resolved by using multiuser detection (MUD) in the physical (PHY) layer. The MUD is performed by employing a modified message passing (MP) algorithm, which treats the MAC structure as a bipartite graph, with each unique packet denoted as a message node (MN), and each slot denoted as a slot node (SN). The graph is simplified by removing the nodes with 0 or 1 connection to reduce the complexity of the MP algorithm. Simulation results demonstrate that the proposed CT-MAC achieves significant performance gains over existing cross-layer MAC schemes. It can support as many as $N = 2.4M$ simultaneous users for a system with M slots per frame, yet most existing schemes can only operate with $N \leq M$.**

I. Introduction

Media access control (MAC) protocols are critical to the efficient operations of wireless networks. In conventional MAC schemes such as slotted ALOHA (SA) or carrier sensing multiple access (CSMA), signals collided at a receiver will be discarded and retransmitted. This results in a waste of the precious spectrum and energy resources.

Various collision-tolerant (CT) MAC protocols have been proposed in the literature by resorting to cross-layer designs [1]–[7]. The concept of multi-packet reception (MPR) is proposed in [1] and [2], where it is assumed that a fraction of the collided signals can be correctly detected with physical (PHY) layer signal processing. In most MPR related works, the effects of channel and PHY layer operations are abstracted into a group of parameters P_{nk}, the probability that k packets can be recovered when there are $n \geq k$ packets in the collision. They do not specify how the collisions can be resolved. An iterative interference cancellation (IC) method is employed in a contention-resolution diversity SA (CRDSA) scheme [3] to achieve MPR. In CRDSA, each packet is transmitted twice at two random slots in a frame. If one of the packet is detected, then it can be used to subtract the interference caused by its twin replica. The IC process is performed iteratively. The performance of CRDSA is further improved with an irregular repetition SA (IRSA) scheme [4] and [5], where the number of repetitions for each packet is determined by a probability distribution, and a coded SA (CSA) scheme [6], where linear block code across the packets is used to replace simple repetitions. All these schemes work well under low offered loads. However, the throughput drops dramatically once the normalized offered load exceeds a saturation point. The sharp drop is due to the fact that there are so many collisions such that the iterative IC process cannot be properly initiated. A CT-MAC with an on-off accumulative transmission (OOAT) is proposed in [7], where a sub-optimum block decision feedback equalizer (BDFE) is used for multiuser detection (MUD).

In this paper, we propose to develop a new cross-layer CT-MAC scheme by employing an iterative message passing (MP) algorithm for MUD. In the MAC layer, each user transmits multiple weighted replicas of a packet over randomly chosen slots in a frame. Such a transmission scheme can be represented as a bipartite graph, where each unique packet can be represented as a message node (MN), and each slot in a frame can be represented as a slot node (SN). The n-th MN is connected to the m-th SN if the n-th user transmits a packet at the m-slot. The indices of the occupied slots of each user is transmitted at a special collision-free slot at the beginning of each frame, so the receiver can construct the graph. We propose to perform MUD by exchanging soft log-likelihood information between the MNs and SNs with a modified MP algorithm. The MP algorithm was originally developed for the decoding of graph-based codes [8] and [9], or iterative IC in single-user systems [10] and [11]. It is extended here for the simultaneous detection in a multi-user network. The graph is simplified by removing some of the nodes that will not benefit from the iterative process, and the soft information collected from the removed nodes is used as *a priori* information for the nodes connected to them. The performance and convergence of the modified MP algorithm is analyzed with the extrinsic information transfer (EXIT) chart [12]. Simulation results demonstrate that the proposed cross-layer MAC with MP detection can achieve significant performance gains over existing MAC schemes, and it can support as many as $N = 2.4M$ simultaneous users in a frame with M slots.

II. System Model

Consider a wireless network with N users transmitting to the same receiver through a shared channel. Each MAC frame is divided into M slots, and the duration of each slot contains K symbols. One packet has K symbols and can thus be transmitted in one slot. Each packet is transmitted in the form of R weighted replicas on R randomly selected slots in a frame.

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Denote $\mathcal{A}(m)$ as the set of users that transmit their respective packets on the slot m. The signal observed by the receiver at the slot m can then be described as

$$y_{mk} = \sum_{n \in \mathcal{A}(m)} h_{mn} w_{mn} x_{nk} + z_{mk}, \text{ for } k = 1, \cdots, K \qquad (1)$$

where h_{mn} is the fading coefficient experienced by the signal from the n-th user at the m-th slot, w_{mn} is a weight coefficient used by the n-th user on the m-th slot, $x_{nk} \in \mathcal{S}$ is the k-th symbol in the packet from the n-th user, with $\mathcal{S}$ being the modulation constellation set with cardinality $S = |\mathcal{S}|$, and y_{mk} and z_{mk} are the received sample vector and noise sample, respectively. The weight coefficients are used to improve the numerical stability of the MUD. In this paper, we choose $w_{mn} = \frac{1}{\sqrt{R}} \exp\left[-j2\pi \frac{nm}{\max(N,M)}\right]$.

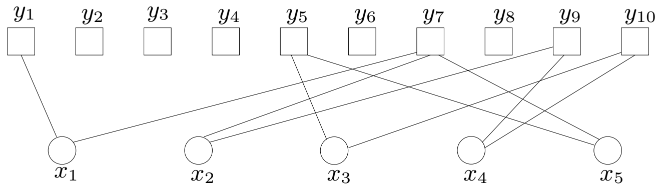
When $R = 1$ and $w_{mn} = 1$, the system degrades to the SA scheme. When $R = 2$ and $w_{mn} = 1$, the system at the transmitter is similar to the CRDSA scheme, where each packet is transmitted exactly twice in a frame. When R varies from user to user based on a certain probability distribution, and $w_{mn} = 1$, the system at the transmitter is similar to the IRSA scheme. None of these systems can operate when the normalized offered load, $G = \frac{N}{M}$, is greater than 1.

In order to perform the joint detection of the information from all the users, the receiver requires the knowledge of the indices of the slots on which a user transmits its packets. To meet this requirement, we propose to prefix a position slot that contains NM bits at the beginning each frame. Each user transmits an M-bit vector, $\mathbf{p}_n = [p_{n1}, \cdots, p_{nM}]^T \in \{0,1\}^M$, to notify the receiver the indices of the slots on which it will transmit in this frame, with $p_{nm} = 1$ if a packet will be transmitted in the m-th slot and $p_{nm} = 0$ otherwise. Because of the importance of the position slot to the final detection, the M-bit position vectors of the N users are transmitted in a deterministic time division manner in a slot of MN bits such that there is no collision. In addition, the position slot can be transmitted with a relatively higher signal-to-noise ratio to improve the reliability of the information.

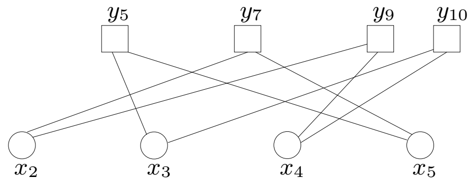
Given M and R, the position vector is randomly generated by each user and is updated for each frame. For a given frame, define the collision order of the system as $N_c = \max_m A_m$, where A_m is the cardinality of the set $\mathcal{A}_m$. Each received sample is thus the superposition of up to N_c transmitted symbols, and the receiver has up to R observations of each transmitted symbol. Therefore the system can be represented as a multiple-input multiple-output (MIMO) system with N_c inputs and R outputs. The receiver can recover the N_c-dimension input by using the R-dimension output. The weight coefficients are used to ensure the MIMO matrix has a rank of $\min(N_c, R)$,

III. Collision Resolution with a Modified Message Passing Algorithm

A modified MP algorithm is proposed in this section to achieve collision tolerance in the MAC layer by performing the MUD in the PHY layer.



(a) The complete graph



(b) The simplified graph

Fig. 1. Graph representations of a CT-MAC system with $N = 5$ users, $M = 10$ slots, and $R = 2$ repetitions.

The MAC scheme with weighted packet repetitions can be represented as a bipartite graph as shown in Fig. 1(a) for a system with $N = 5$ users, $M = 10$ slots, and $R = 2$ repetitions. In the graph, the MN represents a unique packet from a user and it is shown as a circle. The SN represents the observed signal in a given slot at the receiver, and it is represented as a square. The n-th MN is connected to the m-th SN if user n transmits a packet at the m-th slot. In the full graph, there are N MNs and M SNs. In a message passing algorithm, the MN and the SN iteratively exchange soft log-likelihood information to achieve performance improvement.

Define the set of SNs that are connected to the n-th MN as $\mathcal{B}_n$. The set of MNs that are connected to the m-th SN is denoted as $\mathcal{A}_m$. The number of connections that each node has is defined as the order of the node. Therefore, the order of the m-th SN is A_m, and the order of the n-th MN is $B_n = |\mathcal{B}_n|$. For the proposed scheme, $B_n = R, \forall n$, and $|\mathcal{A}_m| \leq N_c$.

A. Graph Simplification and Initialization

The graph shown in Fig. 1(a) can be simplified by removing some of the MNs and SNs that will not benefit from the iterative message passing process.

The order-0 nodes do not contribute to the detection process, thus can be removed from the graph.

For those order-1 SNs, there is no collision at the corresponding slot. In this case, these nodes will not benefit from the iterations of the message passing algorithm. Therefore, we can calculate the log-likelihood information at the order-1 nodes at the beginning of the iteration as *a priori* initial conditions, and remove the order-1 nodes from the actual iteration process. Assume SN m is an order-1 node connected to the n-th MN, as $\mathcal{A}_m = \{n\}$. The log-likelihood function (LLF) for the k-th symbol transmitted at the m-th slot, $\mu_{nk}^{(m)}(x_s) = \log P(y_{mk}|x_{nk} = \chi)$, can be calculated by

$$\mu_{nk}^{(m)}(\chi) = C_{nk1} - \frac{1}{\sigma_z^2}|y_{mk} - h_{mn} w_{mn} \chi|^2, \text{ for } \chi \in \mathcal{S}, \text{ if } \mathcal{A}_m = \{n$$

where $\chi \in \mathcal{S}$, σ_z^2 is the noise variance, and C_{nk1} is a normalization constant to make $\sum_{\chi \in \mathcal{S}} \exp[\mu_{nk}(\chi)] = 1$.

For the SNs with order greater than 1, no *a priori* information is available and initialize the log-likelihood information as

$$\mu_{nk}^{(m)}(\chi) = \log \frac{1}{S}, \ \forall n \in \mathcal{A}_m, \ \text{if } A_m > 1 \tag{2}$$

If all the SNs connected to the n-th MN are order-1 nodes, then we can directly get an estimate of x_{nk} as

$$\hat{x}_{nk} = \underset{\chi \in \mathcal{S}}{\text{argmax}} \sum_{m \in \mathcal{B}_n} \mu_{nk}^{(m)}(\chi) \tag{3}$$

Therefore node n can be removed from the graph if $A_m = 1$, $\forall m \in \mathcal{B}_n$.

After the removal of the nodes, a simplified graph is obtained. Fig. 1(b) shows the simplified graph with only 4 SNs and 4 MNs.

Before the iteration, assign the symbols on each remaining MN an *a priori* LLF as

$$\lambda_{nk}(\chi) = C_{nk2} + \sum_{m \in \mathcal{B}_n} \mu_{nk}^{(m)}(\chi), \tag{4}$$

where C_{nk2} is a normalization constant.

The *a priori* LLF for the SNs in the simplified graph can be calculated from the channel measurements as

$$\mu_{mk}(\mathbf{x}_m) = C_{nk3} - \frac{1}{\sigma_z^2} |y_{mk} - \sum_{n \in \mathcal{A}_m} h_{mn} w_{mn} x_{nk}|^2 \tag{5}$$

where $\mathbf{x}_m = [x_{nk}]_{n \in \mathcal{A}_m}^T$ is a length-A_m vector containing one possible realization of the A_m symbols that collide at the slot m. Since there are S^{A_m} such vectors, each MN is associated with a set of S^{A_m} initial LLFs.

B. Message Passing

The MNs and SNs iteratively exchange soft information to recover the information collided at the receiver.

Denote the message from the m-th SN to the n-th MN about the k-th symbol x_{nk} as $\alpha_{nk}^{(m)}(\chi)$, for $\chi \in \mathcal{S}$, $n \in \mathcal{A}_m$, and $k = 1, \cdots, K$. Similarly, denote the message from the n-th MN to the m-th SN about the k-th symbol x_{nk} as $\beta_{nk}^{(m)}(\chi)$.

1) SN → MN: $\alpha_{nk}^{(m)}(\chi)$.

Each SN collects the soft information from all of its connected MNs, and combine these soft information to get an update of the LLF of the received symbols.

The likelihood function of x_{nk} at the m-th slot can be calculated as

$$P(y_{mk}|x_{nk} = \chi) = \sum_{\boldsymbol{\chi}_m \in \mathcal{S}^{A_m - 1}} P(\mathbf{x}_{mk \backslash n} = \boldsymbol{\chi}_m) \times P(y_{mk}|x_{nk} = \chi, \mathbf{x}_{mk \backslash n} = \boldsymbol{\chi}_m) \tag{6}$$

where $\boldsymbol{\chi}_m \in \mathcal{S}^{A_m - 1}$ contains one possible realization of a length-$(A_m - 1)$ vector with elements from $\mathcal{S}$, $\mathbf{x}_{mk\backslash n} = [x_{uk}]_{u \in \mathcal{A}_m, u \neq n}^T$ is a length-$(A_m - 1)$ vector containing all but x_{nk} related to $\mathcal{A}_m$.

The *a priori* probability $P(\mathbf{x}_{mk\backslash n} = \boldsymbol{\chi}_m)$ can be obtained by combining the soft information from the MNs as

$$\log P(\mathbf{x}_{mk \backslash n} = \boldsymbol{\chi}_m) = \prod_{\chi_u \in \boldsymbol{\chi}_m} \beta_{nk}^{(m)}(\chi_u) \tag{7}$$

where χ_u is an element in $\boldsymbol{\chi}_m$.

The sequence-based LLF in (6) can be obtained from the initial LLF as in (5). Combining (5), (6), and (7), the LLF delivered from the m-th SN to the n-th MN, $\alpha_{nk}^{(m)}(\chi) = \log P(y_{mk}|x_{nk} = \chi)$, can be calculated as

$$\alpha_{nk}^{(m)}(\chi) = \underset{\boldsymbol{\chi}_m \in \mathcal{S}^{A_m - 1}}{\text{logsum}} \Big[\prod_{\chi_u \in \boldsymbol{\chi}_m} \beta_{nk}^{(m)}(\chi_u) + \mu_{mk}(x_{nk} = \chi, \mathbf{x}_{mk \backslash n} = \boldsymbol{\chi}_m) \Big], \tag{8}$$

where

$$\underset{n \in [1, \cdots, N]}{\text{logsum}} [a_n] = \max(\mathbf{a}) + \log \left\{ \sum_{n=1}^{N} \exp\left[a_n - \max(\mathbf{a})\right] \right\}, \tag{9}$$

with $\max(\mathbf{a})$ returning the maximum value in the vector $\mathbf{a} = [a_1, \cdots, a_N]^T$. The log-domain operations in (8) and (9) can avoid the numerical instability caused by overflowing during the iterations.

The LLR sent from the SN to the MN as calculated in (8) incorporates the initial LLFs from the channel measurements, and the soft messages from all but the n-th SN connected to the m-th MN.

2) MN → SN: $\beta_{nk}^{(m)}(\chi)$.

The message from the n-th MN to the m-th SN with $m \in \mathcal{B}_n$ about x_{nk} is

$$\beta_{nk}^{(m)}(\chi) = \sum_{m' \in \mathcal{B}_n \backslash m} \alpha_{nk}^{(m')}(\chi) + \lambda_{nk}(\chi), \tag{10}$$

where $\mathcal{B}_n \backslash m$ is obtained by removing the element m from $\mathcal{B}$.

The soft message to the m-th SN contains the message from all but the m-th SN connected to the n-th MN, and the initial LLF defined in (4). Removing the information from the SN m in the soft message to the SN m can avoid numerical instability caused by positive feedback.

3) Hard Decision.

The iteration terminates if the parity check or cyclic redundancy check is satisfied in all the packets, or if the maximum number of iterations is reached. At the end of the iteration, a hard decision can be made based on the soft information as

$$\hat{x}_{nk} = \underset{\chi \in \mathcal{S}}{\text{argmax}} \sum_{m \in \mathcal{B}_n} \alpha_{nk}^{(m)}(\chi) + \lambda_{nk}(\chi) \tag{11}$$

The complexity of the message passing algorithm is proportional to S^{N_c}. The number of packets in a given slot follows a Poisson distribution with parameters N and $\frac{R}{M}$. Thus the average number collisions is $\frac{NR}{M}$. On average, the complexity of the message passing algorithm is on the order of $\mathcal{O}(N_I S^{\frac{NR}{M}})$, where N_I is the maximum number of iterations.

The complexity of the optimum exhaustive search is on the order of $\mathcal{O}(S^N)$. Since R is usually far less than M, the complexity of the message passing algorithm is usually much lower than the optimum search algorithm.

IV. EXIT Chart Analysis

The convergence of the modified MP algorithm developed for the CT-MAC is studied in this section with the EXIT chart [12], which traces the evolution of mutual information between the data and the soft information through iterations.

The EXIT chart analysis is performed by tracing the evolution of the log-likelihood ratio (LLR) of the binary data. Assume that the binary vector, $\mathbf{b}_{nk} = [b_{nk1}, \cdots, b_{nk\log_2 S}]^T \in \mathcal{B}^{\log_2 S}$, with $\mathcal{B} = \{-1, 1\}$, is mapped to the symbol $x_{nk} \in \mathcal{S}$ through modulation. Define the LLR of b_{nkq} as

$$L(b_{nkq}) = \frac{\sum_{\chi \in \mathcal{S}_q^+} \log P(x_{nk} = \chi)}{\sum_{\chi \in \mathcal{S}_q^-} \log P(x_{nk} = \chi)} \tag{12}$$

where $\mathcal{S}_q^+$ contains all the symbols in $\mathcal{S}$ with the q-th bit in the demodulated vector being 1, and $\mathcal{S}_q^- = \mathcal{S} \backslash \mathcal{S}_q^+$. For the message passed from the m-th SN to the n-th MN, $\log P(x_{nk} = \chi) = \alpha_{nk}^{(m)}(\chi)$; for the message passed from the n-th MN to the m-th SN, $\log P(x_{nk} = \chi) = \beta_{nk}^{(m)}(\chi)$.

The EXIT chart analysis is based on the assumption that the LLRs are independent and identically distributed (i.i.d.) with a conditional pdf, $p_L(l|b)$, given by

$$p_L(l|b) = \frac{1}{\sqrt{2\pi}\sigma_L} \exp\left[-\frac{\left(l - b\sigma_L^2/2\right)^2}{2\sigma_L} \right], \tag{13}$$

where $b \in \mathcal{B}$, σ_L is the variance of the random variable $L(b)$. The conditional pdf given in (13) is a Gaussian pdf with a single parameter σ_L.

With the pdf of the LLR given in (13), define the mutual information between a bit b and its LLR $L(b)$ as

$$I = \frac{1}{2} \sum_{b \in \mathcal{B}} \int_{-\infty}^{+\infty} p_L(l|b) \log_2 \frac{2p_L(l|b)}{p_L(l|1) + p_L(l|-1)} dl. \tag{14}$$

Note that $I = 0$ implies no information about the bit, while $I = 1$ means ideal information. Since the conditional pdf $p_L(l|b)$ is a function of a single parameter σ_L, the mutual information I is completely determined by σ_L.

The MN or SN can be modeled as a mutual information transfer device, *i.e.*, given mutual information at the input, the MN or SN generates a new mutual information at the output by exploring the graph structure. Usually the output mutual information is larger than the input one due to the improvement of reliability achieved through the MP detection.

The values of the mutual information at the output of the MN or SN can be obtained through numerical simulations. For a given input mutual information I, the value of σ_L can be obtained through the mapping in (13) and (14). An ensemble of random input LLRs, $\{L_I(b)\}$, can then be generated following the conditional pdf in (13) and the value of σ_L. Feeding these random LLRs to (8) or (10) leads to an ensemble of LLRs at the output of the SN or MN, respectively. Denote the output LLRs as $\{L_O(b)\}$. An empirical histogram, or probability mass function (PMF), of the output LLRs, $P_{L_O}(l|b)$, can then be numerically generated provided that the number of random samples is large enough.

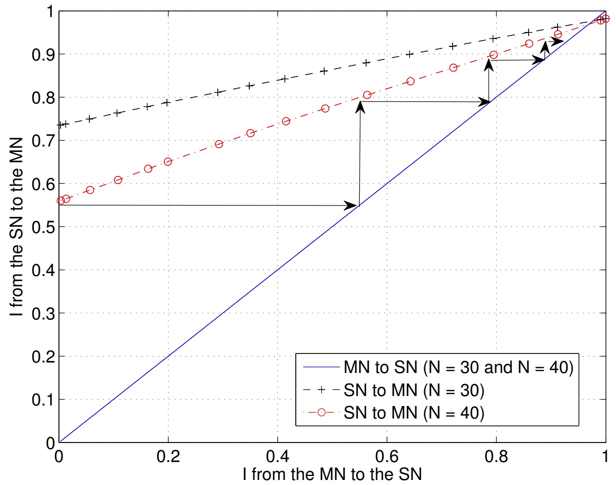


Fig. 2. EXIT chart of a system with $M = 12$ slots and $R = 2$ repetitions.

Fig. 2 depicts the EXIT chart of the modified MP by placing the mutual information transfer curves of the MN and the SN in the same figure. The horizontal axis is the mutual information at the input to the SN (the LLR of bits corresponding to $\beta_{nk}^{(m)}(\chi)$), and the vertical axis is the mutual information at the input to the MN (the LLR of bits corresponding to $\alpha_{nk}^{(m)}(\chi)$). The curves are obtained from systems with $M = 12$ and $R = 2$, at $E_b/N_0 = 10$ dB. The trajector traces visualizes the evolution of the mutual information by following the guide of the "tunnel" between the transfer curves. All transfer curves terminate at $I_O = 1$, which means they can generate ideal outputs. The transfer curve for the MN has a slope 1 when $R = 2$ because in this case a MN simply forwards the message from one SN to the other SN, and there is no further mutual information gain. The transfer curve of the SN has a larger slope when N is small, which means it can converge with less iterations.

V. Simulation Results

Fig. 3 shows the bit error rate (BER) of the proposed system with various number of users N. There are $M = 12$ slots per frame, and each packet is repeated $R = 2$ times. The maximum iteration is set to 6. For comparison, the BER performance with optimum maximum likelihood sequence detection with exhaustive search for $N = 8$ is also shown in the figure. It can be seen that the modified MP can achieve a performance that is almost identical to its optimum counterpart. In addition, it is interesting to note that the BER performance improves slightly as N increases at high SNRs. This can be explained by the fact that more users means a more diverse channel conditions and more node interactions, which contribute positively to the detection process. Therefore, the collision-tolerant MAC with MP detection can support a large number of simultaneous users.

The effect of the number of iterations on the frame error rate (FER) is shown in Fig. 4. There are $N = 20$ active users, $M = 10$ slots per frame, and $R = 2$ repetitions. The largest performance gain is achieved at the second iteration. The performance converges at the 4th iteration, which corroborates

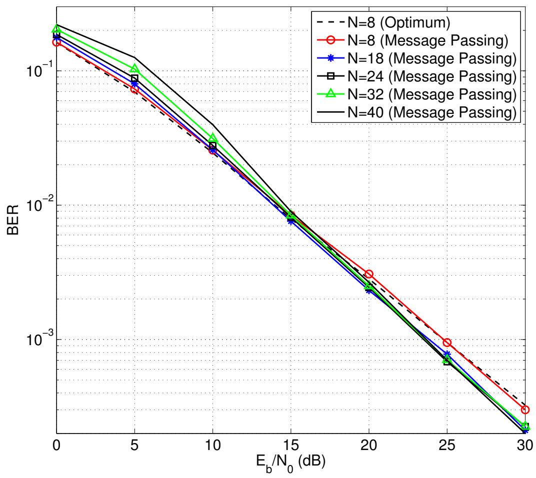


Fig. 3. BER performance of the system with $M = 12$ slots, $R = 2$ repetitions, and the message passing algorithm.

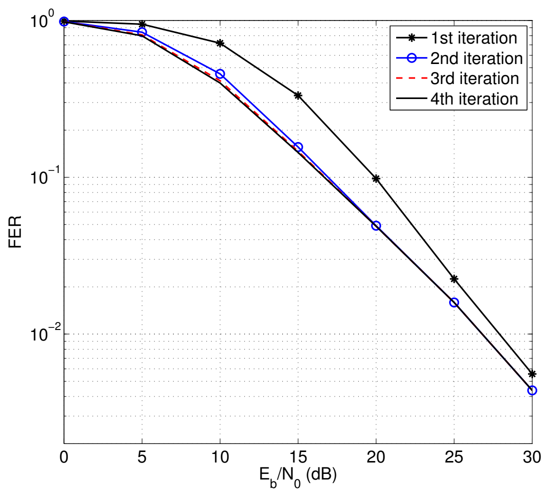


Fig. 4. FER performance of the system with $M = 10$ slots, $N = 20$ users, $R = 2$ repetitions, and the message passing algorithm.

the EXIT chart in Fig. 2.

Fig. 5 shows the normalized throughput as a function of the normalized offered load for various MAC schemes. The SA, CRDSA and IRSA achieve their respective peak throughputs when $G \leq 1$, and the throughputs drop dramatically when $G > 1$. The throughput of the proposed scheme achieves the maximum throughput 1.3 at $G = 2.4$ due to the MUD with the modified MP algorithm.

VI. Conclusions

A cross-layer CT-MAC scheme was proposed in this paper. In the MAC layer, each packet was transmitted in the form of multiple weighted replicas at randomly selected slots in a frame, and the positions of the occupied slots were specified in a collision-free position slot at the beginning of each frame. The collisions in the MAC layer were resolved by using a modified MP algorithm in the PHY layer, which operated on a simplified bipartite graph of the MAC structure. Simulation results demonstrated that the modified MP algorithm

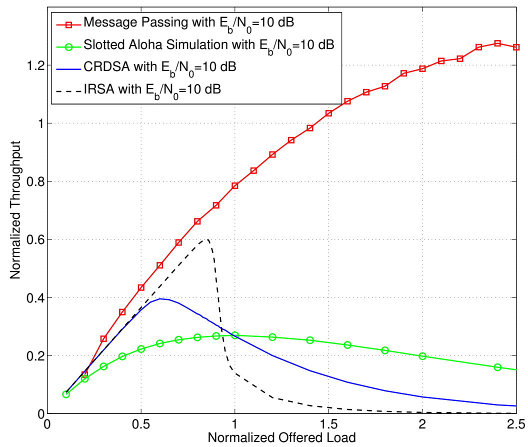


Fig. 5. Normalized throughput v.s. normalized offered load.

can achieve a performance that was almost identical to the optimum maximum likelihood detection, but with a much lower complexity. In addition, the proposed CT-MAC scheme could support up to $N = 2.4M$ simultaneous user for a system with M slots per frame, whereas most existing cross-layer MAC schemes can only support $N \leq M$ users.

Acknowledgment

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