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| Title | Massive Uncoordinated Multiway Relay Networks with Simultaneous Detections |
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| Citation | 2015 IEEE International Conference on Communication Workshop (ICCW): 2175-2180 |
| Issue Date | 2015-06 |
| Type | Conference Paper |
| Text version | author |
| URL | http://hdl.handle.net/10119/13470 |
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| Description | |

# Massive Uncoordinated Multiway Relay Networks with Simultaneous Detections

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***Abstract*—In this paper, we consider multiway relay networks with *massive* number of users. In this situation a fixed transmission scheduling is difficult to apply. We propose uncoordinated communications using the concept of coded slotted ALOHA (CSA), where simultaneous transmitted signals are detected using iterative demapping (IDM) algorithm to improve the success rate probability. We allow each user to transmit the information via any random time slots (during the contention period) to the network. We show the bound of the proposed system and confirm an achievable point using practical coding. We also evaluate the bit-error-rate (BER) performance of the proposed technique via computer simulations. The results indicate that even though with the offered traffic of 1.11 packets/slot, reliable communications is achievable. It is also validated that the proposed system works very well even in relatively low signal-to-noise ratio (SNR) environments. Moreover, the packet-loss-rate (PLR) evaluation shows that the proposed technique outperforms the conventional CSA without simultaneous detection algorithm.**

## I. Introduction

Multiway relay networks have attracted a great deal of attentions from researchers since its potential applications. This network is applicable, e.g., for disaster areas where the base stations are destroyed, satellite communication systems, or high densely populated areas. *Multiway relay channel* is defined as a multiuser communication channel, where multiple users expect to exchange information among themselves with the help of a single relay terminal [1].

So far, only a fixed transmission scheduling is considered for the multiway relay networks. Each user is only allowed to transmit its message on a specific allocated time slot. Indeed, this scheme is applicable to multiway relay networks with few number of users. For networks with massive number of users, the fixed transmission scheduling requires very high complexity scheduling.

In this paper, we apply the notion of *uncoordinated transmissions*, i.e., the users send their information to the network randomly according to a probability distribution. Each user in the network is allowed to transmit its information to the network via randomly chosen time slots (during the contention period). In the uncoordinated scheme, the interference problem occurs when two or more users transmit their information simultaneously in the same time slot. In order to overcome this problem, we adopt the concept of coded slotted ALOHA (CSA) [2], [3], which utilizes a graph based decoding algorithm.

In the conventional way, the collided packets in slotted ALOHA are discarded and have no use. In CSA, these collided packets are kept and resolved by performing successive interference cancellation (SIC) technique. In the asymptotic setting, CSA attains throughput close to 1 packet/slot, which is a great improvement compared to the conventional slotted ALOHA that achieves 0.37 packets/slot.

Further throughput improvement is possible to achieve by performing a multiuser detection by assuming the use of code division multiple access (CDMA) in the decoding scheme of CSA [4]. However, with CDMA, the difficulty is coming from the fact that the number of spreading codes must be at least the same as the number of users. Otherwise, the CDMA does not help the simultaneous detection when number of user is not properly set in the network. From our view point, the future massive multiway relay networks should be flexible without any limitations such as presetting parameter on spreading codes depending on user number.

In this paper, instead of using CDMA, we use an iterative demapping (IDM) algorithm [5] to simultaneously detect the collided packets in the physical layer. By employing the IDM, a reliable communication with throughput of more than 1 packet/slot can be attained. Moreover, the employment of IDM makes multiway relay networks still work well even at relatively low SNR environments.

## II. System Model

Our model is shown in Fig. 1, where $(M+1)$ users want to exchange information among themselves with the help of the relay terminal. Each user wants to decode the information from the other $M$ users. In this paper, it is assumed that there is no direct link between any users, i.e., the users do not receive signals directly from other users except from the relay.[1] This assumption is reasonable since some physical restrictions among the users, e.g., long physical distances, mountainous areas, or high buildings environments.

For the relaying scheme, in general there are three options available: decode-and-forward (DF), compress-and-forward (CF), and amplify-and-forward (AF) relaying scheme. In DF relaying scheme, the relay is forced to decode the received signal and forward it to the destination. For few number of

This research is under the grant of Japan Society for the Promotion of Science (JSPS), Scientific Research KAKENHI KIBAN KENKYU (B) No. 25289113 and in part under the framework of EU FP7 RESCUE project No. 619555.

[1]The link between neighboring users can be seen as a side information. However, it is left for future work.

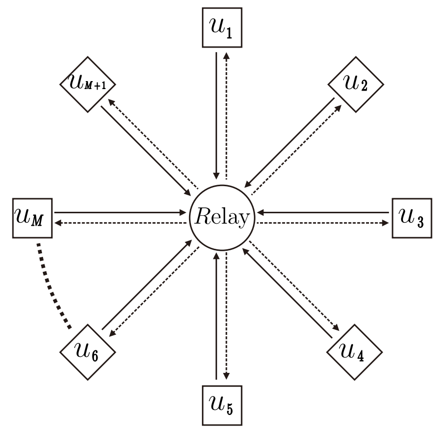


Fig. 1: Multiway relay networks for full data exchange among $M+1$ users.

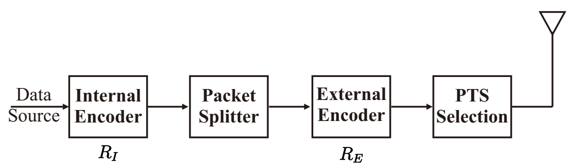


Fig. 2: Transmission scheme of the proposed system.

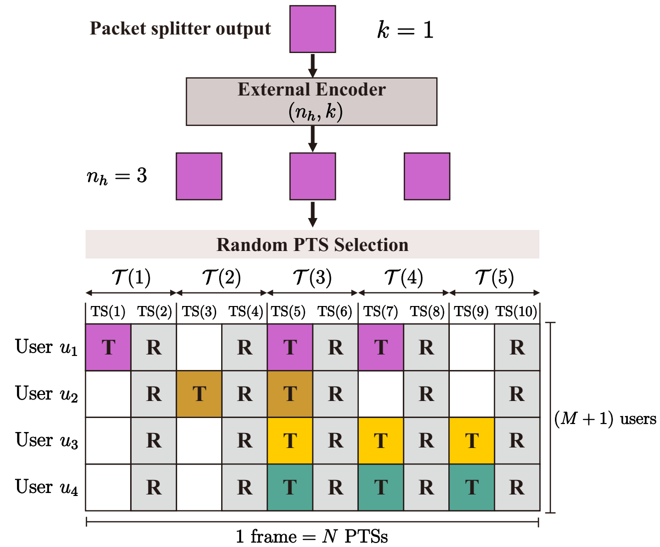


Fig. 3: External encoding and PTS selection.

users, this protocol is preferable. However, for a large number of users, the DF scheme is not optimal and has very high complexity at the relay [1]. In the CF scheme, the relay quantizes the received signal and forwards it to the destination, while in the AF scheme, the received signal is amplified and forwarded by the relay to the destination. The common drawback of CF and AF schemes is that the noise is also quantized or amplified and forwarded to the destination. Due to the low complexity at the relay, CF and AF scheme are suitable for a relaying scheme with a large number of users. Nevertheless, we need to employ SIC in the decoding process. In the case of CF scheme, the more coding and decoding scheme is required. For the AF scheme, the SIC can be performed by simply subtracting the resolved messages from the composite signals. Hence, AF relaying scheme is the best option for the proposed system.

We also consider the half-duplex relaying system which is simple to implement. In the half-duplex case, the information is exchanged within two phases. First phase is multiple access channel (MAC) phase, where some users transmit information simultaneously to the the relay without coordination with other users. The second phase is broadcast channel (BC) phase, where the relay broadcast the received information to all users.

Fig. 2 describes the transmitter structure of a single user. Data source is encoded by an internal encoder with rate $R_I$, split into $k$ packets, and encoded by external encoder with rate $R_E$. Subsequently, the encoded packets are transmitted via randomly chosen time slots.

In our proposed system, since MAC phase is always followed by BC phase, we define the both time slots (TS) of the corresponding phases as a *pair of time slots* (PTS),[2] denoted as $\mathcal{T}$. The $j$-th PTS, $\mathcal{T}(j)$, consists of two consecutive time slots (TS), i.e., TS$(2j-1)$ and TS$(2j)$, $j = \{1, 2, ..., N\}$, as described in Fig. 3. Subsequently, we define a frame of transmission composed of $N$ PTSs.

Figs. 2 and 3 illustrate the transmission process in each user. The data from the source is encoded by the internal encoder which is equivalent to a channel encoder. Please note that the employment of IDM algorithm requires the internal encoder to be soft-input soft-output encoders, the decoder of which can both accept and produce log-likelihood ratio (LLR) values.

The output of the internal encoder is then split into $k$ packets. Each user randomly selects a type of external encoder $c_h \sim (n_h, k)$ from a set of codes $\mathcal{C} = \{c_1, c_2, ..., c_h, ..., c_{n_c}\}$ according to a probability distribution $\Lambda = \{\Lambda_1, \Lambda_2, ..., \Lambda_{n_c}\}$, where $\sum_{h=1}^{n_c} \Lambda_h = 1$, to encode the packets. A code $c_h$ is a packet-oriented linear code with length $n_h$, dimension $k$, and rate $R_{E_h} = k/n_h$. The code length $n_h$ indicates how many transmissions or PTSs are required to convey the information to the network. The average rate of the external encoder for one user, by assuming the same $k$ for each user, is defined as

$$R_E = \frac{k}{\overline{n}}, \tag{1}$$

where

$$\overline{n} := \sum\nolimits_{h=1}^{n_c} \Lambda_h n_h \tag{2}$$

is the expected length of the codes. The $n_h$ encoded packets are then transmitted via $n_h$ randomly selected PTSs. We provide an example in Fig. 3. Users $u_1$, $u_3$, and $u_4$ choose a $(3,1)$ repetition code as the external encoder to encode their $k=1$ packet. User $u_2$ encodes its packet by (2,1) repetition code. All users then randomly select PTSs to transmit their encoded packets. For instance, user $u_1$ then randomly chooses PTS

[2] The notation *PTS* and *slot* are interchangeably used in this paper, especially, when we mention *packet/slot* for the offered traffic.

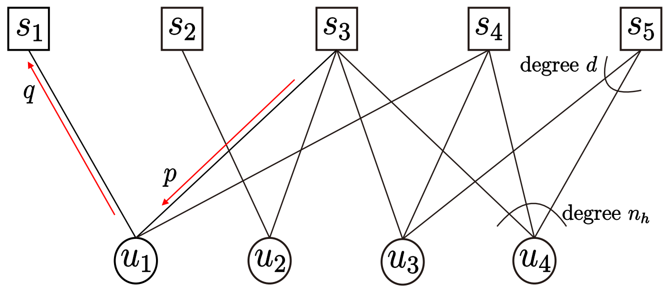


Fig. 4: Bipartite graph representation of received signals in one frame for each user corresponding to the example in Fig. 3.

$\mathcal{T}(1)$, $\mathcal{T}(3)$, and $\mathcal{T}(4)$ to transmit the encoded packets to the relay (MAC phase).

We define the normalized offered traffic[3] delivered to one user as

$$G = \frac{kM}{N}, \tag{3}$$

where $M$ is number of the other users, $k$ is number of packets, and $N$ is number of PTSs in one frame transmission.

The relay always amplifies and forwards (BC phase) the received signal to all users. Accordingly, all users receive the same information from the network. We assume that a pointer is equipped in every encoded packet. The pointer contains information of which PTSs are used by the corresponding user to transmit the encoded packets. In this case, the system can be modeled by a bipartite graph $\mathcal{G} = (\mathcal{U}, \mathcal{S}, \mathcal{E})$ as illustrated in Fig. 4.

The graph $\mathcal{G}$ is composed of set of *user nodes* $\mathcal{U} = \{u_1, u_2, ..., u_{M+1}\}$, set of *slot nodes* $\mathcal{S} = \{s_1, s_2, ..., s_N\}$,[4] and set of edges $\mathcal{E}$ that connect a user node and a slot node. The user node corresponds to the user that transmits the information to the network, while the slot node corresponds to the PTS used by the users to transmit the information. The user node $u_i \in \mathcal{U}$ is connected by an edge $\mathcal{E}_{ij}$ to the slot node $s_j \in \mathcal{S}$ if and only if the user $u_i$ transmits one of its encoded packets to the network via the PTS $\mathcal{T}(j)$. The user node $u_i$ has degree $n_h$, which means the user $u_i$ chooses a code type $c_h \sim (n_h, k)$ to encode its $k$ packets and generate $n_h$ encoded packets. On the other hand, the slot node $s_j$ has degree $d$, which expresses that there are $d$ users transmit one of their encoded packets simultaneously to the relay via PTS $\mathcal{T}(j)$. The connection of slot nodes and all users can also be represented by a matrix with size of $N \times (M+1)$, where $N$ is number of PTSs and $(M+1)$ is number of users. For example, matrix

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} \tag{4}$$

shows the connection of the system shown in Fig. 4. The rows and columns correspond the PTS and the user, respectively.

[3]Note that the offered traffic $G$ in this paper corresponds to offered traffic delivered by network to only one user.

[4]Note that $s_j$ has the same meaning as the PTS $\mathcal{T}(j)$.

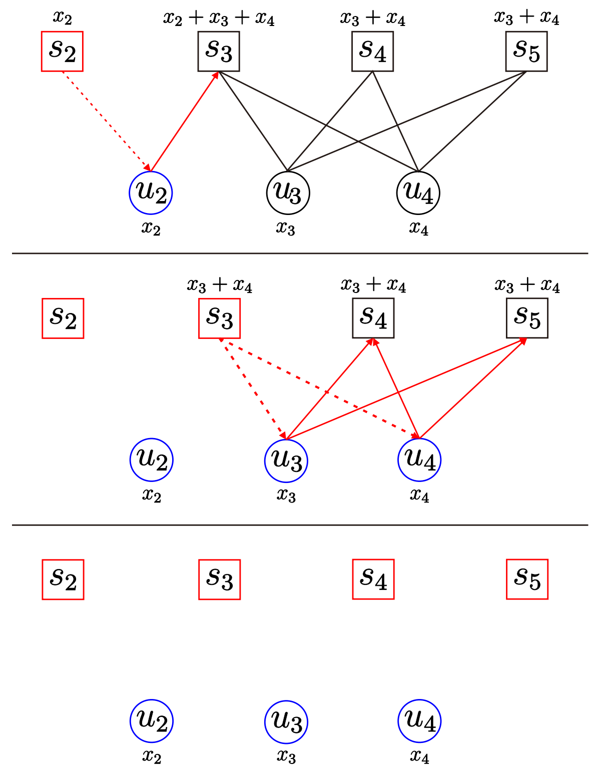


Fig. 5: Decoding illustration performed by user $u_1$ for a system employing irregular repetition codes as the external encoder.

The graph and matrix representations show that the system constructs a coding structure which is similar to low-density parity-check (LDPC) codes.

Prior to decoding process, each receiver subtracts its own signal from the received signals in a frame. After subtraction, each user has unique bipartite graph and matrix representation with size $N \times M$. For example, user $u_1$ has

$$B_1 = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}, \tag{5}$$

the graph of which is shown in Fig. 5. It should be noted here that iterative decoding is performed in the internal receiver, not between the relay and the users. For slot node with degree $d = 1$, local *maximum-a-posteriori* (MAP) decoding is easily performed to decode the packet. For slot node with degree $d = 2$, IDM algorithm that has capability of decoding two unknown packets simultaneously is exploited. The slot node with degree more than two is left for the next iteration. It will be regarded as lost packet after iteration is completed but the degree is still more than two. The results of local decoding in slot node are passed to the connected user nodes. User node performs local MAP decoding to decode the unknown edges and pass them back to the connected slot nodes. Subsequently, in slot node, SIC is exploited to cancel the interference coming from the revealed packets, which implies that the degree of slot nodes is then reduced.

## III. CONVERGENCE ANALYSIS

We perform asymptotic analysis in one user receiving the information randomly sent by all users in the network. We set the number of users and PTSs to be infinite, $\{(M+1), N\} \rightarrow \infty$, while keeping $G = kM/N$ constant.

### A. Degree Distribution of Nodes

In each frame, each user selects a code type $c_h \sim (n_h, k)$ to encode its packets generating $n_h$ packets to be transmitted into $n_h$ randomly chosen PTSs. The selection of a code type is managed according to a probability distribution $\Lambda = \{\Lambda_1, \Lambda_2, ..., \Lambda_{n_c}\}$. It is convenient to introduce a polynomial to represent the degree distribution of user node from *nodes perspective* as follows

$$\Lambda(x) = \sum_{h=1}^{n_c} \Lambda_h x^h. \tag{6}$$

From *edges perspective*, the degree distribution of user node is given by

$$\lambda(x) = \frac{\Lambda'(x)}{\Lambda'(1)} = \sum_{h=1}^{n_c} \lambda_h x^{h-1}, \tag{7}$$

where

$$\lambda_h = \frac{\Lambda_h h}{\sum_{h=1}^{n_c} \Lambda_h h}. \tag{8}$$

The degree distribution of slot nodes from *nodes perspective* is defined as

$$\Psi(x) = \sum_{d \geq 1} \Psi_d x^d, \tag{9}$$

where $\Psi_d$ is the probability of a slot node having degree $d$. The degree of slot nodes $s_j$ is equivalent to number of users that transmit one of their encoded packets simultaneously via PTS $\mathcal{T}(j)$. The probability of a slot node having degree $d$ follows the binomial distribution

$$\Psi_d = \binom{M}{d} \left(\frac{\overline{n}G}{kM}\right)^d \left(1 - \frac{\overline{n}G}{kM}\right)^{M-d}. \tag{10}$$

If we let $M \rightarrow \infty$, we get

$$\Psi(x) = \exp\left(-\frac{\overline{n}}{k} G(1-x)\right). \tag{11}$$

The degree distribution of slot nodes from *edges perspective* can also be defined in the similar way as (7)

$$\rho(x) = \frac{\Psi'(x)}{\Psi'(1)} = \exp\left(-\frac{\overline{n}}{k} G(1-x)\right). \tag{12}$$

### B. EXIT Function and Upper Bound

As described in the previous section, the proposed multiway relay network constructs a coding structure which is similar to LDPC codes. Consequently, the similar analysis, i.e. density evolution, is applicable for the proposed system.

We evaluate the probability of an edge having unresolved or erasure packet. Let define $p_\ell$ and $q_\ell$ is the probability of an edge comes out from slot node to user node and user node to slot node, respectively, carrying an erasure at iteration $\ell$ as illustrated in Fig. 4. Similar to [2], the probability of an edge having erasure after user node local MAP decoding $q_\ell$ is defined as

$$q_\ell = \frac{1}{\overline{n}} \sum_{h=1}^{n_c} \Lambda_h \sum_{t=0}^{n_h-1} p_{\ell-1}^t (1-p_{\ell-1})^{n_h-1-t} \Big[(n_h - t)\tilde{e}_{n_h-t}^{(h)} - (t+1)\tilde{e}_{n_h-1-t}^{(h)}\Big], \tag{13}$$

where $\tilde{e_g}$ is information function of linear block code [6]. The extrinsic information transfer (EXIT) function of user node $f_u(p_{\ell-1})$ can be written as

$$f_u(p_{\ell-1}) := \sum_{h=1}^{n_c} \frac{\lambda_h}{n_h} \sum_{t=0}^{n_h-1} p_{\ell-1}^t (1-p_{\ell-1})^{n_h-1-t} \Big[(n_h - t)\tilde{e}_{n_h-t}^{(h)} - (t+1)\tilde{e}_{n_h-1-t}^{(h)}\Big]. \tag{14}$$

We refer to [4] to derive the EXIT function of slot node. In the proposed system, if the total number of unresolved edges with probability $q_\ell$ connected to a degree-$d$ slot node is less than or equal to two, it can be decoded with probability $1-p_\ell$, which is defined as

$$1 - p_\ell = \sum_{k=0}^{min(2,d)-1} \binom{d-1}{k} q_\ell^k (1-q_\ell)^{d-k-1}. \tag{15}$$

If we make an average over the edge perspective degree distribution of slot nodes, we derive

$$p_\ell = \sum_d \rho_d \left(1 - \sum_{k=0}^{min(2,d)-1} \binom{d-1}{k} q_\ell^k (1-q_\ell)^{d-k-1}\right). \tag{16}$$

From (12) and (16) we obtain

$$f_s(q_\ell) := p_\ell = 1 - \left(1 + q_\ell \frac{G}{R_E}\right) e^{-q_\ell \frac{G}{R_E}}. \tag{17}$$

The recursive erasure evolution functions described in (13) and (16) can be visualized by EXIT chart, which displays the EXIT functions $f_u(p)$ and $f_s(q)^{-1}$. As an example, we analyze a system employing irregular repetition codes in each user. For the irregular repetition codes, the EXIT function of user node $f_s(q)$ in (14) can be simplified to

$$f_u(p) = \sum_{h=2}^{n_c} \lambda_h p^{h-1}, \tag{18}$$

while the EXIT function of slot node remains the same. In Fig. 6, the EXIT chat of a system employing irregular repetition codes with degree distribution $\Lambda_a(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$ and rate $R_E = 0.278$ is presented. The evolution of an edge carrying erasure from user node ($q_\ell$) and slot node ($p_\ell$) converges to zero in a sufficient iteration if and only if there is an open tunnel between two curves $f_u(p)$ and $f_s(q)^{-1}$, i.e., two curves do not intersect each other. This condition is satisfied if the offered traffic is set below the threshold, $G^*$, which is obtained from EXIT chart as the maximum of $G$, when $f_u(p)$ and $f_s(q)^{-1}$ do not intersect each other.[5] From

[5]In the opposite condition, $G > G^*$, the pair of probabilities $(p_\ell, q_\ell)$ will not converge to zero even though an infinite iteration is performed.

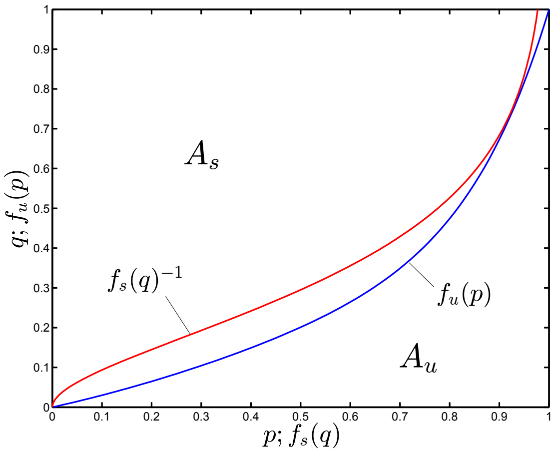


Fig. 6: EXIT Chart for a networks system : irregular repetition code with user nodes degree distribution $\Lambda_a(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$, rate $R_E = 0.278$, and offered traffic $G = 1.58$ packets/slot.

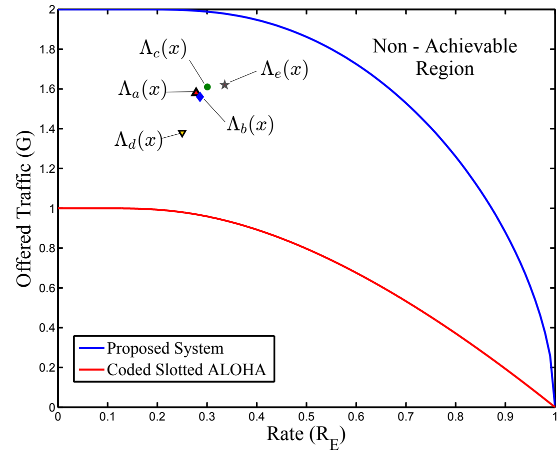


Fig. 7: The upper bound of the proposes system compared to the conventional CSA.

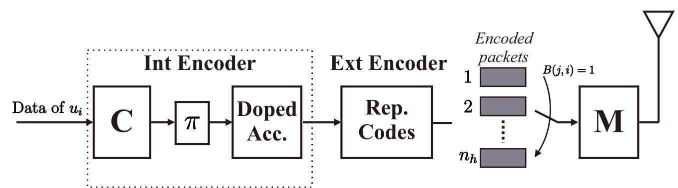


Fig. 8: Transmission blocks of the proposed system with irregular repetition codes.

TABLE I: Thresholds of Offered Traffic Load ($G^*$) for Various User Nodes Degree Distributions.

| Id | Degree Distributions | $R_E$ | $G^*$ |
|---|---|---|---|
| $\Lambda_a(x)$ | $0.5x^2 + 0.28x^3 + 0.22x^8$ | 0.278 | 1.59 |
| $\Lambda_b(x)$ | $0.25x^2 + 0.60x^3 + 0.15x^8$ | 0.2857 | 1.56 |
| $\Lambda_c(x)$ | $0.5465x^2 + 0.1623x^3 + 0.2912x^6$ | 0.3006 | 1.61 |
| $\Lambda_d(x)$ | $0.2x^2 + 0.2x^3 + 0.2x^4 + 0.2x^5 + 0.2x^6$ | 0.25 | 1.38 |
| $\Lambda_e(x)$ | $0.5102x^2 + 0.4898x^4$ | 0.3356 | 1.62 |

the EXIT chart, we obtain $G^*$ for $\Lambda_a(x)$ is 1.59 packets/slot. By the similar way, we obtain the threshold $G^*$ for irregular repetition codes with various degree distributions, which are presented in Table I.

The area theorem in EXIT chart has been exploited to derive the upper bound of the proposed system [7]. The necessary and sufficient condition for successful decoding is the existence of an open tunnel between two curves that satisfies

$$f_s(q^{\ell-1}) > f_u(f_s(q^{\ell})). \tag{19}$$

However, to derive the upper bound, we can use the necessary condition, where the sum of the area under the curve $f_u(p)$, denoted as $A_u$, and area under the curve $f_s(q)$, denoted as $A_s$, is less then 1. In other words, it can be written as

$$A_s + A_u < 1, \tag{20}$$

where

$$A_s = \int_0^1 f_s(q)\mathrm{d}q \tag{21}$$

and

$$A_u = \int_0^1 f_u(p)\mathrm{d}p. \tag{22}$$

From the above equations we obtain

$$R_E + \left(1 + \frac{2R_E}{G}\right) e^{-G/R_E} - \frac{2R_E}{G} < 0, \tag{23}$$

which is the upper bound of the proposed system.[6] Although (23) is not in the closed-form, with some mathematical tricks, it is easy to find the positive solutions, i.e., $G \geq 0$ and $R \geq 0$. These solutions are drawn in the Fig. 7, where the maximum offered traffic is 2 packets/slot using very low rate $R_E$. The threshold $G^*$ of degree distributions presented in Table I are also plotted in Fig. 7 to confirm the achievable points under the bound. The bound indeed can be approached by carefully choosing the degree distribution of the user nodes.

## IV. Simulation and Results

For the sake of simplicity, in our simulation we consider irregular repetition code to be applied in the external encoder. For each user $u_i$, $i = \{1, 2, ..., M + 1\}$, the transmission process is illustrated in Fig. 8. Internal encoder used in this scenario is the same as the encoder used in [5], where half rate convolutional code is serially concatenated with doped accumulator. The total rate of the internal encoder $R_I = 0.5$. The output of the internal encoder is encoded by a packet-oriented repetition code $(n_h, k = 1)$ to generate $n_h$ packets.

[6]The upper bound shown in [7] contains a minor mistake, where the equation (15) of [7] should be written as (23) in this paper.

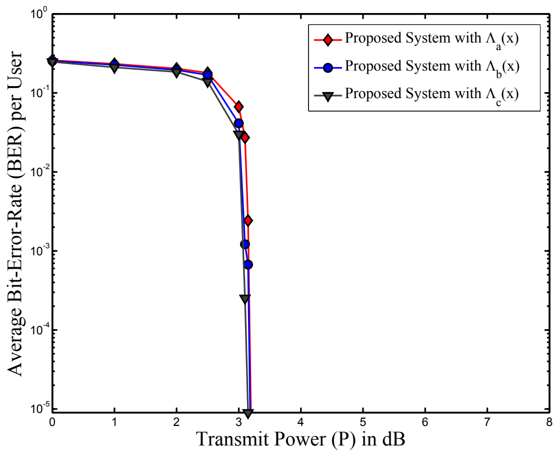


Fig. 9: Average bit-error-rate (BER) per user for the proposed system with $\Lambda_a(x)$, $\Lambda_b(x)$ and $\Lambda_c(x)$.

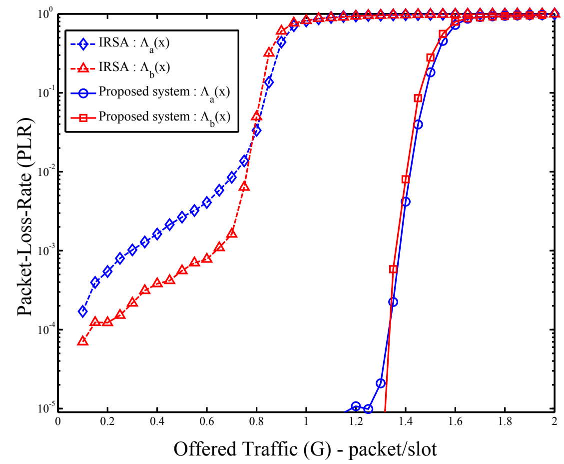


Fig. 10: Packet-loss-rate (PLR) for IRSA system and the proposed system with $\Lambda_a(x)$ and $\Lambda_b(x)$.

One of the encoded packets is then modulated by binary phase shift keying (BPSK) modulation and transmitted over PTS $\mathcal{T}(j)$ if user $u_i$ chooses PTS $\mathcal{T}(j)$, i.e, $B(j,i) = 1$.

In the simulation scenario, we assume additive white Gaussian noise (AWGN) channel. Hence, the complex channel between users and relay in the MAC phase ($h_i^m$) and BC phase ($h_i^b$) are equal to 1. Each user uses an equal power $P_i = P$ to transmit its signal to the relay. The variance of AWGN in all users and the relay is also assumed to be equal, $\sigma_i^2 = \sigma_r^2 = 1$. The amplification factor in the relay is considered to be $Q = 2$.

Fig. 9 depicts bit-error-rate (BER) performance of the proposed system with number of users being 101 and number of PTSs being 90. The corresponding $G$ is equal to 1.11 packets/slot. The degree distributions of user nodes employed in the system are $\Lambda_a(x)$, $\Lambda_b(x)$ and $\Lambda_c(x)$. Fig. 9 shows that a reliable communication with BER lower than $10^{-5}$ can be achieved for $P > 3.2$ dB. We also observe turbo cliff in the BER performance of the proposed system, which is similar to that of [5]. This behavior is the outcome of performing the serial concatenated convolutional decoding of each packet. These results also indicate that the proposed system does not require high SNR as in CSA [3] to work properly.

We also investigate the packet-loss-rate (PLR) performances of the proposed system. In this case, the comparison is made between irregular repetition slotted ALOHA (IRSA) [8] and the proposed multiway relay system. IRSA is regarded as the special case of CSA, where the packets are encoded with a repetition codes ($n_h, k = 1$). The simulation of the systems with number of PTSs 200, number of users $M$ varying according to value of the offered traffic $G$, and degree distribution $\Lambda_a(x)$ and $\Lambda_b(x)$, is performed. The results depicted in Fig. 10 show that to achieve a certain level of PLR, the proposed system offers higher traffic compared to the IRSA. For instance, with $\Lambda_a(x)$, IRSA achieves PLR of $10^{-3}$ for $G = 0.25$ packets/slot, while the proposed system achieves $G$ close to 1.4 packets/slot. Furthermore, the PLR floor of the proposed system with $\Lambda_a(x)$ and $\Lambda_b(x)$ occurs in PLR less than $10^{-5}$. This is also one of the confirmation that the proposed system is working very well with $G \geq 1$ packet/slot.

## V. Conclusions

We proposed massive uncoordinated multiway relay networks, where IDM algorithm is utilized to improve the success rate probability of the detection. We have shown the bound of the proposed system and confirmed the achievable point with practical coding. BER performance results justified that reliable communications with offered traffic of more than 1 packet/slot is achievable. Furthermore, we verified that the systems work properly even in relatively low SNR environments. From the packet-loss-rate (PLR) results, we showed that the proposed system outperforms the conventional CSA without simultaneous detection.

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