En Masse Relay Selection for Decode-and-forward Relaying in Multiple Source-Destination Systems

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***Abstract*—Opportunistic relay selection in a multiple source-destination (MSD) cooperative system involves allocating to each source-destination (SD) pair a relay based on its channel gains. Since each node in the system knows only its local channel gains, a relay selection algorithm is required to quickly identify and assign the best relay to each SD pair. For an MSD system in which the SD pairs communicate in a time-orthogonal manner, we propose two new relay selection algorithms, namely, contention-free en masse assignment (CFEA) and contention-based en masse assignment (CBEA). En masse assignment exploits the fact that in an MSD system a relay can often aid not one but multiple SD pairs, and, therefore, can be assigned multiple SD pairs en masse. We show that CFEA and CBEA require much less time to allocate an SD pair than in single SD systems, and achieve a higher net throughput in several regimes of interest when compared with other selection algorithms proposed in the literature. We also identify the regimes in which CFEA is better than CBEA and vice versa.**

I. Introduction

Cooperative relay-aided transmission schemes have emerged as promising techniques for harnessing spatial diversity in wireless systems. In systems with a single source-destination (SSD) pair [1], [2] and those with multiple source-destination (MSD) pairs [3]–[10], the technique of relay selection has attracted considerable attention. In it, a single 'best' relay is selected based on its channel gains to aid communication between a source-destination (SD) pair. Who the best relay is depends on a system-specific selection *criterion*. Relay selection is appealing because it avoids the need for tight symbol-level synchronization among simultaneously transmitting relays, while achieving full diversity order.

Since each node has only local channel knowledge, no node in the system knows a priori who the best relay for any SD pair is. Therefore, a selection algorithm is required to discover the best relay for each SD pair. Thus, in practice, a cooperative scheme that uses relay selection has to spend time in assigning the best relay for each SD pair.

Various selection criteria and selection algorithms have been well studied for SSD systems [1], [2], [11], [12]. However, in MSD systems, the focus thus far has mostly been on characterizing the diversity, multiplexing, and outage gains achievied by specific relay selection criteria [4]–[8] or on resource allocation once relays have been selected [13]. However, algorithms for discovering best relays for SD pairs have not been well investigated, barring those in [3], [10]. In fact, the channel gains between all pairs of nodes are often assumed to be known centrally for selection purposes [4], [6], [8], [9].

In [3], a simple, contention-free selection algorithm, which we refer to as *Poll-all*, is proposed. In it, every relay feeds back sequentially a vector to a common coordinator (CC) that indicates which SD pairs it can aid. Instead, in [10], a contention-based *distributed pairing scheme (DPS)* is proposed. In it, relays capable of aiding exactly one SD pair pick one slot out of a pairing section, which is a group of contention slots, and transmit in the slot. Relays that collide in a pairing section attempt to transmit successfully in subsequent pairing sections.

Focus and contributions: In this paper, we develop and compare new contention-free and contention-based relay selection algorithms for MSD systems. In them, the sources first transmit data to the relays in a time-orthogonal manner over a common channel. The proposed selection algorithms then assign relays to the SD pairs. Thereafter, the assigned relays transmit data that they decoded to their respective destinations. In such a system, a relay, depending on its current channel gains, may be capable of assisting multiple SD pairs. This observation motivates a simple, yet powerful new concept of *en masse assignment* for designing selection algorithms for MSD networks. In it, a selected relay is assigned to as many unallocated SD pairs as it can aid. While the idea of assigning a relay to aid multiple SD pairs has been studied before [14], [15], its use in the design of fast relay selection algorithms is a novel contribution of this paper.

We first introduce a simple, contention-free en masse algorithm (CFEA). In it, a new relay is polled in every slot and is assigned to *all* the unallocated SD pairs it can aid. We then propose a novel contention-based en masse algorithm (CBEA) that generalizes the splitting-based selection scheme for SSD systems [16]. In it, a relay transmits depending on whether the number of unallocated SD pairs it can currently aid lies between two thresholds. The thresholds are updated depending on whether no relay (idle), one relay (success), or multiple relays (collision) transmitted in the previous slot. In case of a success, for the relay that transmitted, all the unallocated SD pairs that it can aid are assigned en masse to it.

We show that both CFEA and CBEA are extremely fast and outperform Poll-all and DPS in several regimes of interest. For instance, both CFEA and CBEA require less than 0.85 slots per SD pair for a system with 10 SD pairs and 10 relays when the probability that a relay can aid an SD pair is as low as 0.3. Whereas, if the relays are assigned one SD pair after another, at least two slots per SD pair, on average, are required by the same system. We also benchmark the net system throughput,

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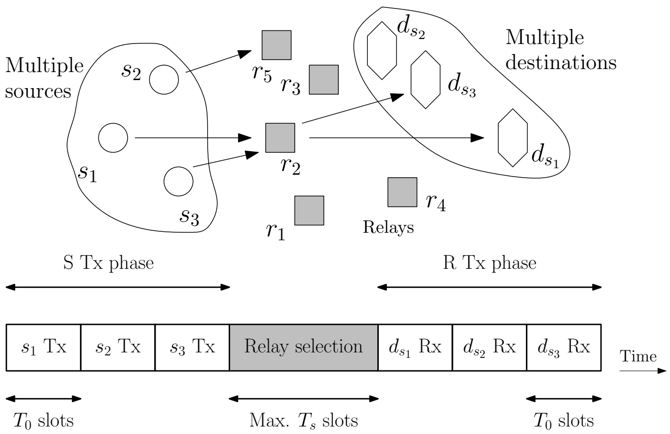

Fig. 1. Illustration of multi-source, multi-relay, multi-destination system and the data transmission protocol ($S = 3$ SD pairs and $N = 5$ relays).

which accounts for the time overhead of selection of CFEA and CBEA, and show that it is higher than other algorithms proposed in the literature. An important observation that comes out of our study is that even with fast selection, the impact of relay selection overhead on the net throughput cannot be neglected.

The paper is organised as follows. The system model is developed in Sec. II. Selection algorithms are presented in Sec. III. Simulation results in Sec. IV are followed by our conclusions in Sec. V.

II. System model

As shown in Figure 1, we consider an MSD relay network with S SD pairs and N DF relays. The set of source nodes is $\{s_1, \ldots, s_S\}$ and the set of relay nodes is $\{r_1, \ldots, r_N\}$. The SD pair s-d_s denotes the source s and its destination d_s. This model encompasses many existing models in the MSD literature such as the single source, multiple destinations model of [6], [8], the single destination, multiple sources model of [4], [5], [9], and the multiple source, multiple destination models of [3], [13], [17].

Let H_{sr} denote the power gain of the channel from source s to relay node r. Similarly, let H_{rd_s} denote the power gain of the channel from a relay node r to a destination node d_s. The source-relay (SR) channel gains are independent and identically distributed (i.i.d.), and so are the relay-destination (RD) channel gains. They remain constant within a coherence interval. In order to focus on relay selection and its implications, the direct link between any SD pair is assumed to be weak [5], [13], [17]. Otherwise, techniques such as incremental relaying and signal combining at destinations can be also used to improve system performance. A relay r only knows H_{sr} and H_{rd_s}, for $1 \leq s \leq S$, and not any other relay's gains.

A CC coordinates the assignment process during the relay selection phase. It could be, for instance, a pre-chosen source or destination node. The CC can decode a message when exactly one relay transmits. However, when multiple relays transmit simultaneously, a collision occurs and the CC cannot decode any of the transmissions [16], [18], [19]. Every relay is assumed to reliably receive the messages broadcast by the CC, which is justifiable given their low payload [12], [16].

Data transmission is assumed to be time-slotted. A coherence interval, during which data packet transmission occurs, is divided into the following three phases:

1) Source-to-relay transmission: In this phase, each source broadcasts its data packet for T_0 slots at a rate of R bits per second (bps) [3], [9], [12]. The transmissions by different sources occur over the same bandwidth and are time orthogonal. Thus, the duration of this phase is ST_0 slots. A relay r can decode the signal from source s only if

$$R \leq \log_2(1 + \gamma_{sr} H_{sr}), \quad (1)$$

where γ_{sr} is the fading-averaged signal-to-noise-ratio (SNR) of the SR link.

2) Relay selection: This phase attempts to allocate each SD pair to an appropriate relay. It lasts for a maximum duration of T_s slots. If all the SD pairs get allocated before T_s slots, the relay assignment phase ends as well. A relay r aids the pair s-d_s if it can decode s's signal, as per (1), *and* can transmit it successfully to d_s, which is described next. The relay is then said to be *feasible* for the pair s-d_s. Clearly, any DF relay that is feasible for an SD pair can be selected. *The relay selection algorithm's goal is to allocate every SD pair to a feasible relay, if any.*

3) Relay-to-destination transmission: This phase occurs after the relay assignment phase. In it, a relay that was assigned to an s-d_s pair forwards to d_s the data that it decoded from s. The assigned relays transmit in a time orthogonal manner at rate R for T_0 slots each. Thus, this phase also lasts for ST_0 slots. A destination d_s can decode the signal from relay r if

$$R \leq \log_2(1 + \gamma_{rd_s} H_{rd_s}), \quad (2)$$

where γ_{rd_s} is the fading-averaged SNR of the RD link. If no relay is assigned to an SD pair, no data will be transmitted in the T_0 slots corresponding to the SD pair during this phase.

III. En masse relay selection algorithms

In this section, we present CFEA and CBEA algorithms for assigning feasible relays en masse to the SD pairs.[1] We first introduce the following terminology. For a relay r, its *feasibility bit* (FB) X_{sr} associated with the SD pair s-d_s is 1 if it is feasible for s-d_s, and is 0 otherwise. We refer to the S-tuple $(X_{s_1 r}, \ldots, X_{s_S r})$ as the *feasibility vector* of relay r. In any slot, a relay's *availability* is the number of unallocated SD pairs it is feasible for.

From (1) and (2), the probability p_f that a relay is feasible for an SD pair is given by

$$p_f = \mathbf{P}[X_{sr} = 1] = \mathbf{P}\left[H_{sr} > \frac{2^R - 1}{\gamma_{sr}}\right] \mathbf{P}\left[H_{rd_s} > \frac{2^R - 1}{\gamma_{rd_s}}\right]. \quad (3)$$

[1] In our model, the transmit-power of a relay is fixed and it expends a fixed amount energy for every SD pair that it aids. This is justified because transmissions for different SD pairs are time orthogonal. Instead, in [3], a relay proportionally reduces the power it expends on an SD pair according to the number of SD pairs it aids.

For Rayleigh fading with unit mean channel power gain, (3) simplifies to $p_f = \exp\left(-(2^R-1)(\gamma_{sr}^{-1}+\gamma_{rd_s}^{-1})\right)$. Notice that as R increases, p_f rapidly decreases.

A. Contention-free en masse assignment (CFEA)

In this simple algorithm, the relays transmit their feasibility vector sequentially to the CC, one slot after the other, in a contention-free manner. A key idea of the algorithm is that the CC then assigns en masse to the relay all the currently unallocated SD pairs for which it is feasible. The set of allocated SD pairs is broadcast after every slot by the CC. This proceeds until all the S SD pairs are allocated, or all the N relays have transmitted, or T_s slots have been used up. If required, the average energy consumption per relay can be made the same across all relays by randomizing the polling order.

B. Contention-based en masse assignment (CBEA)

In CBEA, a splitting algorithm is used to select the relay with the highest availability and assign to it en masse all the unallocated SD pairs it is feasible for. Briefly, it operates as follows. Every relay decides whether to transmit or not in a slot, depending on whether its availability lies within two thresholds. At the end of every slot, the CC broadcasts an idle, success, or collision outcome indicating whether zero, one, or multiple relays, respectively, transmitted. Based on the outcomes, the relays update their thresholds for the next slot. After every success slot, the CC assigns en masse to the relay that transmitted all the unallocated SD pairs for which the relay is feasible. After each assignment, the remaining relays update their availabilities. This process is repeated until all possible SD pairs are allocated or T_s slots are used up.

The design inherently ensures that the relay that transmits in a success slot has the highest availability among the contending ones. We shall term the time duration between subsequent successes, which is a random variable (RV), as an *SD allocation period* (SAP). After every success slot, a new SAP starts.

Due to the unique features of en masse assignment, CBEA differs in multiple ways from other splitting algorithms. Firstly, the availability of a relay is a discrete RV. Thus, more than one relay can have the same availability with a non-zero probability. Secondly, the availability of a relay can change every time a success occurs. Thirdly, the change depends on the SD pair assignments in previous SAPs, as described below.

State variables: The algorithm maintains three state variables in every slot k of the nth SAP: left threshold $L_n(k)$, right threshold $R_n(k)$, and a collision bit $C_n(k) \in \{0,1\}$. The algorithm is said to be in *non-collision mode* if $C_n(k)=0$, which indicates that no collision has occured in the first k slots of the SAP, and is in *collision mode* ($C_n(k)=1$) otherwise.

We first describe how the availabilities statistically change during the course of the algorithm, as this drives the choice of the thresholds $L_n(k)$ and $R_n(k)$. We then formally define the algorithm and explain its design.

1) Availability distribution: Let $\nu_n(r)$ denote the availability of relay r during the nth SAP. It changes only at the start of a new SAP. Let $F_n(\cdot)$ denote the cumulative distribution function (CDF) of the discrete RV $\nu_n(r)$. For $n \ge 1$, let a_n denote the number of SD pairs allocated in the nth SAP and let b_n denote the number of unallocated SD pairs at the end of the nth SAP. Hence, $b_n = S - \sum_{i=1}^n a_i$, for $n \ge 1$. Since all the unallocated SD pairs of a selected relay in a success slot get allocated, it does not participate in the algorithm thereafter.

For $n \ge 2$, F_n depends on the history of assignments in the previous SAPs. For example, in the first SAP, $\nu_1(r)$ has a binomial probability distribution with parameters S and p_f, i.e., $\mathbf{P}\left[\nu_1(r)=k\right] = \binom{S}{k} p_f^k (1-p_f)^{S-k}, 1 \le k \le S$. If a_1 SD pairs are allocated at the end of the 1st SAP, we know that $\nu_2(r) \le \min\{a_1, S-a_1\}$. Thus, the probability distribution of $\nu_1(r)$ depends on a_1. The following key result shows how F_n should be updated.

Proposition 1: For $0 \le k \le \min\{a_n, b_n\}$,

$$F_{n+1}(k) = F_{n+1}(k-1) + \frac{\sum_{t=0}^{N-n-1} \frac{\binom{N-n-1}{t}}{(t+1)} x^{t+1} y^{N-n-1-t} \sum_{j=0}^{a_n-1} d_{jk}}{\frac{1}{N-n+1}\left[(x+y)^{N-n+1} - y^{N-n+1}\right]} + \frac{d_{a_n k} \sum_{t=1}^{N-n} \frac{\binom{N-n-1}{t-1}}{(t+1)} x^t y^{N-n-t}}{\frac{1}{N-n+1}\left[(x+y)^{N-n+1} - y^{N-n+1}\right]},$$

where $d_{jk} = \frac{(F_n(j+1)-F_n(j))\binom{a_n}{j-k}\binom{b_n}{k}}{\binom{a_n+b_n}{j}}$, $y = F_n(a_n-1)$, and $x = F_n(a_n) - F_n(a_n-1)$. Initially, for $0 \le l \le S$, we have $F_1(l) = \sum_{i=0}^{l} \binom{S}{i} p_f^i (1-p_f)^{S-i}$.

Proof: The proof is omitted due to space constraints. ■

2) Algorithm definition: We now specify CBEA during the nth SAP, for $n \ge 1$. The slots are numbered relative to the beginning of the SAP they are in.

SAP Initialization ($k=1$): At the start of the first slot of a SAP, a relay r forms its *selection metric* using the CDF of its availability as follows:

$$\mu_n(r) = F_n(\nu_n(r)-1) + U\left[F_n(\nu_n(r)) - F_n(\nu_n(r)-1)\right], \tag{4}$$

where U is an RV uniformly distributed in $(0,1)$ that is independent of $\nu_n(r)$. Thus, $\mu_n(r)$ is also uniformly distributed in $(0,1)$. Therefore, with probability one, no two relays have the same selection metric, even though they might have the same availability. Further, a relay with lower availability will necessarily have a lower metric than a relay with a higher availability. This idea is similar to proportional expansion used in [19] for SSD systems. Now, the relay with the highest availability is also the relay with the highest metric.

Initially, $L_n(1) = 1 - \frac{1}{N-n+1}$, $R_n(1)=1$, and $C_n(1)=0$.

Transmission rule in slot k: A relay r transmits its feasibility vector in slot k of the nth SAP only if

$$L_n(k) \le \mu_n(r) < R_n(k). \tag{5}$$

Outcomes: After each slot, the CC broadcasts: (i) *idle*, if no relay transmitted, or (ii) *collision*, if at least two relays transmitted and collided, or (iii) *success*, when one relay transmitted and was, thus, decoded by the CC. The unallocated SD pairs the relay is feasible for are assigned to it and its feasibility vector is broadcast by the CC. The other unassigned relays then set to zero their FBs for SD pairs that got allocated.

State variable update rules in the nth SAP: Let $\Delta_n(k) = R_n(k) - L_n(k)$ denote the interval length in slot k.

- *If slot k is an idle:* $\Delta_n(k+1)$ is updated as follows:

$$\Delta_n(k+1) = \begin{cases} \frac{L_n(k)}{N-n+1}, & C_n(k) = 0 \\ \frac{\Delta_n(k)}{2}, & C_n(k) = 1 \end{cases}. \tag{6}$$

  Then, $R_n(k+1) = L_n(k)$, $L_n(k+1) = R_n(k+1) - \Delta_n(k+1)$, and $C_n(k+1) = C_n(k)$.
- *If slot k is a collision:* In this case, $R_n(k+1) = R_n(k)$, $\Delta_n(k+1) = \frac{\Delta_n(k)}{2}$, $L_n(k+1) = R_n(k+1) - \Delta_n(k+1)$, and $C_n(k+1) = 1$.
- *If slot k is a success:* The $(n+1)$th SAP begins unless the algorithm terminates.

Termination: The algorithm terminates when all the S SD pairs are allocated or $R_n(k) \leq F_n(0)$, which means that none of the relays is feasible for the remaining unallocated SD pairs, or T_s slots have been used up for selection.

3) Explanation of the algorithm: In every SAP, the algorithm essentially scans the interval $(0, 1)$ from the right, searching for the relay with the highest metric. The thresholds are successively lowered in every slot until a non-idle slot occurs.

The algorithm behaves differently during the collision and the non-collision modes. The two modes adhere to the following design rules: (i) *Non-collision mode:* Here, one node, on average, transmits in a slot. This maximizes the probability of success in the slot [16]. The interval length update $\Delta_n(k+1) = \frac{L_n(k)}{N-n+1}$ in (6) ensures this since, after k consecutive idle slots, the selection metrics of the $N-n+1$ unassigned relays are uniformly distributed in $(0, L_k)$, (ii) *Collision mode:* The average number of relays that transmit in a slot is half the number that had collided previously. The interval length update $\Delta_n(k+1) = \frac{\Delta_n(k)}{2}$ in (6) ensures this. This continues until a success occurs.

When $R_n(k) \leq F_n(0)$, CBEA terminates as the availability of every relay is zero and no more feasible relays remain.

IV. Simulation and Results

We now characterise the performance of CFEA and CBEA using Monte Carlo simulations that use 10^6 channel realizations. In the simulations, the SR and RD channel gains are exponentially distributed with unit mean, which models Rayleigh fading. Further, $\gamma_{sr} = \gamma_{rd_s} = \gamma$, for every s-d_s pair.

A. Selection speed

To compare the selection speeds of the algorithms, we study them without a time limit on the selection duration. Figure 2 plots the ratio of the average number of slots required for relay selection to the average number of allocated SD pairs as a function of p_f for a system with $S = 10$ SD pairs for $N = 5$

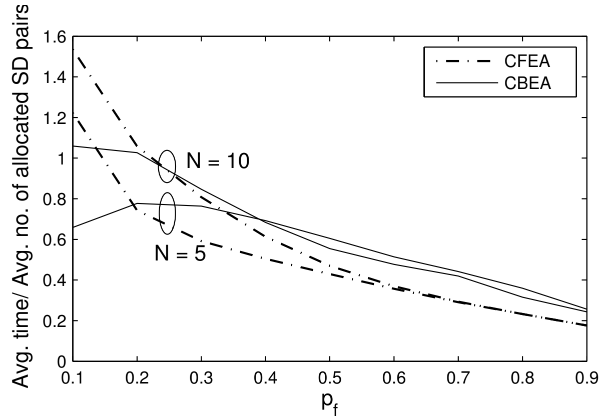

Fig. 2. Effect of N: Comparison of the ratio of average time taken to the average number of allocated SD pairs for CFEA and CBEA as a function of p_f ($S = 10$).

and $N = 10$ relays. We see that both algorithms are extremely fast for most values of p_f. For example, for $p_f = 0.3$ and $N = 10$, CFEA and CBEA take just 0.80 and 0.85 slots per SD pair, on average, respectively. The ratio decreases as p_f increases since the probability that a relay is feasible for an SD pair increases. We observe that CBEA outperforms CFEA for $p_f \leq 0.2$ for $N = 5$ and $p_f \leq 0.25$ for $N = 10$. However, as p_f increases, CFEA is faster. This is because, for larger p_f values, a relay is feasible for a larger number of SD pairs. This enables CFEA to allocate all the SD pairs early on.

Figure 3 enunciates the main advantage of en masse assignment in MSD systems. It plots the aforesaid ratio as a function of p_f for a system with $N = 10$ relays. For $S = 1$, which corresponds to an SSD system, at least one slot, on average, is required to assign a relay to an SD pair. The ratio is much lower for $S = 10$, which shows that en masse assignment speeds up selection. Further, while CFEA outperforms CBEA for $p_f \geq 0.42$ when $S = 1$, it does so for $p_f \geq 0.2$ when $S = 10$. Thus, in an MSD system, contention-free algorithms are competitive, in terms of speed, to contention-based algorithms over a larger range of parameters.

B. Net throughput benchmarking

While several selection criteria have been proposed and analyzed in the literature on MSD systems, selection algorithms for discovering best relays are limited, such as Poll-all and DPS. These were described in Sec. I. We therefore, benchmark CFEA and CBEA against them. In the simulations, three pairing sections are considered for DPS, as per [10].

Figure 4 plots the net throughput in bps as a function of the source rate R for CFEA, CBEA, Poll-all, and DPS for $S = 10$ SD pairs and different values of N and γ. We see that for most values of R, either CFEA or CBEA outperforms the benchmark algorithms. For example, when $N = 10$ and $\gamma = 3$ dB, they respectively have 25% and 18% larger net throughputs than Poll-all at $R = 0.5$ bps. At $R = 2.5$ bps, CBEA has 43% larger net throughput than both CFEA and Poll-all. DPS performs markedly worse than all

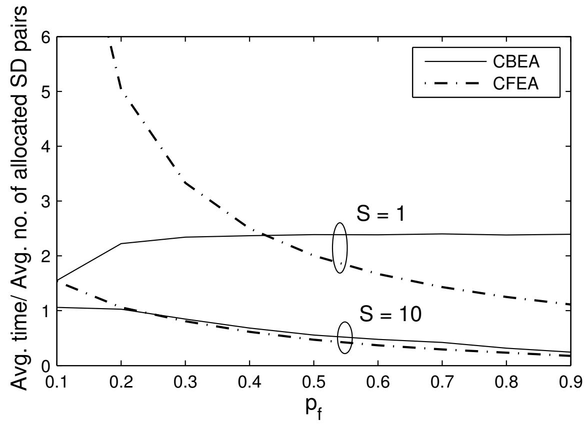

Fig. 3. Effect of S: Comparison of the ratio of average time taken to the average number of allocated SD pairs for CFEA and CBEA as a function of p_f ($N = 10$).

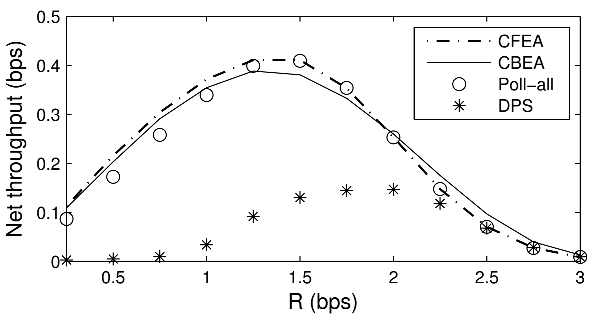

Fig. 4. Plot of net throughput as a function of source rate R for CFEA, CBEA, Poll-all, and DPS ($S = 10$, $T_0 = 10$, and $T_s = 9$).

other selection algorithms. Also, CFEA and Poll-all have the same net throughput for large R because the presence of fewer feasible relays makes CFEA also poll all the relays. For small R, CFEA outperforms CBEA because the probability p_f that a relay is feasible for an SD pair is large. As R increases, CBEA becomes faster than CFEA. When there are more relays in the system, e.g., $N = 20$, CBEA can select relays with larger availabilities, on average, and, hence, outperforms the other algorithms for a larger range of R.

Another important point to note is that impact of relay selection is not negligible. For example, when $N = 10$ and $\gamma = 3$ dB, the maximum net throughput of CFEA occurs at $R = 1.25$ bps. At this point, the average time spent on selection turns out to be 8.2% of the SR data transmission phase duration and 7.4% of the SD pairs remained unallocated. The other algorithms also show similar trends.

V. Conclusion

We proposed two relay selection algorithms – CFEA and CBEA – for an MSD cooperative system that uses DF relays. Both algorithms use en masse assignment, which exploits the fact that a relay in an MSD system can often aid more than one SD pair. In both algorithms, a selected relay is assigned to all the unallocated SD pairs that it can possibly aid.

We saw that the average time per allocated SD pair required by both these algorithms is much less than one slot, and is markedly lower than in SSD systems. These algorithms also achieve a higher net throughput compared to the other algorithms proposed in the literature. We saw that CBEA is faster than CFEA when the number of relays increases. At the same time, CFEA is better than CBEA over a wider range of channel parameters than in SSD systems. Furthermore, we noted that the time spent on selection cannot be neglected, and must accounted for in the system design.

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