Relay Selection with Limited and Noisy Feedback

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***Abstract*—Relay selection is a simple technique that achieves spatial diversity in cooperative relay networks. Nonetheless, relay selection algorithms generally require error-free channel state information (CSI) from all cooperating relays. Practically, CSI acquisition generates a great deal of feedback overhead that could result in significant transmission delays. In addition to this, the fed back channel information is usually corrupted by additive noise. This could lead to transmission outages if the central node selects the set of cooperating relays based on inaccurate feedback information. In this paper, we propose a relay selection algorithm that tackles the above challenges. Instead of allocating each relay a dedicated channel for feedback, all relays share a pool of feedback channels. Following that, each relay feeds back it identity only if its effective channel (source-relay-destination) exceeds a threshold. After deriving closed-form expressions for the feedback load and the achievable rate, we show that the proposed algorithm drastically reduces the feedback overhead and achieves a rate close to that obtained by selection algorithms with dedicated error-free feedback from all relays.**

I. Introduction

Cooperative relaying networks, in which wireless nodes act as relays and cooperate in forwarding packets to a destination node, promise significant performance gains in the overall network capacity [1]-[3]. Relaying techniques can be generally classified, based on their forwarding strategy and required processing at the relay terminals, as *decode and forward* (DF) or *amplify and forward* (AF) [4]-[7]. In DF relaying, the relay decodes the source data, prior to re-encoding and transmitting it to the destination, whereas in the AF relaying, the relay amplifies and retransmits the received data without decoding it. Occasionally, a cooperating relay may have poor channel conditions to either the source or the destination.

To preserve the diversity gains of cooperative communication networks, selective relaying techniques are often employed [3]-[6]. In selective relaying, multiple relays are deployed and the source selects a single or multiple relays with relatively good equivalent (source-relay-destination) channel conditions to forward its data to the destination. To achieve this, each relay is required to feed back its equivalent channel condition to the source. Based on the feedback the source receives, it selects a relay with good equivalent channel conditions to forward its data to the destination. For a small number of relays, the amount of feedback (from relays to the source) might be negligible, however, for large number of relays, the feedback load becomes prohibitively large. This results in significant transmission delays since more air-time is invested in relay selection rather than data transmission. Most relay selection algorithms proposed in the literature (see e.g. [8]-[15]): i) concentrate on limiting the number of relay nodes feeding back and do not account for the feedback air-time, e.g. [8]-[10], ii) do not consider the effect of noise on the feedback channels, e.g. [8]-[14], and iii) discard feedback collisions e.g. [10]. Since in practice, feedback channels are subjected to both fading and additive noise, it is imperative to design relay selection algorithms that minimize the selection time (overhead) and account for the feedback noise as well.

In this paper, we propose a limited feedback relay selection algorithm that accounts for both fading and additive noise in the feedback channels. To minimize the feedback overhead, relays with favorable channel conditions simultaneously feedback their identities over a limited number of shared, noisy, and fading feedback channels. Instead of discarding feedback collisions (unlike the well known timer algorithm [10]), we embrace collisions and employ *Compressive Sensing* (CS) theory [16]-[19] to recover the identity (ID) of the strong relays. Unlike [20] that employs CS for relay aided multicast networks, we focus on single source, single destination networks in this paper.

II. System Model

We consider a relay network with a single source, and a single destination and R independent and identically distributed (i.i.d.) single antenna relays operating in half duplex mode as shown in Fig. 1. It is assumed that there is no direct link between the source and the destination, and thus, communication must take place in a two-hop fashion via a relay as is done, for example, in [10]. Let f_r represent the channel between the source and the rth relay, g_r represent the channel between the rth relay and the destination. Here, f_r and g_r are zero mean unit variance complex Gaussian random variables. All relays are assumed to be synchronized and all channels are assumed to be reciprocal. The transmission power of the source and the rth relay are P and P_r respectively. Additive white Gaussian noise with zero mean and variance σ^2 is assumed at the source, relay and the destination.

The feedback/transmission frame structure is shown in Fig. 2. Each frame (or slot), of duration $T_{\rm f}$, consists of a pilot broadcast sub-slot, of duration $T_{\rm pilot}$ used for channel estimation at the relays, L shared feedback mini-slots, each of duration $T_{\rm ms}$, and a data transmission slot of duration T as outlined in Fig. 2. The channel is assumed to be constant throughout the frame duration $T_{\rm f}$. In the pilot broadcast sub-slot, the source and the destination exchange *Ready-to-Send* (RTS) and *Clear-to-Send* (CTS) data packets from which all

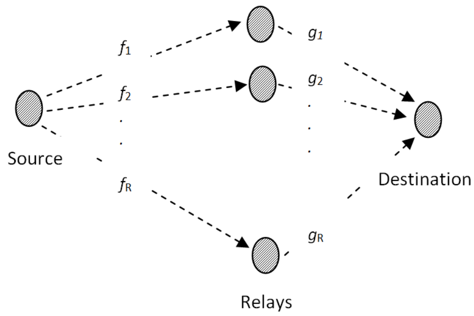

Figure 1. Wireless relay network with multiple relay nodes.

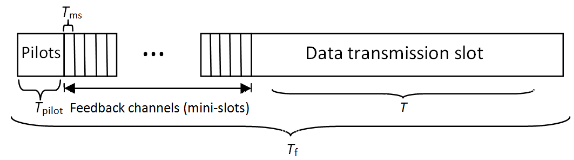

Figure 2. A structure of a frame (of duration T_{f} time units) that consists of a broadcast sub-slot (of duration T_{pilot} time units) which consists of pilots for channel training, several feedback mini-slots (each of duration T_{ms} time units) for feedback reception, and a data transmission slot (of duration T time units).

the relays estimate their source and destination channels. All relays then simultaneously feed back their CSI to the source using the L feedback mini-slots. For feedback, each relay is allocated a Gaussian ID (codeword) of length $M \leq L$ for use on the feedback channel. The Gaussian IDs are selected from the columns of a normalized real Gaussian matrix, with zero mean and variance $\frac{1}{M}$ i.i.d. entries, and are deterministically assigned to the relays. The choice of M is discussed in Section III. Each relay normalizes its feedback channel and combines its CSI with its allocated feedback code, $\mathbf{b}_r$, and transmits the combination to the source. Let $\mathbf{v} \in \mathbb{R}^{R\times 1}$ represent the relays' CSI vector, the received signal (after uplink channel normalization) at the source becomes

$$\underbrace{\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,R} \\ b_{2,1} & b_{2,2} & \cdots & b_{2,R} \\ \vdots & \vdots & \vdots & \vdots \\ b_{M,1} & b_{M,2} & \cdots & b_{M,R} \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_R \end{bmatrix}}_{\mathbf{v}} + \underbrace{\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_M \end{bmatrix}}_{\mathbf{w}}$$

or equivalently

$$\mathbf{y} = \mathbf{B}\mathbf{v} + \mathbf{w}, \tag{1}$$

where the matrix $\mathbf{B} = [\mathbf{b}_1 \quad \mathbf{b}_2 \quad ... \quad \mathbf{b}_R]$ represent the relays' feedback code matrix, the vector $\mathbf{w} \in \mathbb{R}^{M\times 1}$ represents the additive noise at the source, and v_r represents the rth relay fed back equivalent SNR. From $\mathbf{y}$, the source obtains the sparsity pattern (non-zero elements) of the CSI vector $\mathbf{v}$. We show how this is performed in Section III.

III. Compressive Sensing

Consider the following linear model

$$\boldsymbol{y} = \mathbf{B}\mathbf{v} + \boldsymbol{\omega}, \tag{2}$$

where $\boldsymbol{y}$ is a real $M\times 1$ measurement vector, $\mathbf{B}$ is a real $M\times R$ sensing matrix, $\mathbf{v}$ is a real $R\times 1$ sparse vector, and $\boldsymbol{\omega}$ is a real $M\times 1$ vector of independent stochastic errors with zero mean Gaussian entries and variance σ^2. Compressive sensing theory (see [16] and references therein) permits reconstruction of $\mathbf{v}$ in (2) with only a few sensing measurements. There are many different methods used to solve the above sparse approximation problem, nonetheless, we employ the least absolute shrinkage and selection operator (LASSO) as a recovery method as outlined in [19]. The LASSO estimate is defined as the solution to

$$\arg \min_{\boldsymbol{\nu}\in\mathbb{R}^{R\times 1}} \frac{1}{2}\|\boldsymbol{y} - \mathbf{B}\boldsymbol{\nu}\|_{l_2}^2 + \theta\sigma\|\boldsymbol{\nu}\|_{l_1}, \tag{3}$$

where $\|.\|_{l_1}$ and $\|.\|_{l_2}$ represent l_1 and l_2 norms, respectively, and θ is a regularization parameter. Given the following assumptions: (i) The vector $\mathbf{v}$ is sparse, (ii) The matrix $\mathbf{B}$ is a real Gaussian matrix with unit normed columns and i.i.d. entries, (iii) $\min_{r\in\mathcal{S}} |v_r| > 8\sigma\sqrt{2\log R}$, where $\mathcal{S} = \{r : v_r \neq 0\}$ is the support of $\mathbf{v}$, and (iv) $\theta = 2\sqrt{2\log R}$, then for relatively large R, and $M > CS\log R$, where C is a positive constant and it is assumed to be $C = 4$ throughout this paper, the LASSO estimate identifies all non-zero entries of $\mathbf{v}$ with probability [19]

$$\mathcal{P}_{\text{cs}} \geq 1 - 2R^{-1}\left(\frac{1}{\sqrt{2\pi\log R}} + \frac{S}{R}\right). \tag{4}$$

IV. Proposed Relay Selection Algorithm

In what follows, we outline the various stages carried out to select the forwarding relay.

A. Pilot-Based Equivalent SNR Estimation

Assuming that each relay perfectly knows its source and destination channels (from the RTS and CTS packets), each relay calculates its equivalent SNR γ_r^e as follows [6]:

$$\gamma_r^e = \begin{cases} \min(\gamma_{1r}, \gamma_{r2}), & \text{DF relaying} \\ \frac{\gamma_{1r}\gamma_{r2}}{\gamma_{1r}+\gamma_{r2}+1}, & \text{AF relaying} \end{cases} \tag{5}$$

where $\gamma_{1r} = \frac{P}{\sigma^2}|f_r|^2$ is the instantaneous SNR of the source-rth relay channel (first hop), with mean $\bar{\gamma}_1$, $\gamma_{r2} = \frac{P_r}{\sigma^2}|g_r|^2$ is the instantaneous SNR of the rth relay-destination channel (second hop), with mean $\bar{\gamma}_2$.

B. Relay Feedback

To select a set of strong relays, the source generates K SNR thresholds, $\zeta_K > \zeta_{K-1} > ... > \zeta_1$, where $\zeta_{K+1} = \infty$. The thresholds are set to allow only one relay (on average) to feedback between two consecutive thresholds, i.e., $R(F(\zeta_{K+1}) - F(\zeta_K)) = 1$, and hence

$$F(\zeta_K) = 1 - \frac{1}{R},\ F(\zeta_{K-1}) = 1 - \frac{2}{R}, ..., \ F(\zeta_1) = 1 - \frac{K}{R},$$

Table I
SUMMARY OF THE PROPOSED RELAY SELECTION ALGORITHM

1) **Threshold Determination**: The source forms K threshold levels, $\zeta_K, \zeta_{K-2}, ..., \zeta_1$ (defined in (6)) that results in only a few strong relays to feed back.
2) **SNR Determination**: From RTS and CTS packets, each relay calculates its equivalent SNR (using equation (5)).
3) **CSI Feedback**: Each relay normalizes its source (or feedback) channel and feeds back it ID over M time instances if its SNR is greater than ζ_K, or, otherwise, remains silent. If no relay feeds back, each relay lowers the threshold and compares its SNR with the threshold. This is repeated until at least one relay transmission is heard or the minimum threshold is reached.
4) **Relay ID Determination**: If at least one relay feeds back, the source estimates the identity of the strong relays using the LASSO; (see equation (3) and [19]).
5) **Data Transmission**: If more than one relay is detected, the source randomly selects a forwarding relay. If no relay is detected, an outage is declared.

where $F_{\gamma^e}(.)$ is the equivalent SNR cumulative distribution function (CDF) and it is assumed to be known at the source. Note that the CDF depends on the employed relaying protocol. We can, therefore, set the thresholds as

$$\begin{aligned} \zeta_1 \;&=\; F^{-1}\left(1-\frac{K}{R}\right), \quad \zeta_2 = F^{-1}\left(1-\frac{K-1}{R}\right), \\ &\quad ..., \quad \zeta_K = F^{-1}\left(1-\frac{1}{R}\right). \end{aligned} \tag{6}$$

All relays compare their equivalent SNR with the highest threshold and simultaneously feed back their Gaussian IDs (after normalizing their uplink channels) if their SNR is greater than the threshold, or otherwise remain silent. All relays listen to the channel and if no feedback transmission is detected within M time instances, the threshold is lowered. The threshold is lowered until at least one transmission is detected or the minimum threshold is reached, after which a selection outage is declared. If at least one relay feeds back, the source receives

$$\mathbf{y} = \mathbf{B}\mathbf{v} + \mathbf{w}, \tag{7}$$

where the entires of $\mathbf{w}$ represent the additive noise at the source and $\mathbf{v}$ is a sparse feedback vector.

C. Relay Selection and Data Transmission

Although the system in (7) is under-determined, we will be able to estimate the vector $\mathbf{v}$, i.e. the identity of the relays that fed back, from the vector $\mathbf{y}$ by applying the LASSO to $\mathbf{y}$ in (7). If more than one relay is detected, the source randomly selects one of the identified relays and uses it to forward its data to the destination. For quick referencing, we summarize the feedback algorithm in Table I.

V. PERFORMANCE EVALUATION

We consider the following metrics for the performance evaluation of the proposed feedback algorithm: 1) Feedback load, 2) Achievable rate, and 3) Network Throughput. We study each metric in the following for the proposed relay selection algorithm.

A. Feedback Load

The feedback load (overhead) is defined as the average number of mini-slots required by the source to make a selection decision. As stated in Section III, the number of measurements required to recover the sparsity pattern of a sparse vector is $M > 4\log R$. However, since there are K thresholds, we have to calculate the expected number of consumed mini-slots until at least a selection decision is made. For large number of relays, R, and thresholds, K, the expected number of consumed mini-slots until at least one strong relay feeds back can be expressed as

$$\begin{aligned} L \;&= \textstyle\sum_{t=1}^{K} tM\mathbb{P}(\text{at least one relay feeds back in th } t\text{th period}) \\ &\quad \times \mathbb{P}(\text{no feedback in the previous } (t-1) \text{ periods}). \end{aligned} \tag{8}$$

Note that at the tth threshold interval, all relays feedback with probability $\frac{t}{R}$ (see (6)). Therefore, $\mathbb{P}$(at least one relay feeds back in th tth period) is $1-\left(1-\frac{t}{R}\right)^R$. Hence, we can rewrite (8) as

$$\begin{aligned} L \;&=\; M\sum_{t=1}^{K} t\left(1-\left(1-\frac{t}{R}\right)^R\right) \\ &\quad \times \prod_{j=1}^{t-1} \mathbb{P}\text{ (no feedback in the previous } j \text{ periods)} \\ &=\; M\sum_{t=1}^{K} t\left(1-\left(1-\frac{t}{R}\right)^R\right)\prod_{j=1}^{t-1}\left(1-\frac{j}{R}\right)^R \\ &=\; M\sum_{t=1}^{K} t\left(1-\exp(-t)\right)\prod_{j=1}^{t-1}\exp(-j) \to 1.42M, \end{aligned}$$

where the last equality holds for large R and it converges to 1.42 M for large K. Therefore, for large R and K, the total feedback load becomes

$$L > 5.92\log R. \tag{9}$$

B. Achievable Rate

The achievable rate with the multiple thresholds is given by

$$\begin{aligned} \mathcal{R} \;&=\; \sum_{k=1}^{K}\sum_{r=1}^{R}\binom{R}{r}\log_2(1+\zeta_k)\left([F(\zeta_{k+1})]-[F(\zeta_k)]\right)^r \\ &\quad \times \left([F(\zeta_k)]\right)^{R-r}\mathcal{P}_{\text{cs}}. \end{aligned} \tag{10}$$

Equation (10) states that the rate is $\log_2(1+\zeta_k)$ if at least ones relay is found with an instantaneous SNR lying within the ζ_kth and the ζ_{k+1}th threshold interval, and the LASSO was successful in detecting those relays. Equation (10) can be simplified to

$$\begin{aligned} \mathcal{R} \;&=\; \sum_{k=1}^{K}\log_2(1+\zeta_k)\left([F(\zeta_{k+1})]^R-[F(\zeta_k)]^R\right)\mathcal{P}_{\text{cs}} \\ &>\; \sum_{k=1}^{K}\log_2(1+\zeta_k)\left([F(\zeta_{k+1})]^R-[F(\zeta_k)]^R\right) \\ &\quad \times \left(1-2R^{-1}\left(\frac{1}{\sqrt{2\pi\log R}}+\frac{1}{R}\right)\right), \end{aligned} \tag{11}$$

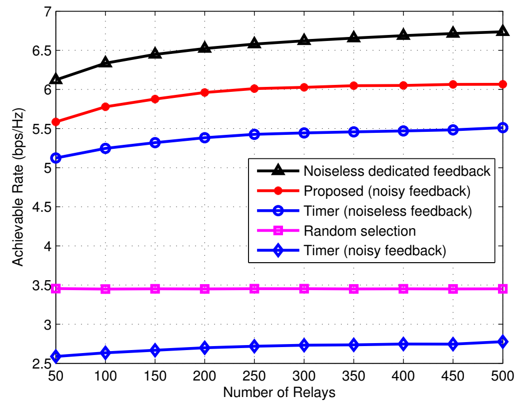

Figure 3. Achievable rate versus the number of relays for different relaying algorithms.

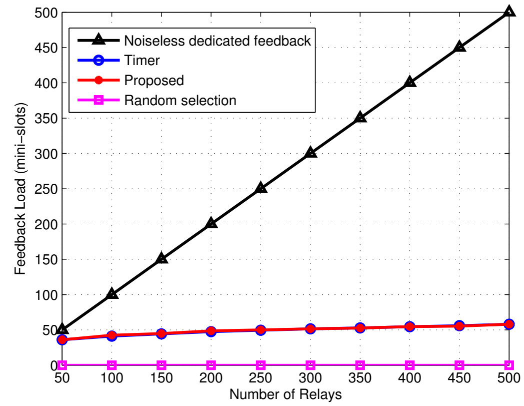

Figure 4. Average feedback load versus the number of relays.

where the inequality is due to the probability of CS detection shown in (4) and the average number of relays that feedback is $\bar{S} = 1$.

C. Network Throughput

The network throughput is defined as the number of transmitted bits per unit time (bits/s/Hz). Let T_{f} represent the total frame time (see Fig. 2), T_{ms} represent the duration of one feedback mini-slot, and T_{pilot} be the duration of the broadcast sub-slot. If we assume T_{pilot} to be negligible, the throughput can be expressed as

$$\begin{aligned} \mathcal{T} &= \text{Achievable rate} \times \frac{(T_{\text{f}} - \text{Feedback load} \times T_{\text{ms}})}{T_{\text{f}}} \\ &= \frac{1}{2}(1 - L\tau)\mathcal{R}, \end{aligned}$$

where $\tau = \frac{T_{\text{ms}}}{T_{\text{f}}}$ is the normalized mini-slot time, and the preceding one half is due to the half duplex operation. The achievable rate $\mathcal{R}$ is derived in (11) and the feedback load is derived in (9).

VI. Results and Discussions

In this section, we study the performance of the proposed CS-based selection algorithm for a DF relay network in a Rayleigh fading environment. The proposed algorithm can be easily applied to other relaying setups since our analysis is based on CDFs. Unless otherwise specified, the number of thresholds is set to $K = 10$ levels and the average SNR per hop is set at $\bar{\gamma}_1 = \bar{\gamma}_2 = 15$ dB in all simulations. To benchmark the performance of the proposed algorithm, we compare its performance with i) algorithms that require noiseless dedicated feedback (full feedback) from all relays (see e.g. [11]), ii) the well known timer algorithm [10], and iii) a random selection algorithm that randomly selects a forwarding relay. In the timer algorithm, each relay sets a timer that is proportional to its effective channel. Each relay broadcasts an SNR/ID flag only when its timer expires [10].

In Fig. 3, we plot the rate achieved by the proposed relay selection algorithm versus the number of relays. As shown in Fig. 3, the rate of the proposed algorithm is close to the rate achieved by the noiseless full feedback algorithm (with infinite SNR resolution) with a rate gap of approximately 0.5 bits/sec/Hz. This rate gap is mainly due to the low SNR resolution of the proposed algorithm (since strong relays only feedback their IDs and not true SNR values). When comparing with the well known timer algorithm (with infinite SNR resolution), we fix the number of feedback mini-slots (for the proposed and timer algorithms) and plot the rate achieved by the timer algorithm with noisy and noiseless feedback links. Recall that the feedback time required by the timer algorithm is lower-bounded by $\frac{d}{E\{\gamma(1)\}}$[1][10], where d is a constant and $\gamma(1)$ is the equivalent SNR of the strongest relay. In Fig. 3, the proposed CS-based algorithm is shown to outperform the timer algorithm (in both noisy and noiseless feedback channels) when we fix the feedback time (in mini-slots). The reason for this is that the timer algorithm suffers from flag collisions[2]. This collision probability decreases with increasing feedback time. The proposed algorithm is superior to the timer algorithm since it is not affected by feedback collisions as long as $M > CS \log R$. The rate achieved by the random relay selection algorithm is constant since the source randomly selects a forwarding relay and does not exploit the multi-relay diversity of the network. The corresponding feedback load of the proposed algorithm and the reference algorithms is shown in Fig. 4. The figure shows that the feedback load of the proposed algorithm is much lower than that of the full feedback algorithm which linearly increases with the number of relays. The feedback load of the random relay selection algorithm is zero since the source randomly selects a relay without any feedback from the relays.

In Figs. 5 and 6, we factor in the feedback time and plot the achievable throughput versus the number of relays. More specifically, we consider a shorter coherence interval ($\tau = \frac{1}{500}$) in Fig. 5 and compare the throughput achieved by the proposed algorithm with the reference algorithms. Thanks to its low

[1]The feedback time in mini-slots is simply lower-bounded by $\frac{d}{\gamma(1)T_{\text{ms}}}$.

[2]The flag collision probability of the timer algorithm is $\mathbb{P}(\frac{1}{\gamma(2)} - \frac{1}{\gamma(1)} < \frac{T_{\text{ms}}}{d})$, where $\gamma(2)$ is the equivalent SNR of the second best relay.

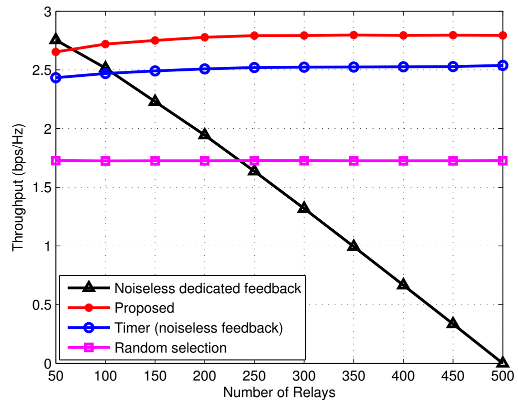

Figure 5. Achievable throughput versus the number of relays assuming long time-slot duration, $\tau = \frac{1}{500}$. The feedback time is fixed for the proposed and the timer algorithms.

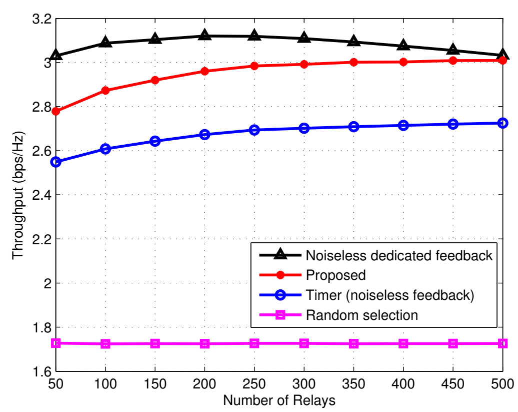

Figure 6. Achievable throughput versus the number of relays assuming long time-slot duration, $\tau = \frac{1}{5000}$. The feedback time is fixed for the proposed and the timer algorithms.

feedback requirements, the proposed algorithm achieves the highest throughput when compared to the reference algorithms. The throughput of the full feedback algorithm is shown to deteriorate with the number of relays. The reason for this is that as the number of relays increases, the feedback time increases and dominates the coherence interval, thus, leaving minimal time for data transmission. In Fig. 6, we consider a larger coherence interval ($\tau = \frac{1}{5000}$) and plot the throughput of the proposed algorithm when compared to the reference algorithms. Fig. 6 shows that when the coherence is high, the full feedback algorithm achieves the highest throughput. This is mainly due to the fact that the feedback time becomes negligible for higher coherence intervals. Nonetheless, the proposed algorithm is still superior to the reference algorithms since we assume noisy feedback channels, while the reference algorithms require noiseless feedback channels.

VII. Conclusions

In this paper, we proposed a compressive sensing based relay selection algorithm in a noisy feedback setting. The proposed algorithm encompasses the most common relaying techniques proposed in the literature, e.g. DF and AF. We showed that with just a few noisy feedback measurements, the proposed algorithm captures most of the multi-relay diversity gain. We also showed that in the presence of noise in the feedback links, the timer algorithm may not be an optimal choice since the flags would be contaminated by noise. This could result in the source basing its transmission/selection decisions on inaccurate CSI. The proposed algorithm deals with noise by requesting relays to only feedback their identity only if their SNR is above a threshold, and not necessary their true SNR.

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