On Blind Sequential Detection of Misbehaving Relay

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***Abstract*—Consider a three-node cooperative system where the relay may misbehave for selfish or adversarial reasons. We propose a blind sequential detection to determine relay's misbehavior with the least number of observations under requirement of detection performance. The likelihood function conditioning on the detected data symbols is derived here for three types of misbehaviors. The destination accumulates log-likelihood ratio (LLR) of current received symbols, and completes detection until the probabilities of false alarm and miss are both guaranteed below required thresholds. Simulation results show that the proposed scheme demands only small number of received symbols at SNR greater than 10dB.**

I. Introduction

Cooperative communication has been extensively discussed for one decade because it allows nodes to exploit additional spatial diversity gain though user cooperation[1]–[3]. Various cooperative strategies have been proposed to enhance power or spectrum efficiency according to topology of cooperative networks and availability of channel information[3]. Most strategies were developed under a basic assumption that relays are fully cooperative. However, if a relay misbehaves due to selfish or adversarial reasons, efficiency of the cooperative system could be degraded severely.

To detect malicious relay, both tracing-based detections [4]–[6] and blind detection[7] have been investigated in the literature. In tracing-based schemes, tracing symbols are randomly generated and inserted into each data block to serve as *ground truth* in misbehavior detection[4]. In absence of instantaneous channel information, noncoherent schemes have been proposed to detect malicious relay in quasistatic fading environment [5], [6]. Performance of tracing-based detections relies on the number of tracing symbols, which leads to tradeoff between accuracy and transmission overhead. Dehnie *et. al.* proposed a blind misbehavior detection scheme according to the correlation between signals received from the source and relay without applying tracing symbols[7].

Misbehavior detections in aforementioned works are based on fixed number of received tracing symbols or data symbols, and detection performance depends on quality of these observations. In this work, we propose a blind sequential detection to determine misbehaving relay as soon as performance requirement on probability of false alarm (P_{FA}) and probability of miss (P_{MISS}) can be met. Sequential detection have been studied for more than half century and applied in various fields [8], [9]. Given performance requirement, it had been proved that sequential detection demands less number of observations in average, compared with likelihood ratio test (LRT) using fixed number of observations. We consider a three-node cooperative where three types of misbehaviora may occur at the relay : 1) Selfish behavior: the relay forwards signal with transmission power less than allocated level, in order to preserve energy for itself. 2) Garbling behavior: the relay garbles forwarded symbols for adversarial attacks. 3) Hybrid misbehavior: both misbehaviors occur simultaneously at the relay. Since no tracing symbols are available, the destination first demodulates data symbols based on the signal received from direct link, which has not been distorted by the relay. We derived likelihood functions of symbols received from the relay link conditioning on the detected symbols for three types of misbehaviors. After accumulating log-likelihood ratio (LLR) of current observations, the destination makes a decision if the value of LLR can guarantee P_{FA} and P_{MISS} lower than required thresholds. Otherwise, the destination keeps observing the received symbols through the relay link, and completes misbehavior detection until the number of observations is sufficient to achieve performance requirement. From simulation results, it shows that selfish behavior demands the largest number of observations, while hybrid misbehavior can be easily detected. Under the requirement that both P_{FA} and P_{MISS} are less than 0.01, the proposed scheme requires at most 30 observations to complete misbehavior detection.

II. System Model

Consider a single-relay cooperative network where a source transmits signal to its destination with assistance of a relay. The cooperative transmission takes two phases. During the first phase, the source transmits data symbols, and signals received at the relay and the destination are respectively

$$\begin{aligned} y_r[m] &= \sqrt{P_s} h_{sr} x_s[m] + w_r[m], \\ y_d^{(1)}[m] &= \sqrt{P_s} h_{sd} x_s[m] + w_d^{(1)}[m], \end{aligned}$$

where P_s is transmission power of the source, $x_s[m]$ is data symbol with unit energy and modulated by quadrature phase shift keying (QPSK) scheme, h_{sr} and h_{sd} are respectively channel coefficients of source-relay link and source-destination link, and $w_r[m]$ and $w_d^{(1)}[m]$ are additive Gaussian white noise with variance σ_w^2. We assume that channel information is perfectly known at the destination for both symbol demodulation and misbehavior detection.

In this work, we consider decode-and-forward relaying protocol. After receiving signal, the relay proceed to decode the source message. To focus our discussion on the misbehavior of the relay, assume that the source-relay link is sufficiently reliable, such that the relay can decode the source message at all time. Denote signal forwarded by the relay as $x_r[m]$. If the relay is trustworthy, it will regenerate the same signal and forward $x_r[m]=x_s[m]$ to the destination. During the second phase, the signal received at the destination is given by

$$y_d^{(2)} = \sqrt{P_r} h_{rd} x_r[m] + w_d^{(2)}[m], \tag{1}$$

where P_r is transmission power allocated to the relay, h_{rd} is the channel coefficient of the relay-destination link, and $w_d^{(2)}[m]$ is white Gaussian noise which has the same statistics with $w_d^{(1)}[m]$. If the relay is fully cooperative, combining $y_d^{(2)}[m]$ with $y_d^{(1)}[m]$ by maximum ratio combining (MRC) scheme is beneficial to improve signal detection at the destination. However, taking MRC may degrade performance of the cooperative system if the relay misbehaves. With this regard, the destination shall perform misbehavior detection before combining both signals.

The signal forwarded by the relay $x_r[m]$ be modeled as

$$x_r[m] = \theta[m] \cdot x_s[m], \tag{2}$$

where variable $\theta[m]$ characterizes the relay's behavior. Specifically, $\theta[m]$ equals to one at all times if the relay is trustworthy. However, if the relay misbehaves, $\theta[m]$ could be a random variable with probability distribution depending on the pattern of misbehaviors. In this work, we consider three types of misbehaviors as follows.

1) **Selfish behavior** : The relay would like to preserve power for itself, and, thus, it retransmits signal with transmission power less than the allocated level. In this case, $\theta[m]$ is less than 1, and we assume that $\theta[m]$ is i.i.d. uniformly distributed between 0 and 1, i.e.,

$$\theta[m] \sim \mathcal{U}[0,1].$$

2) **Garbling behavior** : To destroy signal reception at the destination, the relay garbles source symbols adversely. Since the source symbols are QPSK modulated, we assume that $\theta[m]$ is a discrete random variable which takes value on $e^{jn\pi/2}$ ($n=0,1,2,3$) evenly. That is,

$$\Pr\{\theta[m] = e^{jn\pi/2}\} = 1/4, \ n = 0,1,2,3.$$

3) **Hybrid misbehavior** : Considering the relay misbehaves in both ways, it will distort both the amplitude and phase of the forwarded signal. Assume that the amplitude and phase of $\theta[m]$ have the following distributions:

$$|\theta[m]| \sim \mathcal{U}[0,1],$$
$$\Pr\left\{\measuredangle\theta[m] = \frac{n\pi}{2}\right\} = \frac{1}{4}, \ n = 0,1,2,3.$$

III. Sequential Detection of Misbehaving Relay

In order to distinguish whether the relay misbehaves, the destination needs to examine the signal received in the second phase, and check whether it has been distorted by the relay. In tracing-based method, tracing symbols serve as *ground truth* for detection [4]–[6]. On the other hand, when tracing symbols are not transmitted, the destination may exploit signal received from the source if direct link is reliable[7]. Different from the blind detection scheme in [7] where the destination makes a decision according to correlation coefficient between the signals received in both phases, the destination first demodulates signal received from direct link. Then, likelihood ratio between two cases can be evaluated based on the accuracy of demodulated symbols and corresponding symbol received in the second phase.

More specifically, the destination first detects source symbol based on the signal received from direct link by

$$\hat{x}_s[m] = \frac{1}{\sqrt{2}}\left(\mathrm{sgn}\left\{\Re\left(h_{sd}^* y_d^{(1)}[m]\right)\right\} + j\cdot\mathrm{sgn}\left\{\Im\left(h_{sd}^* y_d^{(1)}[m]\right)\right\}\right).$$

The accuracy of the demodulated symbols depends on the signal to noise ratio (SNR) of the direct link. Without loss of generality, $\hat{x}_s[m]$ can be expressed as $\hat{x}_s[m] = e^{j\phi[m]}x_s[m]$, where $\phi[m]$ is i.i.d. and with probability mass function

$$P_\Phi(\phi) = \begin{cases} (1-\varepsilon)^2, & \phi = 0 \\ (1-\varepsilon)\varepsilon, & \phi = \frac{\pi}{2}, \frac{3\pi}{2} \\ \varepsilon^2, & \phi = \pi \end{cases} \tag{3}$$

where $\varepsilon = Q\left(\sqrt{P_s|h_{sd}|^2/\sigma_w^2}\right)$ is average bit error rate (BER) of the detected symbol $\hat{x}_s[m]$.

Most existing works on misbehavior detections are based on a fixed number of received symbols [4]–[7]. In this work, we proposed a sequential detection scheme to minimize required number of observations subject to satisfying a predetermined requirement on probabilities of miss and false alarm [8], [9]. Thus, with good channel quality, the destination is able to detect relay's behavior and determine whether to perform diversity combining within a short period. In contrast, the destination requires larger number of received symbols to guarantee detection performance if channel is noisy. Let $\mathcal{H}_0$ be the null hypothesis that the relay conforms cooperative strategy, and $\mathcal{H}_1$ be the hypothesis that the relay misbehaves. The destination makes a decision between two hypothesis according to the value of log-likelihood ratio (LLR). Based on first N symbols received from the relay-destination link, LLR between two hypotheses is given by

$$\begin{aligned} \mathrm{LLR}_N &= \log\frac{\prod_{m=1}^N P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_1\right)}{\prod_{m=1}^N P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_0\right)} \\ &= \sum_{m=1}^{M} \log\frac{P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_1\right)}{P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_0\right)} \\ &= \mathrm{LLR}_{N-1} + \log\frac{P\left(y_d^{(2)}[N]\middle|\hat{x}_s[N];\mathcal{H}_1\right)}{P\left(y_d^{(2)}[N]\middle|\hat{x}_s[N];\mathcal{H}_0\right)}, \end{aligned} \tag{4}$$

where the likelihood functions in both numerator and denominator are conditioning on the symbol demodulated in the first phase since the source symbols are unknown at the destination. It is worth mentioning that expression of LLR in (4) is additive. Thus, after receiving the N-th symbol, the destination updates LLR_N by adding up LLR_{N-1} and LLR of the newly-observed symbol. The destination keeps observing signals until the value of LLR_N guarantees that $P_{\mathrm{FA}} \le \alpha$ and $P_{\mathrm{MISS}} \le \beta$, where α and β are system requirements on probabilities of false alarm and miss, respectively. According to Wald's theorem[8], the destination decides $\mathcal{H}_1$ if $\mathrm{LLR}_N \ge \log \frac{1-\beta}{\alpha}$, decides $\mathcal{H}_0$ if $\mathrm{LLR}_N \le \log \frac{\beta}{1-\alpha}$[9]. Otherwise, the destination keeps proceeding misbehavior detection sequentially.

From relationship between $x_s[m]$ and $\hat{x}_s[m]$, likelihood functions in (4) can be written by

$$\begin{aligned} &P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_z\right) \\ &=\sum_{i=0}^{3} P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m],\phi_i;\mathcal{H}_j\right) P_\Phi(\phi_i) \\ &=\sum_{i=0}^{3} P\left(y_d^{(2)}[m]\middle|x_s[m]=\hat{x}_s[m]e^{-j\phi_i};\mathcal{H}_j\right) P_\Phi(\phi_i), \quad (5) \end{aligned}$$

where $\phi_i = i\pi/2$, and $z=0,1$.

Under hypothesis $\mathcal{H}_0$, the relay conforms cooperative strategy and $x_r[m]=x_s[m]$. Thus, the conditional probability in (5) is given by

$$\begin{aligned} &P\left(y_d^{(2)}[m]\middle|x_s[m]=\hat{x}_s[m]e^{-j\phi_i};\mathcal{H}_0\right) \\ &= \frac{1}{\pi\sigma_w^2}\exp\left(-\frac{1}{\sigma^2}\left|y_d^{(2)}[m]-\sqrt{P_r}h_{rd}\hat{x}_s[m]e^{-j\phi_i}\right|^2\right). \quad (6) \end{aligned}$$

On the other hand, the likelihood function under $\mathcal{H}_1$ depends on the misbehaving pattern of the relay since $x_r[m]$ is random even though $x_s[m]$ is given. More specifically, the conditional function in (5) equals to

$$\begin{aligned} &P\left(y_d^{(2)}[m]\middle|x_s[m]=\hat{x}_s[m]e^{-j\phi_i};\mathcal{H}_1\right) \\ &=\int P\left(y_d^{(2)}[m]\middle|x_s[m]=\hat{x}_s[m]e^{-j\phi_i},\theta;\mathcal{H}_1\right) f(\theta)d\theta \quad (7) \\ &=\frac{1}{\pi\sigma_w^2}\int\exp\left(-\frac{1}{\sigma^2}\left|y_d^{(2)}[m]-\sqrt{P_r}h_{rd}\theta\hat{x}_s[m]e^{-j\phi_i}\right|^2\right) f(\theta)d\theta, \end{aligned}$$

where θ, as described in (2), is a random variable to characterize relay's misbehavior and with distribution function $f(\theta)$. Substituting the distribution of θ given in Sec.II into (7), likelihood functions under $\mathcal{H}_1$ for three kinds of misbehaviors are discussed as follows.

1) Selfish behavior : Since $\theta[m] \sim \mathcal{U}[0,1]$, we have

$$\begin{aligned} &P\left(y_d^{(2)}[m]\middle|x_s[m]=\hat{x}_s[m]e^{-j\phi_i};\mathcal{H}_1\right) \\ &=\frac{1}{\pi\sigma_w^2}\int_0^1\exp\left(-\frac{1}{\sigma^2}\left|y_d^{(2)}[m]-\sqrt{P_r}h_{rd}\theta\hat{x}_s[m]e^{-j\phi_i}\right|^2\right)d\theta \\ &=\frac{1}{\sqrt{P_r|h_{rd}|^2\pi\sigma_w^2}}\exp\left(\frac{g^2[m]-|\tilde{y}_d[m]|^2}{\sigma_w^2}\right)\times \\ &\left(1-Q\left(\frac{\sqrt{2}g[m]}{\sigma_w}\right)-Q\left(\frac{\sqrt{2P_r|h_{rd}|^2}-\sqrt{2}g[m]}{\sigma_w}\right)\right), (8) \end{aligned}$$

where $g[m] = \Re\{\tilde{y}_d^*[m]\hat{x}_s[m]e^{-j\phi_i}\}$ and $\tilde{y}_d[m] = y_d^{(2)}[m]h_{rd}^*/|h_{rd}|$. The likelihood function can be obtained by combining (8) and (5).

2) Garbling behavior : In this case, θ takes value evenly over $\{e^{jn\pi/2}\}$. That is, the relay will garble the forwarding symbols as one of QPSK symbols with equal probability regardless of $x_s[m]$. Thus, we can ignore the Bayesian expression in (5) and (7), and express the likelihood function directly as

$$\begin{aligned} &P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_1\right) \quad (9) \\ &=\frac{1}{4\pi\sigma_w^2}\sum_{k=1}^{4}\exp\left(-\frac{1}{\sigma^2}\left|y_d^{(2)}[m]-\sqrt{P_r}h_{rd}e^{\frac{j(2k+1)\pi}{4}}\right|^2\right). \end{aligned}$$

3) Hybrid misbehavior : In this case, the relay distorts both phase and amplitude of the forwarding signal. Similar to previous case, the phase of $x_r[m]$ is equally distributed over $\{(\pm 1 \pm j)/\sqrt{2}\}$. However, the amplitude of $x_r[m]$ is uniformly distributed between 0 and 1. From (7), the likelihood function under $\mathcal{H}_1$ is given by

$$\begin{aligned} &P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_1\right) \\ &=\frac{1}{4\pi\sigma_w^2}\sum_{k=1}^{4}\int_0^1\exp\left(-\frac{1}{\sigma^2}\left|y_d^{(2)}[m]-\sqrt{P_r}h_{rd}\theta e^{\frac{j(2k+1)\pi}{4}}\right|^2\right)d\theta \\ &=\frac{1}{4\sqrt{P_r|h_{rd}|^2\pi\sigma_w^2}}\sum_{k=1}^{4}\exp\left(\frac{\breve{g}^2[m]-|\tilde{y}_d[m]|^2}{\sigma_w^2}\right)\times \\ &\left(1-Q\left(\frac{\sqrt{2}\breve{g}[m]}{\sigma_w}\right)-Q\left(\frac{\sqrt{2P_r|h_{rd}|^2}-\sqrt{2}\breve{g}[m]}{\sigma_w}\right)\right), (10) \end{aligned}$$

where $\breve{g}[m] = \Re\{\tilde{y}_d^*[m]e^{-j(2k+1)\pi/4}\}$.

Finally, we summarize the proposed sequential detection of misbehaving relays in the following.

Initialization : $\mathrm{LLR}_0 = 0$, $m=1$

1. Demodulate the signal received from direct link $\hat{x}_s[m]$ and evaluate corresponding error probability ε.
2. Manipulate LLR value

$$\mathrm{LLR}_m = \mathrm{LLR}_{m-1} + \log\frac{P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_1\right)}{P\left(y_d^{(2)}[m]\middle|\hat{x}_s[m];\mathcal{H}_0\right)}.$$

3. Decide the relay is cooperative if $\mathrm{LLR}_m \le \log\frac{\beta}{1-\alpha}$, while determine that the relay misbehaves if $\mathrm{LLR}_m \ge \log\frac{1-\beta}{\alpha}$. Otherwise, $m+1 \leftarrow m$ and go to step 2.

IV. Computer Simulations

In this section, we demonstrate detection performance of the proposed scheme through Monte Carlo Simulations. The simulated environment is quasi-static and Rayleigh faded, and assume that all channel coefficients are complex Gaussian distributed with zero mean and unit variance. In our simulations, the source and relay transmit signal with the same power, i.e., $P_s = P_r = P$. Fig.1 and Fig.2 compare detection performance

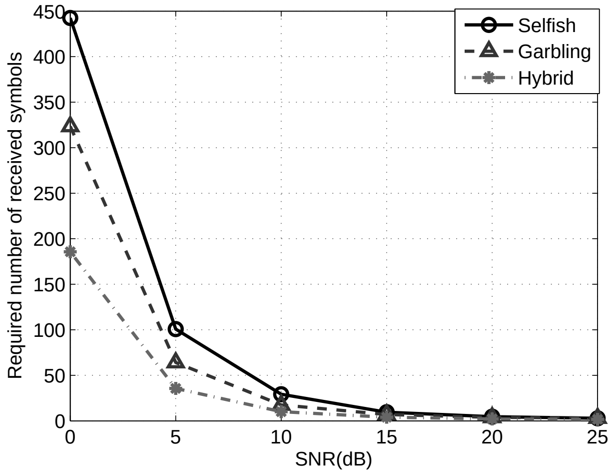

Fig. 1. Required number of received symbols for sequential misbehavior detection as target $\alpha = \beta = 0.01$.

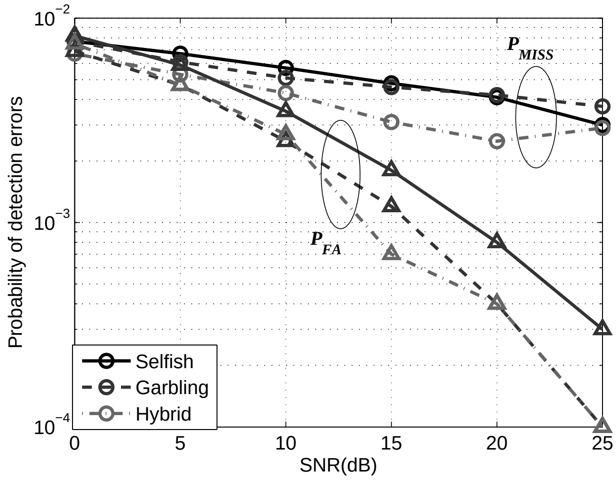

Fig. 2. Average probabilities of false alarm and miss detection of sequential misbehavior detection as target $\alpha = \beta = 0.01$.

regarding three types of misbehaviors with system requirements on P_{FA} and P_{MISS} setting as $\alpha = \beta = 0.01$. In this case, the proposed scheme determines the relay as misbehaving one as soon as LLR exceeds 4.5951, or determines the relay as cooperative one as LLR exceeds -4.5951. Fig.1 shows thats that selfish behavior demands more number of observations to meet detection requirement, because a selfish relay behaves the most similar to a cooperative relay since it does not distort phases of the forwarded symbols. Our scheme requires at most 30 received symbols to achieve detection performance at $\mathtt{SNR} = 10$ dB. Fig.2 verifies that P_{FA} and P_{MISS} of the proposed scheme is below 0.01 for all kinds of misbehavior. Note that simulated values of P_{MISS} are greater than those of P_{FA} because the distribution of LLR under $\mathcal{H}_1$ is closer to zero. In Fig.3, we compare required number of received symbols in term of target detection performance α(or β) at $\mathtt{SNR} = 10$ dB. When the requirement on detection performance becomes more stringent, required number of observations increases linearly with the negative order of α.

V. Conclusions

In this work, we adopt blind sequential detection to determine relay's behavior. The likelihood function conditioning on the detected symbols has been derived for three types of misbehavior. Simulation results show that selfish behavior requires the most observations to achieve detection requirements.

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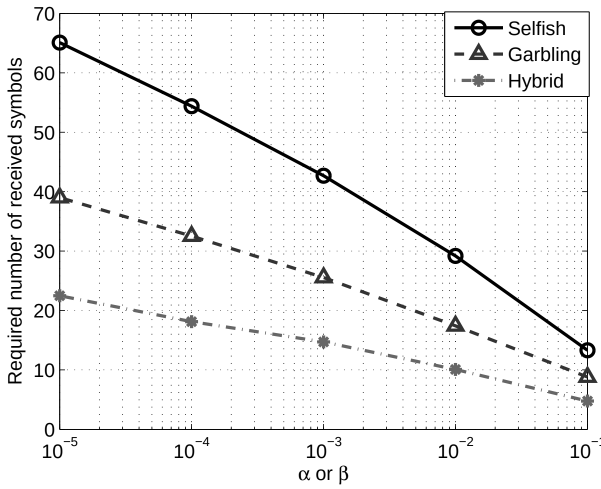

Fig. 3. Required number of received symbols for sequential misbehavior detection as $\mathtt{SNR} = 10$ dB.

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