Soft Information Relaying in Fading Channels

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***Abstract*—This letter considers the mutual information based soft forwarding (MIF) scheme for a memoryless parallel relay network in Rayleigh fading channels. The exact analytical expression for soft noise variance in Rayleigh fading channels is first given. A tight upper bound of the soft noise variance of the relayed signal and the input-output relationship at the relay is then derived. Furthermore, it is revealed that the MIF scheme in Rayleigh fading channels can achieve a full diversity order. Simulation results show that the MIF scheme yields about 0.8 - 1.8 dB signal-to-noise ratio (SNR) gains compared to the various full diversity-achieving schemes in the literature.**

***Index Terms*—Diversity order, fading channels, parallel relay network, soft information relaying, symbol-wise mutual information.**

I. Introduction

WIRELESS relaying technologies [1–4] have emerged as an energy-efficient method to extend communications range and provide diversity to combat fading in wireless communications systems. Many relay protocols have been proposed in the literature to reap such benefits. Out of those various relay protocols, memoryless relay protocols [5] are the simplest ones in terms of the complexity, latency, and energy consumption. In a memoryless relay network, the signal transmitted by the relay depends only on the current received signal at the relay. There are three major memoryless relay protocols: amplify-and-forward (AF) [1], detect-and-forward (DF) [2], and estimate-and-forward (EF) [5].

AF preserves reliability information, however, it suffers from noise amplification. In an ideal situation of perfect detection at the relays, DF performs better than AF [2]. However, with imperfect detection at the relay, the performance of a DF relay network can be degraded due to the propagation of erroneous decisions. Soft information relaying [5–7] has been shown to be very effective in reducing the error propagation to the destination, thereby, achieving an overall better bit error rate (BER) performance. A generalized signal-to-noise ratio (GSNR) optimal relay protocol, namely EF, has been proposed for memoryless relay networks in additive white Gaussian noise (AWGN) channels in [5]. It is shown that EF maximizes the GSNR at the destination. A BER optimal solution for the scenario with one relay and no direct link between source and destination is described in [6]. The approach, however, does not generalize to more than one relay.

Recently a novel soft forwarding technique based on symbol-wise mutual information (SMI), referred to as mutual information based forwarding (MIF), has been proposed for parallel relay networks in AWGN channels [7]. In MIF scheme, each relay node calculates the log-likelihood ratio (LLR) and a corresponding SMI of the received symbols. The sign of the soft decision is determined by the sign of LLR values, and the SMI conditioned on the absolute value of the LLR is used as a reliability measure in generating the soft forwarding symbols. It was shown in [7] that the MIF scheme achieves a superior BER performance in a parallel relay network compared with other memoryless forwarding schemes, such as AF, DF, and EF.

The end-to-end performance of AF and DF schemes in fading channels has been analyzed in [8] and [9], respectively. However, till date, it has not been reported in the literature how much diversity order can be achieved by the soft forwarding technique in fading channels. This is primarily due to the complexity of finding the exact distribution of soft noise variance of the relayed signal, and consequently finding the exact average BER of a soft forwarding parallel relay network.

In this letter, we will focus on soft information relaying for memoryless relay networks in Rayleigh fading channels. As finding the exact distribution of the soft noise variance is involved, we derive the exact analytical expressions for the soft noise variance. In particular, we find that it is possible to calculate the soft noise variance based on channel signal-to-noise ratio (SNR) only, and no knowledge of exact or estimated information bits is required. Note that in the existing literature, the soft noise variance could only be determined through Monte Carlo simulation. We also derive a tight upper bound of the soft noise variance which can be calculated from a Q-function table. The asymptotic input-output SNR relation at the relay is then derived. Finally, the diversity order of MIF scheme is revealed. We show that with the soft noise variance available at the destination, the MIF scheme can achieve a full diversity order. We also compare the BER performance of the MIF scheme with other full diversity-achieving schemes. It is observed that the MIF scheme achieves about $0.8-1.8$ dB SNR gains over various full diversity-achieving schemes previously reported in the literature.

This letter is organized as follows. In Section II, we present the system model. Analytical expressions for the soft noise variance and diversity order in Rayleigh fading channels are derived in Section III . Some concluding remarks are presented in Section IV.

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II. SYSTEM MODEL

We consider a parallel relay network consisting of one source S, one destination D, and K parallel relays, all of which have a single antenna. We assume that the direct link between the source and the destination is not available, which may result from heavy shadowing. There are two phases in the transmission. In the first phase, the source broadcasts its signal to the relays. In the second phase, the K relays transmit the regenerated versions of the received signal to the destination through orthogonal channels. For example, it could be realized by employing time-division multiple access (TDMA) scheme. Each relay has the same average energy $P_{R,i} = P_R/K$, where P_R denotes the total relay signal energy. Rayleigh fading channels are assumed. At the destination, the signal from all the relays are combined by a maximum ratio combiner (MRC).

The received signal at the i-th relay is given by

$$r_i = \sqrt{P_S} h_{\mathrm{SR}_i} x + n, \tag{1}$$

where P_S denotes the source signal energy, h_{SR_i} is the fading coefficient between the source and the i-th relay which are modeled as independent zero mean Gaussian random variables with unit variance, i.e., $E[|h_{\mathrm{SR}_i}|^2] = 1$, and n is an AWGN with zero mean and variance $\sigma_n^2 = N_0/2$. Throughout the paper, we consider binary phase-shift keying (BPSK) modulation, where $x = +1$ or -1. The SNR is defined as $\frac{E_b}{N_0} = \frac{P_S}{2\sigma_n^2}$. Assuming perfect knowledge of source-to-relay channel state information (CSI) at the relay, the associated channel LLR is computed at the i-th relay as

$$\begin{aligned}\Lambda_i &= \log \frac{p(r_i|x=+1, h_{\mathrm{SR}_i})}{p(r_i|x=-1, h_{\mathrm{SR}_i})} \\ &= \frac{2\sqrt{P_S}}{\sigma_n^2} \mathrm{Re}\{h_{\mathrm{SR}_i}^* r_i\} \\ &= \frac{2\sqrt{P_S}}{\sigma_n^2} (|h_{\mathrm{SR}_i}|^2 \sqrt{P_S} x + |h_{\mathrm{SR}_i}| n)\end{aligned} \tag{2}$$

with conditional probability density function (PDF)

$$p(r_i|x, h_{\mathrm{SR}_i}) = \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{\left|r_i - h_{\mathrm{SR}_i}\sqrt{P_S}x\right|^2}{2\sigma_n^2}}.$$

The soft information at the i-th relay of the MIF scheme in Rayleigh fading channels, denoted by $\tilde{x}_i$, is given by [7]

$$\tilde{x}_i = \mathrm{sign}(\Lambda_i)\Theta(\Lambda_i), \tag{3}$$

where we have [7]

$$\Theta(\Lambda_i) = \left(\frac{1}{1+e^{\Lambda_i}} \log_2 \frac{2}{1+e^{\Lambda_i}} + \frac{1}{1+e^{-\Lambda_i}} \log_2 \frac{2}{1+e^{-\Lambda_i}}\right).$$

The received signal at the destination from the i-th relay, denoted by $y_{\mathrm{RD},i}$, can be written as

$$\begin{aligned}y_{\mathrm{RD},i} &= h_{\mathrm{R}_i\mathrm{D}} \beta_i \tilde{x}_i + n_{d,i} \\ &= h_{\mathrm{R}_i\mathrm{D}} \beta_i \psi_i (x + e_i) + n_{d,i},\end{aligned} \tag{4}$$

where β_i is the normalization factor at the i-th relay, and it is given by $\beta_i = \sqrt{\frac{P_{R,i}}{E[\tilde{x}_i^2]}}$, e_i is the soft noise of the soft information $\tilde{x}_i$ at the i-th relay, defined as $e_i = \frac{\tilde{x}_i}{\psi_i} - x$ with variance $\sigma_{e,i}^2$, ψ_i is the scalar coefficient to take into account the correlation between x and the correlated soft noise, and it can be calculated as $\psi_i = E[x\tilde{x}_i]$ [5], $h_{\mathrm{R}_i\mathrm{D}}$ is the fading coefficient between the i-th relay and the destination, which is modeled as independent zero mean Gaussian random variables with unit variance, i.e., $E[|h_{\mathrm{R}_i\mathrm{D}}|^2] = 1$, and $n_{d,i}$ is the destination noise with zero mean and $\sigma_n^2 = N_0/2$ variance.

III. ANALYTICAL SOFT NOISE VARIANCE AND DIVERSITY ANALYSIS IN FADING CHANNELS

In this section, we first state the following Lemma that gives the exact analytical soft noise variance $\sigma_{e,i}^2$.

Lemma 1: The soft noise variance at the i-th relay of the MIF scheme in Rayleigh fading channels can be derived as

$$\begin{aligned}\sigma_{e,i}^2 &= \frac{E[\tilde{x}_i^2|_{(x=1)}]}{\mu_{\tilde{x}}^2|_{(x=1)}} - 1 \\ &= \left(\frac{\int_{-\infty}^{\infty} \tilde{x}_i^2|_{(x=1)} p(\Lambda_i|X=x, h_{\mathrm{SR}_i}) d\Lambda_i}{\left(\int_{-\infty}^{\infty} \tilde{x}_i|_{(x=1)} p(\Lambda_i|X=x, h_{\mathrm{SR}_i}) d\Lambda_i\right)^2}\right) - 1,\end{aligned} \tag{5}$$

where the PDF of Λ_i, conditioned on $X = x$ and h_{SR_i}, is given by

$$p(\Lambda_i|X=x, h_{\mathrm{SR}_i}) = \frac{1}{\sqrt{2\pi}\sigma_{\Lambda_i}} e^{-\frac{\left|\Lambda_i - \mu_{\Lambda_i} x\right|^2}{2\sigma_{\Lambda_i}^2}}$$

with $\mu_{\Lambda_i} = 2P_S|h_{\mathrm{SR}_i}|^2/\sigma_n^2$ and $\sigma_{\Lambda_i}^2 = 4P_S|h_{\mathrm{SR}_i}|^2/\sigma_n^2$.

Proof: See Appendix A. ∎

The following Theorem states the relationship between the input SNR (denoted by $\gamma_{\mathrm{in},i}$), where $\gamma_{\mathrm{in},i} = |h_{\mathrm{SR}_i}|^2 \frac{E_b}{N_0}$, and the output SNR (denoted by $\gamma_{\mathrm{out},i}$), where $\gamma_{\mathrm{out},i} = \frac{1}{\sigma_{e,i}^2}$, at the i-th relay.

Theorem 1: The asymptotic input-output SNR relationship at the i-th relay of the MIF scheme in Rayleigh fading channels can be expressed as

$$\lim_{\gamma_{\mathrm{in},i}\to\infty} \gamma_{\mathrm{out},i} \geq \lim_{\gamma_{\mathrm{in},i}\to\infty} \frac{1}{2} \exp(\gamma_{\mathrm{in},i}). \tag{6}$$

Proof: For $x = 1$, the event $\tilde{x}_i = \Theta(\Lambda_i)$ happens with probability $1 - P_b(e_i)$, and that $\tilde{x}_i = -\Theta(\Lambda_i)$ happens with probability $P_b(e_i)$, where $P_b(e_i))$ represents the BER of the source to i-th relay link. Hence, we get

$$\begin{aligned}&E[\tilde{x}_i^2|_{(x=1)}] \\ &= E[\Theta^2(\Lambda_i)](1 - P_b(e_i)) + E[(-\Theta(\Lambda_i))^2]P_b(e_i) \\ &= E[\Theta^2(\Lambda_i)],\end{aligned} \tag{7}$$

and

$$\begin{aligned}&\mu_{\tilde{x}_i}^2|_{(x=1)} \\ &= (E[\Theta(\Lambda_i)](1 - P_b(e_i)) + E[-\Theta(\Lambda_i)]P_b(e_i))^2 \\ &= (1 - 2P_b(e_i))^2 E^2[\Theta(\Lambda_i)].\end{aligned} \tag{8}$$

Hence, the soft noise variance in (5) can be written as

$$\sigma_{e,i}^2 = \frac{E[\Theta^2(\Lambda_i)]}{(1 - 2P_b(e_i))^2 E^2[\Theta(\Lambda_i)]} - 1. \tag{9}$$

As $E[\Theta^2(\Lambda_i)] \geq E^2[\Theta(\Lambda_i)]$, (9) can be written as

$$\sigma_{e,i}^2 \leq \frac{1}{(1 - 2P_b(e_i))^2} - 1. \tag{10}$$

At a very high input SNR, we have

$$\begin{aligned}\lim_{\gamma_{\text{in},i}\to\infty}\sigma_{e,i}^2 &\le \lim_{\gamma_{\text{in},i}\to\infty}\frac{1}{(1-2P_b(e_i))^2}-1\\ &= \lim_{\gamma_{\text{in},i}\to\infty}\frac{1}{\left(1-2Q\left(\sqrt{2\gamma_{\text{in},i}}\right)\right)^2}-1\\ &\overset{(a)}{\le} \lim_{\gamma_{\text{in},i}\to\infty}\frac{1}{\left(1-\exp\left(-\gamma_{\text{in},i}\right)\right)^2}-1\\ &= \lim_{\gamma_{\text{in},i}\to\infty}\frac{2\exp\left(-\gamma_{\text{in},i}\right)-\exp^2\left(-\gamma_{\text{in},i}\right)}{1-2\exp\left(-\gamma_{\text{in},i}\right)+\exp^2\left(-\gamma_{\text{in},i}\right)}\\ &= \lim_{\gamma_{\text{in},i}\to\infty}2\exp\left(-\gamma_{\text{in},i}\right), \qquad (11)\end{aligned}$$

where (a) is obtained based on $Q(x) \le \frac{1}{2}\exp\left(\frac{-x^2}{2}\right)$. Substituting $\sigma_{e,i}^2 = \frac{1}{\gamma_{\text{out},i}}$ into (11) results in Theorem 1. ■

In Fig. 1, we plot the ratio of input and output SNRs at the relay i of the MIF scheme, denoted by $\frac{\gamma_{\text{in},i}}{\gamma_{\text{out},i}}$, with respect to (w.r.t) transmit SNR $\left(\frac{E_b}{N_0}\right)$, where we assume $P_S = 1$. It shows that the value of $\frac{\gamma_{\text{in},i}}{\gamma_{\text{out},i}}$ is always less than one, i.e., $\gamma_{\text{out},i}$ is always larger than $\gamma_{\text{in},i}$. In Fig. 1, we also plot the exact analytical expression of the soft noise variance $\sigma_{e,i}^2$, given by (5), and the upper bound of the soft noise variance $\sigma_{e,i}^2$, given by (10). We see that the upper bound given by (10) is fairly tight at high SNR. This is because that in the high SNR region, the variance of the SMI $\Theta(\Lambda_i)$ approaches zero, i.e., $E[\Theta^2(\Lambda_i)]$ approaches $E^2[\Theta(\Lambda_i)]$. Hence, the exact expression of $\sigma_{e,i}^2$, given in (5), approaches its upper bound given in (10) in the high SNR region. This implies that we can estimate $\sigma_{e,i}^2$ from the SNR or a Q-function table. It also shows that the soft noise variance $\sigma_{e,i}^2$ decays exponentially w.r.t $\gamma_{\text{in},i}$, as predicted in Theorem 1, which means that the MIF scheme compresses the noise at the relay. This is different from the AF scheme, which only forwards the scaled version of the received symbols from the source to the destination, and may amplify the noise.

The following theorem quantifies the diversity order of the MIF scheme in Rayleigh fading channels.

Theorem 2: The MIF scheme with K parallel relays can achieve a full diversity order of K in Rayleigh fading channels.

Proof: From (4), the instantaneous received SNR of the MIF scheme at the destination from the i-th relay can be derived as

$$\begin{aligned}\gamma_{\text{MIF}_i} &= \frac{|h_{\text{R}_i\text{D}}|^2\beta_i^2\psi_i^2}{|h_{\text{R}_i\text{D}}|^2\beta_i^2\psi_i^2\sigma_{e,i}^2|h_{\text{R}_i\text{D}}|^2+\sigma_n^2}\\ &= \frac{\gamma_{\text{out},i}\gamma_{\text{R}_i\text{D}}}{\gamma_{\text{out},i}+\gamma_{\text{R}_i\text{D}}+1}, \qquad (12)\end{aligned}$$

where $\gamma_{\text{R}_i\text{D}} = \frac{P_{R,i}}{\sigma_n^2}|h_{\text{R}_i\text{D}}|^2$.

The instantaneous received SNR of the AF scheme at the destination from the i-th relay is given as $\gamma_{\text{AF}_i} = \frac{\gamma_{\text{SR}_i}\gamma_{\text{R}_i\text{D}}}{\gamma_{\text{SR}_i}+\gamma_{\text{R}_i\text{D}}+1}$ [1], where $\gamma_{\text{SR}_i} = \gamma_{\text{in},i} = |h_{\text{SR}_i}|^2\frac{E_b}{N_0}$. Hence, we can write

$$\begin{aligned}\lim_{\gamma_{\text{in},i}\to\infty}\frac{\gamma_{\text{MIF}_i}}{\gamma_{\text{AF}_i}} &= \lim_{\gamma_{\text{in},i}\to\infty}\frac{\gamma_{\text{out},i}\gamma_{\text{SR}_i}+\gamma_{\text{out},i}(\gamma_{\text{R}_i\text{D}}+1)}{\gamma_{\text{out},i}\gamma_{\text{SR}_i}+\gamma_{\text{SR}_i}(\gamma_{\text{R}_i\text{D}}+1)}\\ &= \lim_{\gamma_{\text{in},i}\to\infty}\frac{\gamma_{\text{out},i}\gamma_{\text{in},i}+\gamma_{\text{out},i}(\gamma_{\text{R}_i\text{D}}+1)}{\gamma_{\text{out},i}\gamma_{\text{in},i}+\gamma_{\text{in},i}(\gamma_{\text{R}_i\text{D}}+1)}\\ &\overset{(a)}{\ge} 1, \qquad (13)\end{aligned}$$

where (a) is based on the fact that $\gamma_{\text{out},i} \ge \gamma_{\text{in},i}$, which could be deduced from (6) and has been observed in Fig. 1.

The AF scheme was shown to be able to achieve full diversity [1, 12]. It is clear from (13) that $\gamma_{\text{MIF}_i} \ge \gamma_{\text{AF}_i}$ always holds at high SNRs. As a result, one can conclude that the MIF scheme with K orthogonal parallel relays can also achieve a full diversity order of K. ■

The BER performance of the MIF scheme in Rayleigh fading channels is presented in Fig. 2. In the simulation P_S = P_R = 1 is assumed. In line with the theoretical prediction of

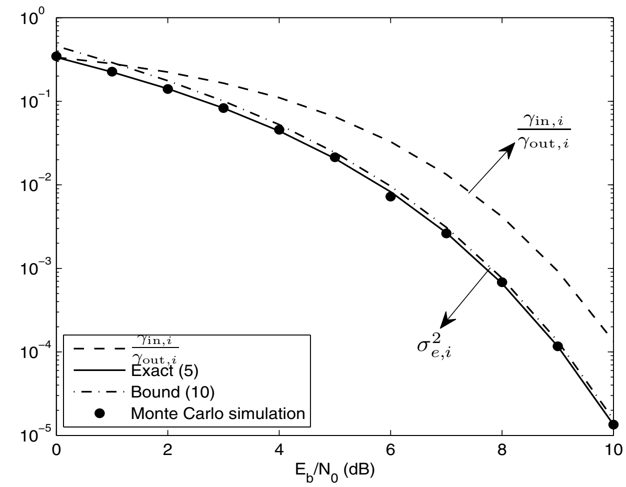

Fig. 1. Exact and upper bound of soft noise variance and input-output SNR ratio of the MIF scheme.

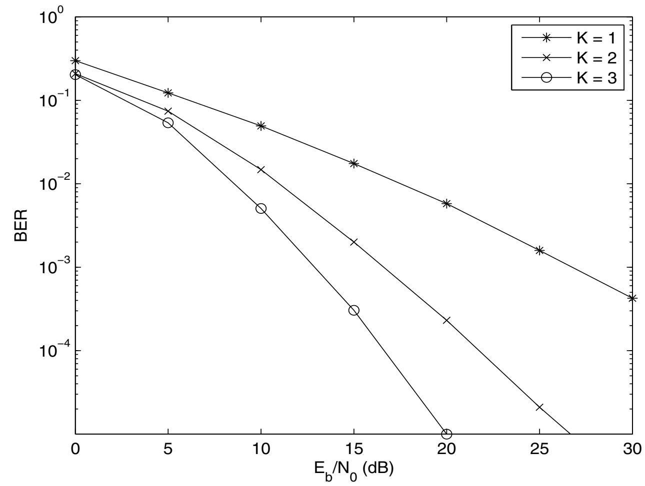

Fig. 2. BER performance comparison of the MIF scheme in Rayleigh fading channels.

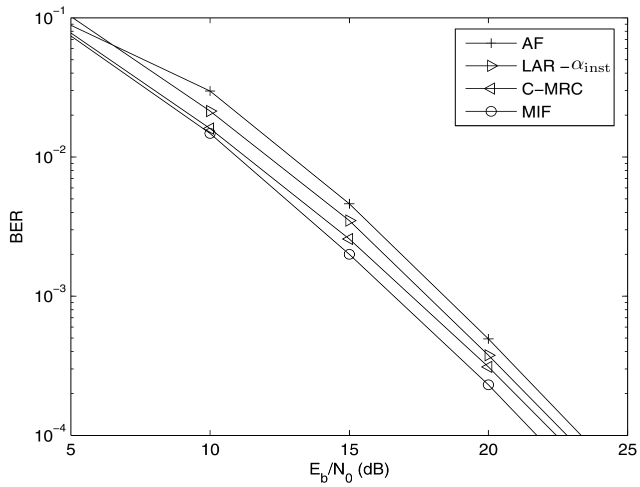

Fig. 3. BER performance comparison of various relaying techniques in Rayleigh fading channels ($K = 2$).

diversity order in Theorem 2, the simulation results show that the MIF scheme can achieve the full diversity.

Next we compare the BER performance of the MIF scheme with various full diversity-achieving relay forwarding schemes in Fig. 3 for $K = 2$. In the simulation $P_S = P_R = 1$ is assumed. We see that the MIF scheme yields around 0.8, 1.2, and 1.8 dB SNR gains over the cooperative maximum ratio combining (C-MRC) [10], link-adaptive regeneration (LAR-α_{inst}) [11], and AF [1] schemes, respectively. The improved BER performance of a parallel relay network with the MIF scheme is attributed to the MIF relay function that preserves reliability avoiding making hard decision at the relay, and also to the availability of soft noise variance at the destination.

IV. Conclusion

This letter analyzed the mutual information based soft forwarding scheme in Rayleigh fading channels. Analytical expressions for the soft noise variance of the relayed signal were derived. The derived new analytical expression for the soft noise variance only relied on the transmit SNR, and eliminated the necessity to have the access to the exact or estimated information bits. All analytical results were confirmed by the Monte Carlo simulations. Moreover, it was shown that the MIF scheme can achieve a full diversity order in Rayleigh fading channels and can achieve about $0.8 - 1.8$ dB SNR gains over various full diversity-achieving schemes.

Appendix A
Proof of Lemma 1

We can write

$$\begin{aligned}\sigma^2_{e,i}|_{(x=1)} &\triangleq E\left[e_i^2|_{(x=1)}\right] - \mu^2_{e,i}|_{(x=1)} \\ &= E\left[e_i^2\right] - \mu^2_{e,i}|_{(x=1)} \\ &= \sigma^2_{e,i} - \mu^2_{e,i}|_{(x=1)},\end{aligned} \tag{14}$$

where $\mu_{e,i|_{(x=1)}} = E[e_i|_{(x=1)}]$, and the second equality follows from the fact that the conditional and unconditional even order moments of a symmetric random variable are the same. Re-arranging (14), we can write

$$\sigma^2_{e,i} = \sigma^2_{e,i}|_{(x=1)} + \mu^2_{e,i}|_{(x=1)}. \tag{15}$$

As the soft noise is defined as

$$e_i = \frac{\tilde{x}_i}{\psi_i} - x, \tag{16}$$

if we assume all the transmitted bits are '1', i.e, $x = 1$, and take the expectation on both sides of (16), we can deduce the conditional mean of the soft noise $\mu_{e,i|_{(x=1)}}$ as

$$\mu_{e,i|_{(x=1)}} = \frac{E[\tilde{x}_i|_{(x=1)}]}{E[\tilde{x}_i|_{(x=1)}]} - 1 = 0, \tag{17}$$

and the conditional variance of the soft noise $\sigma^2_{e,i}|_{(x=1)}$ as

$$\sigma^2_{e,i}|_{(x=1)} = \frac{E[\tilde{x}_i^2|_{(x=1)}]}{\mu^2_{\tilde{x}_i}|_{(x=1)}} - 1, \tag{18}$$

where $\mu_{\tilde{x}_i}|_{(x=1)} = E[\tilde{x}_i|_{(x=1)}]$. Substituting (17) and (18) into (15) results in Lemma 1.

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