On the Aggregate SNR of Amplified Relaying Channels

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Abstract – **This paper considers the aggregate signal to noise ratio of amplified relaying channels, where the term aggregate refers to the inclusion of propagated noise terms generated as relaying terminals amplify both the information and noise portions of received signals. This consideration is motivated by recent findings for wireless relaying networks indicating that the performance of amplified relaying can approach and in some cases exceed the performance of decoded relaying [2,3,5-7]. Expressions for the aggregate signal to noise ratio are developed for general amplified relaying channels with a given set of source, destination, and relaying terminals, link connectivity, link attenuation, transmit power, and receiver noise. These expressions provide a method for analyzing the impact of varying the link connectivity or power allocation for a given set of terminals, and support the comparison of amplified relaying channels with decoded relaying channels [3].**

I. Introduction

Wireless relaying networks allow mobile terminals to participate in the transmission of information when they are neither the initial source nor the final destination. These intermediate relay terminals enable the development of new schemes and protocols with the capability to increase coverage, throughput, and capacity [1-3,5-7,9,10]. The mesh connectivity of the mobile terminals allows the application of various spatial diversity techniques without requiring the use of physical antenna arrays.

Relaying at intermediate terminals can take two general forms. *Decoded relaying* corresponds to the case where each intermediate terminal combines, digitally decodes, and re-encodes the received signals from all immediately preceding terminals before retransmission. Decoded relaying is also referred to in the literature as decode-and-forward transmission [5-7] or regenerative relaying [4]. *Amplified relaying* corresponds to the case where each intermediate terminal simply combines and amplifies the received signals from all immediately preceding terminals before retransmission. Amplified relaying is also referred to in the literature as amplify-and-forward transmission [5-7] or non-regenerative relaying [4].

Traditional packet relaying networks generally assume the application of decoded relaying. However, recent findings applicable to wireless relaying networks indicate that the performance of amplified relaying can approach and in some cases exceed the performance of decoded relaying [2,3,5-7]. Therefore, it is important to further develop our understanding of amplified relaying channels. Specifically, this paper considers the *aggregate signal to noise ratio* of amplified relaying channels, where the term aggregate refers to the inclusion of propagated noise terms. These propagated noise terms are generated as amplified relaying terminals amplify both the information and noise portions of received signals indiscriminately.

Development of the aggregate signal to noise ratio for amplified relaying channels is performed in three steps. Results are developed for channels where all inter-terminal links are connected in serial, in parallel, and arbitrarily. Figs. 1-3 show example serial, parallel, and general amplified relaying channels.

II. System Model

The system model for amplified relaying channels is composed of a source terminal, a destination terminal, and a variable number of intermediate relaying terminals. Let T_S, T_I, and T_D respectively denote the sets of source, intermediate, and destination terminals. Therefore $T_T = T_S \bigcup T_I$ denotes the set of all transmitting terminals and $T_R = T_I \bigcup T_D$ denotes the set of all receiving terminals. Let $T_{P(i)}$ denote the set of terminals that transmit a signal received by terminal T_i. Finally, let $T_{R(i)}$ denote the set that includes terminal T_i and the receiving terminals that precede terminal T_i in the channel. This defined set notation is used in variable subscripts of the form x_{T_i} to denote specific terminals or groups of terminals. Notation of the form x_{T_i} is abbreviated to x_i for simplicity of exposition.

Each terminal T_i transmits a discrete-time signal with complex baseband amplitude given by

$$s_i = \sqrt{\varepsilon_i}\,(\alpha_i + \beta_i), \tag{1}$$

where ε_i is the transmitted power, α_i is the complex amplitude of the information symbol over a given signaling interval, and β_i is propagated noise. This model normalizes the transmitted signal such that $|\alpha_i|^2 + E[|\beta_i|^2] = 1$. For source terminals, which do not propagate noise, $\beta_i = 0$ and $|\alpha_i|^2 = 1$. The definition of ε_i has been modified from [2] such that it is now the transmitted power of both the information and propagated noise portions of the transmitted signal, instead of only the information portion. The result is equations for amplified relaying channels that are more amenable to analysis and transmit power optimization.

Each inter-terminal link experiences distance-dependant attenuation, shadowing, and fading. The statistics of different inter-terminal links are considered to be mutually independent. Each terminal T_i then receives from each immediately preceding terminal $T_k \in T_{P(i)}$ a discrete-time signal with complex baseband amplitude given by

$$r_{k,i} = a_{k,i}\sqrt{\varepsilon_k}(\alpha_k + \beta_k) + z_{k,i}, \tag{2}$$

where $a_{k,i}$ captures the effects of distance-dependant attenuation, shadowing, and fading between T_k and T_i, and $z_{k,i}$ is a zero-mean Gaussian random variable with variance $N_{k,i}$ that captures the combined effects of local thermal noise and other interference.

The *aggregate signal to noise ratio* at T_i for the signal from each immediately preceding terminal $T_k \in T_{P(i)}$ is defined as

$$\gamma_{k,i} = \frac{\varepsilon_k |\alpha_k|^2}{\varepsilon_k E[|\beta_k|^2] + N_{k,i} / |a_{k,i}|^2}. \tag{3}$$

Note that the formulation of the aggregate signal to noise ratio includes propagated noise terms. The *link signal to noise ratio* at T_i for the link from each immediately preceding terminal $T_k \in T_{P(i)}$ is defined as

$$\psi_{k,i} = \frac{\varepsilon_k}{N_{k,i} / |a_{k,i}|^2}. \tag{4}$$

Note that the link SNR is identical to the aggregate SNR when there is no propagated noise, $\beta_k = 0$.

Each intermediate terminal amplifies the set of received signals, relaying both information and noise portions towards the destination terminal. The amplification factor at each intermediate terminal T_i is simply the transmitted power over the received power and is given by

$$A_i = \frac{\varepsilon_i}{\sum_{T_k \in T_{P(i)}} (|a_{k,i}|^2 \varepsilon_k + N_{k,i})}. \tag{5}$$

III. Aggregate SNR Results

Theorem 1 – Serial Amplified Relaying Channels: The aggregate SNR at terminal T_i for a set of preceding amplified relaying terminals in serial is given by

$$\gamma_{P(i),i} = (\psi_{k,i}^{-1} + \gamma_{P(k),k}^{-1} + \psi_{k,i}^{-1}\gamma_{P(k),k}^{-1})^{-1}, T_k \in T_{P(i)}, \tag{6}$$

where $\gamma_{P(k),k}$ is the aggregate SNR of the immediately preceding terminal T_k. Note that each terminal has only a single immediately preceding terminal so that the cardinality of $T_{P(i)}$ is one. These recursive terms can be expanded to result in a sum of products form given by

$$\begin{aligned}\gamma_{P(i),i} = (&\sum_{T_j \in T_{R(i)}} \psi_{P(j),j}^{-1} + \sum_{\substack{T_j, T_k \in T_{R(i)} \\ T_j \neq T_k}} \psi_{P(j),j}^{-1}\psi_{P(k),k}^{-1} \\ &+ \sum_{\substack{T_j, T_k, T_l \in T_{R(i)} \\ T_j \neq T_k \neq T_l}} \psi_{P(j),j}^{-1}\psi_{P(k),k}^{-1}\psi_{P(l),l}^{-1} + \ldots)^{-1},\end{aligned} \tag{7}$$

where there is one multiplicative term for each possible unordered combination of serial links. This expression generalizes some of the results of [5,7]. When there are only two hops this reduces to the results for amplify-and-forward transmission presented in [5,7].

Proof: Consider an amplified relaying channel with *n* links in serial with source terminal T_1, intermediate terminals T_2 through T_n, and destination terminal T_{n+1}. Note that $T_{P(k)} = T_{k-1}$ since each receiving terminal has a single immediately preceding terminal. Selecting any intermediate terminal, the signal received by terminal T_k is given by

$$r_{P(k),k} = a_{P(k),k}\sqrt{\varepsilon_{P(k)}}(\alpha_{P(k)} + \beta_{P(k)}) + z_{P(k),k},$$

and the aggregate SNR at terminal T_k is given by

$$\gamma_{P(k),k} = \frac{|\alpha_{P(k)}|^2}{E[|\beta_{P(k)}|^2] + N_{P(k),k} / |a_{P(k),k}|^2 \varepsilon_{P(k)}}.$$

If this signal is amplified according to (5) then the signal transmitted by terminal T_k is given by

$$\begin{aligned}s_k = &(a_{P(k),k}\sqrt{\varepsilon_{P(k)}}(\alpha_{P(k)} + \beta_{P(k)}) + z_{P(k),k}) \\ &\times (\sqrt{\varepsilon_k} / \sqrt{|a_{P(k),k}|^2 \varepsilon_{P(k)} + N_{P(k),k}}),\end{aligned}$$

the signal received by terminal T_i, $T_k \in T_{P(i)}$ is given by

$$\begin{aligned}r_{k,i} = &a_{k,i}(a_{P(k),k}\sqrt{\varepsilon_{P(k)}}(\alpha_{P(k)} + \beta_{P(k)}) + z_{P(k),k}) \\ &\times (\sqrt{\varepsilon_k} / \sqrt{|a_{P(k),k}|^2 \varepsilon_{P(k)} + N_{P(k),k}}) + z_{k,i},\end{aligned}$$

and the aggregate SNR at terminal T_i is given by

$$\begin{aligned}\gamma_{k,i} &= |\alpha_{P(k)}|^2 \begin{pmatrix} E[|\beta_{P(k)}|^2] + N_{P(k),k} / (|a_{P(k),k}|^2 \varepsilon_{P(k)}) \\ + (1 + N_{P(k),k} / (|a_{P(k),k}|^2 \varepsilon_{P(k)}))(N_{k,i} / |a_{k,i}|^2 \varepsilon_k) \end{pmatrix}^{-1} \\ &= \begin{pmatrix} \dfrac{E[|\beta_{P(k)}|^2] + N_{P(k),k} / (|a_{P(k),k}|^2 \varepsilon_{P(k)})}{|\alpha_{P(k)}|^2} + (\dfrac{N_{k,i}}{|a_{k,i}|^2 \varepsilon_k}) \\ + (\dfrac{E[|\beta_{P(k)}|^2] + N_{P(k),k} / (|a_{P(k),k}|^2 \varepsilon_{P(k)})}{|\alpha_{P(k)}|^2})(\dfrac{N_{k,i}}{|a_{k,i}|^2 \varepsilon_k}) \end{pmatrix}^{-1} \\ &= (\gamma_{P(k),k}^{-1} + \psi_{k,i}^{-1} + \gamma_{P(k),k}^{-1}\psi_{k,i}^{-1})^{-1}.\end{aligned}$$

Note the use of the normalization $|\alpha_i|^2 + E[|\beta_i|^2] = 1$ in the derivation. Rearranging the order of terms results in the given theorem.

Lemma 1 – Parallel Amplified Relaying Channels: The aggregate SNR at terminal T_i for a set of preceding amplified relaying terminals in parallel is lower bounded by

$$\gamma_{P(i),i} \geq \sum_{T_k \in T_{P(i)}} \gamma_{k,i}. \tag{8}$$

Note that this form implies diversity combining of the multiple input signal links using a maximal ratio combiner.

Proof: First consider the case where the propagated noise components of the signals from the parallel preceding terminals are mutually independent. It is well known that the optimal combiner for a set of input signals with noise components that are mutually independent is a maximal ratio combiner with output signal to noise ratio equal to the sum of the input branch signal to noise ratios [8]. Therefore, when the propagated noise components from the parallel preceding terminals are mutually independent the optimal combiner is a maximal ratio combiner and the received signal to noise ratio is equal to the sum of the input branch signal to noise ratios.

Now consider the case where the propagated noise components of the signals from the parallel preceding terminals are correlated. Although the derivation of the optimal combiner that leverages this correlation and resultant output signal to noise ratio are beyond the scope of this paper, the output signal to noise ratio of the optimal combiner can be lower bounded in the following fashion. It is well known that the lowest output signal to noise ratio of an optimal combiner occurs when the noise components for the set of input signals are mutually independent [8]. Therefore, the sum of the input signal to noise ratios is a lower bound on the received signal to noise ratio.

Generalizing the described equality for mutually independent input signal links and lower bound for correlated input signal links results in the given lemma.

Corollary 1 – General Amplified Relaying Channels: The aggregate SNR at terminal T_i for a general set of preceding amplified relaying terminals is lower bounded by

$$\gamma_{P(i),i} \geq \sum_{T_k \in T_{P(i)}} (\psi_{k,i}^{-1} + \gamma_{P(k),k}^{-1} + \psi_{k,i}^{-1}\gamma_{P(k),k}^{-1})^{-1}. \tag{9}$$

This result provides a method for analyzing the impact of varying the link connectivity or power allocation for a given set of terminals. Note that the *amplified relaying multihop diversity channel* presented in [2,3] is a special case of general amplified relaying channel where all intermediate terminals belong to a single primary route from source to destination and all terminals are fully connected.

Proof: Combining the results of Theorem 1 and Lemma 1, the aggregate SNR of general amplified relaying channels can be considered in the light of resistance theory for electrical circuits. Signal links in serial are analogous to resistors in parallel (with additional multiplicative terms). Signal links in parallel are analogous to resistors in serial. Deriving the aggregate SNR in a recursive fashion by employing Theorem 1 and Lemma 1 results in the given corollary.

IV. Discussion

Some interesting qualitative statements can be extrapolated from the form of the developed results. The performance of serial amplified relaying channels is sensitive to the performance of the single weakest link. Therefore, the performance will be improved when more power is allocated to the weakest link relative to the other links. The performance of parallel-amplified relaying channels is insensitive to the performance of the single weakest link. Therefore, the performance will be improved when less power is allocated to the weakest link relative to the other links. This can be applied to general amplified relaying channels where the performance will be improved by allocating relatively more power to weak links that are not parallel to strong links and relatively less power to weak links that are parallel to strong links.

When a serial amplified relaying channel is composed of strong links the lower order multiplicative terms dominate the aggregate SNR and the performance is approximately linear with respect to the component link SNRs. When a serial amplified relaying channel is composed of weak links the higher order multiplicative terms dominate the aggregate SNR and the performance is less than linear with respect to the component link SNRs. This means that for amplified relaying channels where there are many weak links in serial the performance will be significantly degraded with respect to a linear relation.

V. Examples

The results presented in Section III are applied to determine the aggregate SNR of a set of example amplified relaying channels. These examples illustrate the increase in the aggregate SNR as the link connectivity is improved from the minimally connected serial amplified relaying channel of Fig. 1, through the partial connectivity of Figs. 2, 3, and 4, to the fully connected amplified relaying channel of Fig. 5. The examples also allow analysis of the qualitative statements presented in Section IV.

Fig. 1 and Fig. 5 respectively correspond to the multihop and multihop diversity channels of [2,3]. Fig. 2 corresponds to the multi-user diversity channel of [1]. Figs. 2 and 3 are examples of possible connectivity when only destination terminals perform combining.

The aggregate SNR at terminal T_4 for the serial amplified relaying channel in Fig. 1 is given by

$$\begin{aligned}\gamma_{P(4),4} &= (\psi_{3,4}^{-1} + \gamma_{P(3),3}^{-1} + \psi_{3,4}^{-1}\gamma_{P(3),3}^{-1})^{-1} \\ &= (\psi_{3,4}^{-1} + (\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1}) \\ &\quad + \psi_{3,4}^{-1}(\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1}))^{-1}.\end{aligned}$$

The aggregate SNR at terminal T_4 for the parallel amplified relaying channel in Fig. 2 is given by

$$\begin{aligned}\gamma_{P(4),4} &= (\psi_{2,4}^{-1} + \gamma_{P(2),2}^{-1} + \psi_{2,4}^{-1}\gamma_{P(2),2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + \gamma_{P(3),3}^{-1} + \psi_{3,4}^{-1}\gamma_{P(3),3}^{-1})^{-1} \\ &= (\psi_{2,4}^{-1} + \psi_{1,2}^{-1} + \psi_{2,4}^{-1}\psi_{1,2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + \psi_{1,3}^{-1} + \psi_{3,4}^{-1}\psi_{1,3}^{-1})^{-1}.\end{aligned}$$

The aggregate SNR at terminal T_4 for the partially connected amplified relaying channel in Fig. 3 is given by

$$\begin{aligned}\gamma_{P(4),4} &= (\psi_{2,4}^{-1} + \gamma_{P(2),2}^{-1} + \psi_{2,4}^{-1}\gamma_{P(2),2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + \gamma_{P(3),3}^{-1} + \psi_{3,4}^{-1}\gamma_{P(3),3}^{-1})^{-1} \\ &= (\psi_{2,4}^{-1} + \psi_{1,2}^{-1} + \psi_{2,4}^{-1}\psi_{1,2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + (\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1}) \\ &\quad + \psi_{3,4}^{-1}(\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1}))^{-1}.\end{aligned}$$

The aggregate SNR at terminal T_4 for the partially connected amplified relaying channel in Fig. 4 is given by

$$\begin{aligned}\gamma_{P(4),4} &= (\psi_{2,4}^{-1} + \gamma_{P(2),2}^{-1} + \psi_{2,4}^{-1}\gamma_{P(2),2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + \gamma_{P(3),3}^{-1} + \psi_{3,4}^{-1}\gamma_{P(3),3}^{-1})^{-1} \\ &= (\psi_{2,4}^{-1} + \psi_{1,2}^{-1} + \psi_{2,4}^{-1}\psi_{1,2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + (\psi_{1,3} + (\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1})^{-1})^{-1} \\ &\quad + \psi_{3,4}^{-1}(\psi_{1,3} + (\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1})^{-1})^{-1})^{-1}.\end{aligned}$$

The aggregate SNR at terminal T_4 for the fully connected amplified relaying channel in Fig. 5 is given by

$$\begin{aligned}\gamma_{P(4),4} &= \psi_{1,4} + (\psi_{2,4}^{-1} + \gamma_{P(2),2}^{-1} + \psi_{2,4}^{-1}\gamma_{P(2),2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + \gamma_{P(3),3}^{-1} + \psi_{3,4}^{-1}\gamma_{P(3),3}^{-1})^{-1} \\ &= \psi_{1,4} + (\psi_{2,4}^{-1} + \psi_{1,2}^{-1} + \psi_{2,4}^{-1}\psi_{1,2}^{-1})^{-1} \\ &\quad + (\psi_{3,4}^{-1} + (\psi_{1,3} + (\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1})^{-1})^{-1} \\ &\quad + \psi_{3,4}^{-1}(\psi_{1,3} + (\psi_{2,3}^{-1} + \psi_{1,2}^{-1} + \psi_{2,3}^{-1}\psi_{1,2}^{-1})^{-1})^{-1})^{-1}.\end{aligned}$$

Fig. 6 compares the aggregate SNR of the example amplified relaying channels of Figs. 1 to 5. Link attenuations, noise variances, and transmit powers are identical for all channels to allow fair comparison. The graph shows the resultant aggregate SNR versus the component link SNRs. In order to clearly highlight the comparison of link connectivity the link SNRs are assumed to be uniform such that

$$\psi_{1,2} = \psi_{1,3} = \psi_{2,3} = \psi_{2,4} = \psi_{3,4}, \text{ and}$$

$$\psi_{1,4} = 0.5 \times (\psi_{1,2}^{-1} + \psi_{2,4}^{-1} + \psi_{1,2}^{-1}\psi_{2,4}^{-1})^{-1}.$$

The performance increase of Fig. 3 compared to Fig. 1 when the link is added between terminal T_2 and terminal T_4 is significant. The performance increase of Fig. 4 compared to Fig. 3 when the link is added between terminal T_1 and terminal T_3 is moderate. The performance increase of Fig. 4 compared to Fig. 2 when the link is added between terminal T_2 and terminal T_3 and the performance increase of Fig. 5 compared to Fig. 4 when the link is added between terminal T_1 and terminal T_4 are relatively less significant. Generally, the performance of amplified relaying channels is less sensitive to the performance of links that have higher parallel redundancy with other links.

Fig. 6 also indicates that the parallel amplified relaying channel of Fig. 2 has the best performance of the considered amplified relaying channels under the constraint that relay terminals are not able to perform combining. However, it is important to note that this result is dependent on the specific link SNRs that were used. This result would not hold if the link between terminal T_1 and terminal T_3 were poor.

Fig. 7 compares the actual aggregate SNR of the example amplified relaying channels with the linear approximate aggregate SNR that would result if the higher order multiplicative terms of (7) were removed such that there was a linear relation between the link SNRs and resultant aggregate SNR. The dotted lines show this linear approximate aggregate SNR. For clarity, only Figs. 1, 2, and 5 are shown with their corresponding linear relations. For high component link SNRs the resultant aggregate SNRs are approximately linear with respect to the link SNRs. For low component link SNRs that resultant aggregate SNRs are significantly less than linear with respect to the link SNRs. This result indicates that amplified relaying may be less appropriate for very low SNR channel conditions.

VI. Conclusion

Expressions for the aggregate signal to noise ratio are developed for general amplified relaying channels with a given set of source, destination, and relaying terminals, link connectivity, link attenuation, transmit power, and receiver noise. These expressions provide a method for analyzing the impact of varying the link connectivity or power allocation for a given set of terminals, and support the comparison of amplified relaying channels with decoded relaying channels [3]. The performance of amplified relaying channels is shown to be generally less sensitive to the performance of links that have higher parallel redundancy with other links. The relation of the aggregate SNR with the component link SNRs is shown to be approximately linear for high link SNRs but significantly less than linear for low link SNRs, implying that amplified relaying may be less appropriate for very low SNR channel conditions. Finally, these expressions can be used to extend some of the results of [5,7] to more than two hops.

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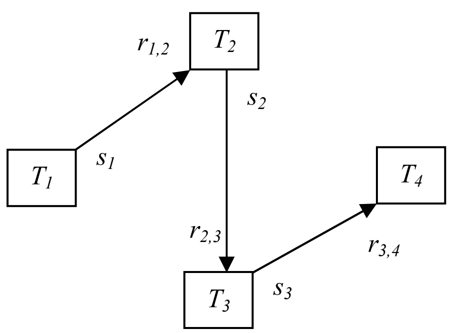

Fig. 1. Serial Amplified Relaying Channel

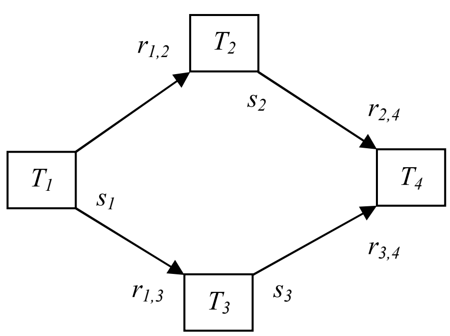

Fig. 2. Parallel Amplified Relaying Channel

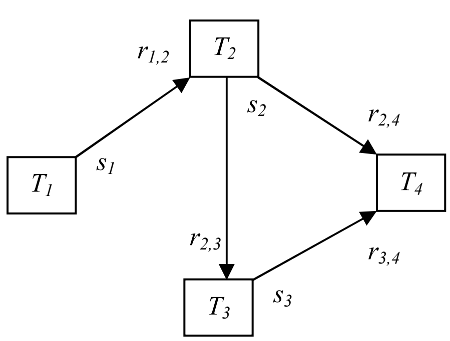

Fig. 3. General Amplified Relaying Channel

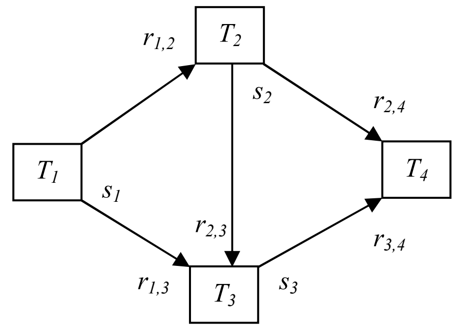

Fig. 4. Another General Amplified Relaying Channel

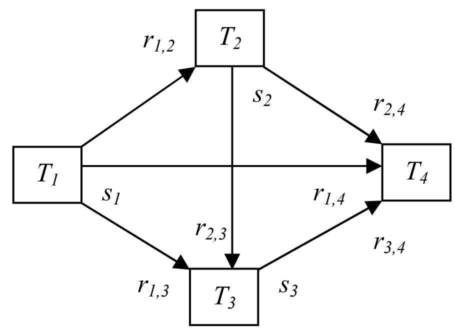

Fig. 5. Fully Connected Amplified Relaying Channel

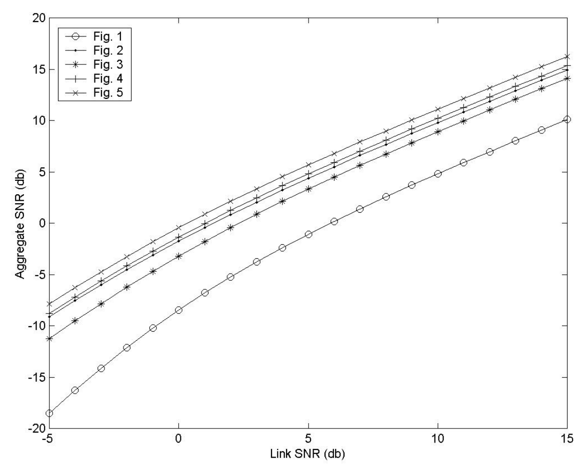

Fig. 6. Aggregate SNR vs. Link SNR

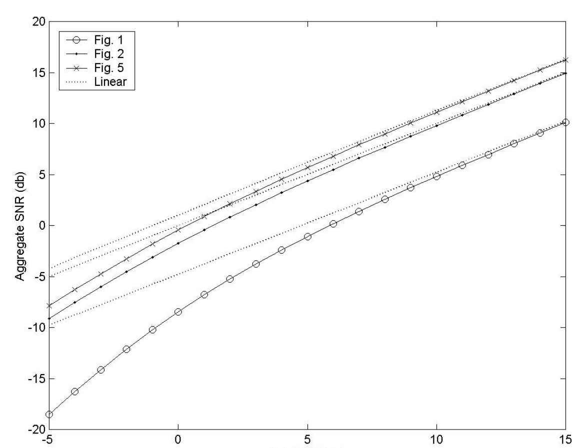

Fig. 7. Comparison with a Linear Relation