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AWGN and Rayleigh Fading Behavior of the Wireless Decode-and-Forward Relay Channel with Arbitrary Time and Power Allocation

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Article Info	ABSTRACT
	Relying has in use for decades to tackle some of the challenges of wireless communication such as extending transmitting distance, transmitting over rough terrains. Diversity achieved through relaying is also a means to combat the random behavior of fading channels. In this work, effect of time and power allocation on relay performance is studied. The channel considered is the three-node channel with half-duplex constraint on the relay. The relaying technique assumed is decode-and-forward. Mutual information is used as the criteria to measure channel performance. There is half-duplex constraint and a total transmission power constraint on the relay source node and the relay node. A model is established to analyze the mutual information as a function of time allocation and power allocation in the case of AWGN regime. The model is extended to the Rayleigh fading scenario. In both AWGN and Rayleigh fading, results showed that the importance of relaying is more apparent when more resources are allocated to the relay. It was also shown that quality of the source to destination link has direct impact on the decision to relay or not to relay. Relatively good source to destination channel makes relaying less useful. The opposite is true for the other two links, namely the source to relay channel and the relay to destination channel. When these two channels are good, relaying becomes advantageous. When applied to cellular systems, we concluded that relaying is more beneficial to battery-operated mobile nodes than to base stations.

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1. INTRODUCTION

Relay applications are widely used in wireless communication. Relaying is very efficient in extending the transmission range over rough terrains or simply when the curvature of the earth become the obstacle for long range transmission. Example systems include multi-hop trunk systems and satellite communication systems. Recently, relaying is also proposed as a means to improve transmission reliability. More recent works has also suggested combined data transmission and power transfer through relaying by employing energy harvesting techniques [1]-[3].

In cases where fading is the dominant channel effect, outage can be reduced by offering diversity transmission through relaying [4]. Applications extends over many systems from cellular systems to sensor networks [1]-[2]. For instance, relaying is used in 4G and 5G mobile communication standards. The

combination of relay scheme of HDC (Hybrid DF-CF) and HDA (Hybrid DF-AF) improve the transmission rate significantly. Particularly, relaying is very helpful in improving connectivity with cell-edge users [6].

Recently studies showed that cooperative relaying is advantageous over non-cooperative relaying [7]. In cooperative relaying, the destination node receives multiple copies of the transmitted signal from repeated transmission of the source's message. In contrary, the destination in non-cooperative transmission uses only signal received from the relay to decode the source's message. It was shown that cooperative relaying can achieve high gains in sensor networks [5] in terms of increased throughput and longer lifetime.

The three-node channel studied is the simplest relay channel. It consists of a source node, a relay node and a destination node. Van der Muelen introduced this model and later it was extensively investigated by Cover and El-Gamal [8],[9]. Broadly speaking, there are three techniques used by the relay node to aid the transmission from the source node to the destination node. These are Amplify-and-Forward (A&F) relaying, Decode-and-Forward (D&F) relaying and coded relaying [8]. Each technique describes a different relay behavior and they differ in terms of performance and the degree of complexity. In practice, D&F has received more attention due to its good performance and reasonable implementation complexity compared with the other two techniques. In this work we consider D&F relaying.

One of the challenges faced by relay transmission is when the relay node is a half-duplex wireless transceiver. A half-duplex relay node cannot receive and transmit at the same time in the same frequency band. Accordingly, the source node and relay node have to share the available degree of freedom [6]. For instance, when available transmission time is shared, the source node transmit for a fraction of the available time and then goes into idle state. Following, the relay node transmits for the remaining time.

Having the source node and the relay node to take turns to transmit wastes valuable resources. Therefore, relay channels with half-duplex constraint may lead to degradation in channel performance [10]. For a particular case, relaying is deemed useful if using relaying is advantageous over direct transmission. Specifically, relaying is useful if the transmission rate achievable through relaying is higher that the transmission rate achievable via direct transmission. One objective of this study is to investigate the conditions that leads to useful relaying. Useful relaying requires careful allocation of resources. Optimal resource allocation has been under investigation by many researchers, for example [1], [10]–[13]. The problem of resource allocation is also related to routing in multi-hop relaying [14].

This paper extends the work in [13]. The aim is to investigate the performance of the three-node D&F relay channel with half-duplex constraint under different time and power allocation policies. Channel performance is measured in terms of mutual information. In information theory, mutual information is a measure of the mutual independence between two variables [15], [16]. In [13], for the communication links between channel nodes, it is assumed that the channel is governed by Additive White Gaussian Noise (AWGN) regime. This paper extends the work to include Rayleigh fading as well. In the fading case, average mutual information is used as the performance measure. Alternatively, outage probability can also be used for performance evaluation as done, for example, in [12].

To achieve our objectives, a proper mathematical model is established. Derived equations are then used to plot performance graphs which are analyzed to come with conclusions. The rest of this paper is organized as follows. In Section 2, mutual information formula are derived as a function of time and power allocation. Simulation results and discussion on results is in Section 3. Finally, concluding remarks are given in Section 4.

2. CHANNEL MODEL

In this section, model of the wireless D&F relay channel is demonstrated. As illustrated in Figure 1, the 3-node relay channels consists of three nodes: the source node (S) that has a message to send, the destination node (D) intended to receive the source's message; and the relay node (R) to aid the transmission from the source to the destination.
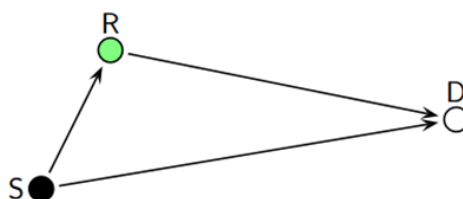

Figure 1. Representation of the three-node relay channel

The relay node is half-duplex constraint, meaning that it can either transmit or receive at one time. It cannot do both transmit and receive at the same time in the same frequency band. As a consequence, transmission from the source to the destination takes place in two phases. First, the source transmits the message to both the relay node and the destination node. Then, in the second phase, after successfully decoding the source's message sent in the first phase, the relay node re-sends that message to the destination node. In the second phase the source node remains idle. As a result of this two-phase transmission, the destination node receives two copies of the source message; one received directly from the source node and another through the relay node. The destination uses both signals to decode the source's message. There are three main techniques that can be used by the destination node to combine these two copies of the sent message; namely Selection Combining (SC), Equal-Gain Combining (EGC) and Maximal-Ratio Combining (MRC). MRC performance is better than the other two techniques. We assume that the destination applies MRC to decode the source's message.

The above described transmission method is known as cooperative transmission or cooperative relaying. In contrast, in non-cooperative relaying, the destination ignores the signal received directly from the source node and rely solely on that received from the relay node to decode the message.

As explained in Figure 2, the channel can be view from two perspectives: Broadcast Channel (BC) where the source node transmits to two destinations, the relay node and the destination nodes; and a Multiple-Access Channel (MC) where the destination receives from two nodes, the source node and the relay node.

a) Broadcast channel.   b) Multiple-Access Channel.

Figure 2. The 3-node relay channel can be viewed as a combination of two channels, a broadcast channel with the source transmitting to the relay and the destination; and a multiple-acess channel with source and the relay transmitting to the destination

2.1. Allocation of Available Time

Conventionally, available degree-of-freedom is allocated equally between the source node and the relay node. For example, available transmission time can be divided into two halves whereas the source node transmits during the first half and the relay node transmits during the second half. For optimizing channel operation we assume arbitrary time allocation instead. Fraction (not necessary half) of the available time (or spectrum) is allocated to the source and the remaining time is used by the relay transmission.

Let $\tau \in [0,1]$ be the time used by the relay for repeating the source message. Then the source has $(1 - \tau)$ fraction of the time to transmit. The relay must be able to fully decode source's signal in the first phase before it can assist in the second phase.

τ can be seen as a measure of cooperation. Greater τ indicates more cooperation from the relay node. $\tau = 0$ is the case of no cooperation while $\tau = 1$ is the full cooperation scenario. $\tau = 1/2$ is the conventional equal-time allocation set up. Note more cooperation does not necessary mean improved performance. For example, the rate for the full cooperation case is zero, since the source is allocated zero-time to transmit. The mutual information between the source and the destination as a function of τ is given by [10],[11],

$$I_{S,R:D}(\tau) = \begin{cases} \min\{I_{S,R}(\tau), I_0(\tau)\}, & \tau < 0 \\ I_{S,D}, & \tau = 0 \end{cases} \tag{1}$$

where, $I_{S,R}(\tau)$ is the mutual information from the source to the relay. $I_0(\tau)$ is the mutual information from the source to the destination after receiving two copies of the message, one from the source and another one from the relay. Finally, $I_{S,D}$ is the direct transmission rate from the source to the destination. $I_{S,D}$ assumes the relay has no role on the transmission. $I_{S,D}$ is given by,

$$I_{S,D} = \log_2(1 + \gamma_{S,D}) \tag{2}$$

where $\gamma_{S,D}$ IS the received Signal-to-Noise Ratio (SNR) at the destination node from the source transmission. $I_{S,R}(\tau)$ is given by,

$$I_{S,R}(\tau) = (1 - \tau) \log_2 (1 + \gamma_{S,R}) \tag{3}$$

where $\gamma_{S,R}$ the received SNR at the relay node from the source transmission. Finally, $I_0(\tau)$, on the other hand, is given by,

$$I_0(\tau) = (1 - \tau) \log_2 \; [\gamma_{S,D} + (1 + \gamma_{R,D})]^{\frac{\tau}{1-\tau}} \tag{4}$$

where $\gamma_{R,D}$ is the SNRs from the relay to the destination. Note that $I_{S,D}$ in (2) is not function of τ since all time is allocated to source in this case. The scenario described by (1) is for an adaptive relay channel where the source revert to direct transmission if $\tau = 0$. In other words, the source ignores the presence of the relay if it is not assisting the transmission.

2.2. Allocation of Transmission Power

$\acute{\gamma}_{S,R}$ in (3) is the received SNR at the relay given transmission from the source node. It is a result of several factors including the source node transmission power, the distance between the two nodes, noise, signal power degradation rate over distance and channel fading. $\acute{\gamma}_{S,R}$ can be expressed as,

$$\acute{\gamma}_{S,R} = \frac{P_S}{d_{S,R}^{\alpha}} \frac{h_{S,R}}{N_0} \tag{5}$$

where, P_s is the source node transmission power, $d_{S,R}$ is the distance between the source node and the destination node, α is the power loss factor, N_0 is the noise power and $h_{S,R}$ is a factor to capture other channel effects such as long-term and short-term fading. In an AWGN regime we can assume $h_{S,R} = 1$. Similarly, $\gamma_{S,D}$ and $\gamma_{R,D}$ are given, respectively, by,

$$\acute{\gamma}_{S,D} = \frac{P_S}{d_{S,D}^{\alpha}} \frac{h_{S,D}}{N_0} \tag{6}$$

and

$$\acute{\gamma}_{R,D} = \frac{P_R}{d_{R,D}^{\alpha}} \frac{h_{R,D}}{N_0} \tag{7}$$

P_R in (7) is relay transmission power. This work considers a constraint on the channel total transmission power, P. That implies,

$$P \leq P_S + P_R \tag{8}$$

Let a be the power allocation factor. In this case, $a \in [0,1]$ is the fraction of power allocated to the relay node. Accordingly,

$$\gamma_{S,R} = (1 - a)\acute{\gamma}_{S,R} \tag{9}$$

where,

$$\acute{\gamma}_{S,R} = \frac{P_S}{d_{S,R}^{\alpha}} \frac{h_{S,R}}{N_0} \tag{10}$$

Similarly, $\gamma_{S,D}$ and $\gamma_{R,D}$ can be written as,

$$\gamma_{S,D} = (1 - a)\acute{\gamma}_{S,D} \tag{11}$$

and

$$\gamma_{R,D} = a\acute{\gamma}_{R,D} \tag{12}$$

Respectively. Similar to τ, a also measures the degree of cooperation where $a = 0$ and $a = 1$ indicate no cooperation and full cooperation, respectively. Accordingly, we may re-write (1) as below,

$$I_{S,R:D}(\tau, a) = \begin{cases} \min\{I_{S,R}(\tau, a), I_0(\tau, a)\}, & \tau < 0 \\ I_{S,D}, & \tau = 0 \end{cases} \qquad (13)$$

where,

$$I_{S,R}(\tau, a) = (1 - \tau) \log_2\big(1 + (1 - a)\acute{\gamma}_{S,R}\big) \qquad (14)$$

$$I_0(\tau, a) = (1 - \tau) \log_2 \big[(1 - a)\acute{\gamma}_{S,D} + (1 + a\acute{\gamma}_{R,D})\big]^{\frac{\tau}{1 - \tau}} \qquad (15)$$

2.3. Fading Channels

In a AWGN regime, $h_{S,R}$, $h_{S,D}$, and $h_{R,D}$ in (5), (6) and (7), respectively; are fixed. Therefore, $\acute{\gamma}_{S,R}$, $\acute{\gamma}_{S,D}$, and $\acute{\gamma}_{R,D}$ are fixed too. In the contrary, in a fading scenario, $h_{S,R}$, $h_{S,D}$, and $h_{R,D}$; and consequently , $\acute{\gamma}_{S,R}$, $\acute{\gamma}_{S,D}$, and $\acute{\gamma}_{R,D}$; are all changing randomly.

Rayleigh fading model is commonly used to model the fading effect. In Rayleigh fading, $\gamma_{i,j}$, where $(i, j) = (S, R), (S, D)$ or (R, D), is an exponential random variable. For a random variable X, the probability distribution function is given by,

$$f_X(x) = \begin{cases} \lambda e^{-\lambda x}, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (16)$$

where,

$$\lambda = \frac{1}{E[X]} \qquad (17)$$

and $E[X]$ is the expected value of the random variable X. For the source-to-relay, source-to-destination and relay-to-destination links the distribution is given, respectively, by,

$$f_{S,R}(x) = \begin{cases} \lambda_{S,R} e^{-\lambda_{S,D} x}, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (18)$$

$$f_{S,D}(x) = \begin{cases} \lambda_{S,D} e^{-\lambda_{S,D} x}, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (19)$$

$$f_{R,D}(x) = \begin{cases} \lambda_{R,D} e^{-\lambda_{S,D} x}, & x \geq 0 \\ 0, & x < 0 \end{cases} \qquad (20)$$

where,

$$\lambda_{S,R} = \frac{1}{E[\acute{\gamma}_{S,R}]} = \frac{d_{S,R}^{\alpha} \times N_0}{P_S \times E[h_{S,R}]} \qquad (21)$$

$$\lambda_{S,D} = \frac{1}{E[\acute{\gamma}_{S,D}]} = \frac{d_{S,D}^{\alpha} \times N_0}{P_S \times E[h_{S,D}]} \qquad (22)$$

$$\lambda_{R,D} = \frac{1}{E[\acute{\gamma}_{R,D}]} = \frac{d_{R,D}^{\alpha} \times N_0}{P_R \times E[h_{R,D}]} \qquad (23)$$

The distribution of $I_{S,R:D}$ is given in [10]. One way to evaluate channel performance in a fading is to consider the average mutual information, $E[I_{S,R:D}]$.

It is worth noting that mathematically, channel performance in the fading case is worse than the AWGN case if aveage SNR in the fading case is same as the SNR in AWGN. This This prediction is made based on Jensen's inequality which states that for a random variable X and any function $f(.)$,

$$E[f(X)] \leq f(E[X]) \qquad (24)$$

3.   SIMULATION RESULTS AND DISCUSSION

In this section simulation results are presented. Plotting of mutual information of the channel against τ and a help understand the effect of changing time allocation and power allocation on channel performance. Consequently, optimal operation of the channel may be achieved.

3.1. Channel Behaviour in AWGN Environment

To understand the behaviour of the channel $I_{S,R;D}$ is first plotted versus τ using (13) as shown in Figure 3. $\acute{y}_{S,R}$, $\acute{y}_{S,D}$, and $\acute{y}_{R,D}$ are set as 13, 5, and 11, respectively. This is a typical case where the link between the source node and the relay node is particularly weak due to for example, shadowing effect. In this case relaying can be considered as an effective method to improve transmission performance. In a AWGN regime, $\acute{y}_{S,R}$, $\acute{y}_{S,D}$, and $\acute{y}_{R,D}$ are fixed throughout the simulation. The AWGN assumption changing slowly (slow fading channel) and therefore remain constant throughout the simulation time.
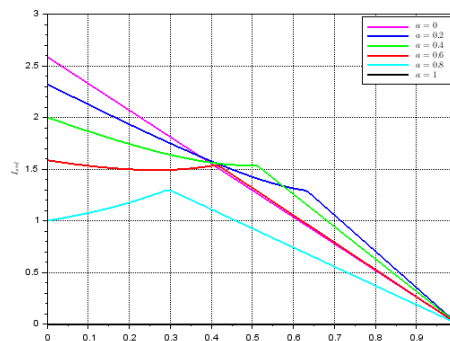

Figure 3. Mutual information versus τ for different power allocation

It can be seen from Figure 3 that for a given power allocation, channel performance changes as time allocated to the relay is changed. The best time allocation policy can be readily selected from Fig. 3. We notice that for the scenario considered here, out of the 6 different values for a, direct transmission is clearly preferred in 5 of them, namely $a = 0, a = 0.2, a = 0.4, a = 0.5$ and $a = 1$. The only time when relaying was useful is when $a = 0.8$ achieving a maximum rate $I_{S,R;D} = 1.3$ b/s/Hz for $\tau = 0.3$. in other words, allocating more power to the relay node makes it more useful to the channel. This is particularly true for half-duplex channels.

We also notice that in the case when all power is allocated to the relay, information rate is null regardless of the time allocation. In Figure 4, (13) is also used to plot $I_{S,R;D}$ against a for different values of τ. $\acute{y}_{S,R}$, $\acute{y}_{S,D}$, and $\acute{y}_{R,D}$ remain unchanged. Similar behavior is noted in Figure 4. Allocating more time to the relay node makes it useful for transmission. In the scenario considered, direct transmission is optimum for the first three cases of $\tau = 0, \tau = 0.2$ and $\tau = 0.4$. However, relaying is preferable when more time is allocated to the relay node. In this particular case the optimum power allocation is none-zero for $\tau = 0.6$ and $\tau = 0.8$. We also notice that mutual information is zero when $\tau = 1$ regardless of the power allocation.
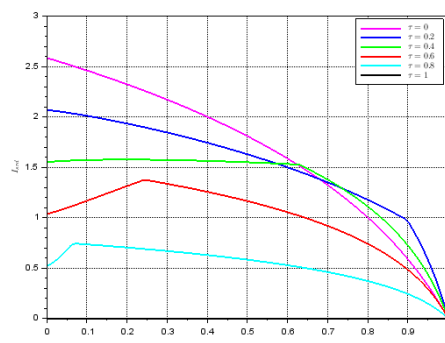

Figure 4. Mutual information versus a for different time allocation

To see the combined effect of time allocation and power allocation, $I_{S,R:D}$ versus τ and a is plotted in Figure 5. The observation made in Figure 3 and Figure 4 is demonstrated in Figure 5 in the form of increased mutual information in the direction of decreasing a and τ. This implies that when there is a half-duplex constraint, relaying is not a good option if there is a good channel between the source node and the relay node. Particularly, rather than improving performance, relaying led to degradation in transmission rate for this particular case.
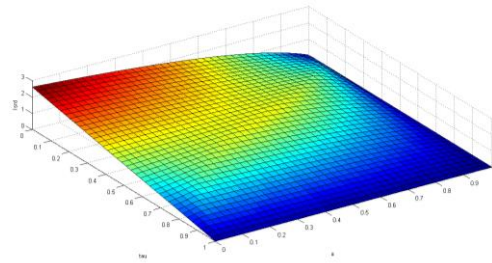

Figure 5. Mutual information versus a for different time allocation

In contrary, in a different setting where there is weak or no channel between the source node and the destination node the relay node can play a positive role in transmission. Carefully allocating time and power to the relay node results in improved transmission rate. This situation is clearly demonstrated in Figure 6 where we can see that transmission rates greater than direct transmission rate are achievable for some $\tau \neq 0$ and $a \neq 0$.
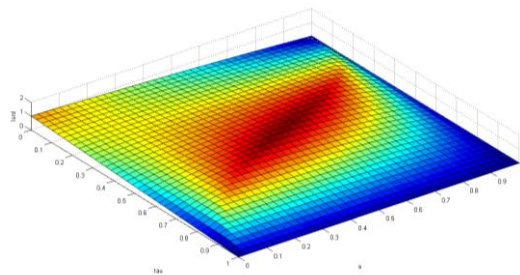

Figure 6. Plot of mutual information versus a and τ. Weak source to destination channel

To further highlight the effect of source to destination channel, Table 1 shows the optimum resource allocation policy for different source to destination channel conditions. We observe that in this scenario, relaying is useful only when the source to destination channel is weak, i.e., $\acute{y}_{S,D} = 0$ and when $\acute{y}_{S,D} = 1$.

In contrary, improved source to relay and relay to destination channel conditions makes relaying more favorable. This clearly illustrated in Table 2 and Table 3 below. When source to relay channel SNR increases in Table 2, there is more chances that the relay becomes useful. Similarly, in Table 3, improving the relay to destination channel made the relay node more useful for information transmission.

Table 1. Illustration of the effect of relay to destination channel on relay usefulness.
Good relay to destination channel makes relaying more useful for transmission

$\acute{y}_{S,D}$	$\acute{y}_{S,R}$	$\acute{y}_{R,D}$	τ_{opt}	a_{opt}	$I_{S,R:D}$ max
1	13	0	0	0	1
1	13	1	0	0	1
1	13	2	0	0	1
1	13	3	0	0	1
1	13	4	0.5641	0.641	1.0764
1	13	5	0.5641	0.5897	1.1599
1	13	6	0.5385	0.5897	1.2202

1	13	7	0.5385	0.5641	1.2632

Table 2. Illustration of the effect of relay to destination channel on relay usefulness.
Good relay to destination channel makes relaying more useful for transmission

$ý_{S,D}$	$ý_{S,R}$	$ý_{R,D}$	τ_{opt}	a_{opt}	$I_{S,R:D}$ max
1	13	0	0	0	1
1	13	1	0	0	1
1	13	2	0	0	1
1	13	3	0	0	1
1	13	4	0.5641	0.641	1.0764
1	13	5	0.5641	0.5897	1.1599
1	13	6	0.5385	0.5897	1.2202
1	13	7	0.5385	0.5641	1.2632

3.2. Channel Behaviour in Rayleigh Fading Environment

In Rayleigh fading, SNR for the source-to-relay link, source-to-destination link and relay-to-destination link are all exponentially distributed random variables. Hence, average mutual information is considered for channel performance evaluation. $I_{S,R:D}$ is averaged using (13) over many channel observations. Typically, in this work $I_{S,R:D}$ is averaged over 10000 observations. In addition, $E[ý_{S,R}]$, $E[ý_{S,D}]$, and $E[ý_{R,D}]$ are set as 13, 5, and 11, respectively.

Figure 7 shows the average mutual information versus τ. A general observation can be made by comparing Figure 7 with Figure 3. Clearly, performance of the channel in fading regimes is less than that in the AWGN case, as predicted by (23). We also notice from Figure 7 that, similar to AWGN, different power allocation policies affect channel behavior. Most of the time, direct transmission is advantageous over relaying. The only case when relaying performance outperformed direct transmission is again when 80% of the transmission power is allocated to the relay node. Interestingly, the optimum time allocation to maximize mutual information is approximately 0.3, similar to the AWGN case.
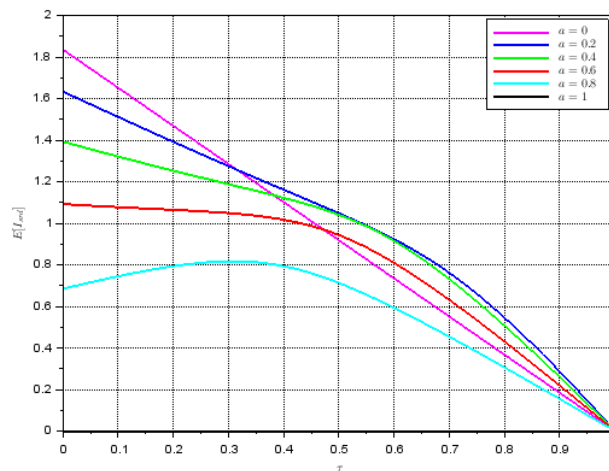

Figure 7. Average mutual information versus τ for different power allocation

In Figure 8, the $E[I_{S,R:D}]$ is plotted against a for different time allocations. Results again confirms the degradation in channel performance due to fading. Also, clearly noticed that allocating more time for the relay node makes it useful for transmission.
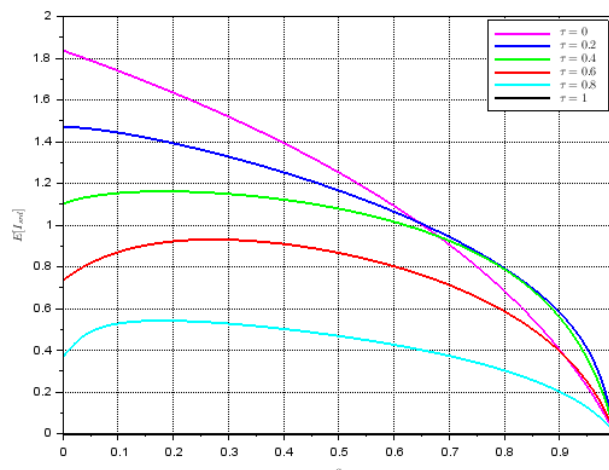
Figure 8. Average mutual information versus a for different power allocation

In light of all these results we can make an important conclusion with regard to relaying in cellular systems. The deployment of multiple relay nodes within the cell coverage area can indeed be effective in improving the average throughput from mobile users to the base station, especially for edge users. When one of these battery-operated, power constraint mobile users is transmitting to the base-station the presence of a fixed relay nodes results in higher transmission rate. However, the opposite is not necessary true. Base stations have higher transmission power and therefore, direct transmission the preferred mode of transmission in this case.

4.   CONCLUSION

This paper studied the effect of time allocation and power allocation on the performance of the 3-node decode-and-forward channel. Mathematical models were derived for the channel where mutual information was used for performance measurement. The relay node is half-duplex constraint. There is also a total transmission power constraint on the source and relay nodes. Derived model considered both the AWGN and the Rayleigh fading scenarios. Numerical results showed that relaying becomes more useful as more resource are allocated to the relay node. It is concluded that, with the half-duplex constrain on the relay, direct transmission is preferred unless source to destination channel is much worse than the source to relay and relay to destination channels. Applied to the cellular systems, relaying is more beneficial to the battery operated mobile nodes sitting at cell edges or without line-of-site than to base stations.

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