Performance Evaluation of Amplify-Quantize and Forward Protocol for Multi-relay Cooperative Networks

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ABSTRACT

Fading which occurs during the process of information transmission can significantly degrade system performance. The cooperative communication system is a well-known diversity technique that is able to mitigate the impact of fading. The relay protocol is the core of such systems. In this research, we evaluated the performance of amplify-quantize and forward (AQF) relays using a hybrid of two protocols: amplify-and-forward (AF) and quantize-and-forward (QF). The outage probability and throughput of multi-relay cooperative networks were derived, and computer simulation was used to evaluate the impact of a number of parameters on the performance of the AQF relay for multi-relay cooperative networks. We also compared the outage probability and throughput of AF, QF, and direct link networks. The outage probability of AQF decreased as the number of relays increased, whereas the throughput increased. We demonstrated that amplification values and quantization levels have a significant impact on the performance of AQF multi-relay networks. Overall, AQF performed better in terms of outage probability and throughput than AF and QF, for multi-relay cooperative networks. In addition, channel capacity of AQF was simulated, that is higher than those of AF and QF relays.

Keywords: Performance, Outage probability, Amplify-quantize and forward, Multi-relay, Cooperative network.

1. INTRODUCTION

Rapid developments in wireless communications have enhanced their reliability, throughput, data rate, and system capacity. Wireless communications face many challenges in the process of sending data. Fading is a characteristic wireless communications issue, caused by obstacles in the transmission path. Fading causes reflection, refraction, and scattering of the information sent by the sender, as well as changes the phase, polarization, and level of the signal. This reduces signal quality and increases errors in the data received by the receiver [1], [2]. In previous work, diversity techniques for multi-input multi-output (MIMO) technology were show to mitigate the impact of fading, by the use of multiple antennas in the transmitter and receiver [2]. Diversity improved the reliability of the system through combining similar independent signals in the receiver. However, MIMO technology is ineffective in mobile communication devices such as mobile phones and tablets, because of factors such as size, the relatively high cost of components, and limitations in the hardware specification. Cooperative communication systems have therefore been introduced to overcome these problems with MIMO technology. In a cooperative communications system, the source sends data through one or more relay nodes, which form a virtual multi-antenna system for transmitting data [3]. A key focus of cooperative communication systems has been the issue of the relay. Conventional relay protocols include amplify-and-forward (AF) [4-6], decode-and-forward (DF) [7-9], and quantize-and-forward (QF) [10-12].

The AF protocol is the simplest protocol used in cooperative communication. In this protocol, a relay node simply amplifies the signal received from the source before forwarding it to the destination. Amplification of the signal in the AF protocol is able to balance the weakening of the signal during transmission. However, while amplifying the signal, the noise in the signal is also amplified, decreasing the signal quality. In the DF protocol, the received signal in the relay node is decoded again before being forwarded to the destination. This approach is more complicated than AF and moreover, the relay node cannot decode the signal if the signal-to-noise ratio (SNR) value is poor. In the QF protocol, the received signal in the relay node is quantized before being forwarded. The QF system has no decoding, and so it is simpler than the DF protocol. The quantization process is able to reduce the noise in the signal, but the performance under the QF protocol is lower than under AF or DF protocol [13]. It is therefore necessary to combine the AF, DF, and QF protocols to get the full benefits. Hybrid protocols are being introduced, such as the DAF protocol, which combines the DF

Manuscript received on August 22, 2016 ; revised on September 19, 2016.

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and AF protocols in cooperative communication [14] and AQF, which combines the AF and QF protocols [15], [16]. However, research on the benefits of using the AQF protocol in cooperative communication is under-developed. The goal of the AQF protocol is to combine the benefits of the AF and QF schemes. AF has been shown to be more suitable for use in an analog communications system, whereas QF and DF can be used in digital communications systems. Whereas the DF protocol requires a decoding process, modulation, and retransmission, such processes are not needed in AF and QF. This affects the cost, power consumption, and size of the relays. It is hoped that a hybrid AQF can be implemented in digital communications, whilst offering the lower complexity of the AF and QF protocols.

The benefit of AF relay is low complexity since it does not require encoding and decoding process of the source signal that cooperate in a distributed fashion which can be an attractive alternative in cooperative networks. The relay is fast and simple as it only requires less computation. Another advantage of AF relay is that the relay can also be active when the source-relay link is in the outage. However, this scheme can only be used to an analog relay since it only amplifies the signal and then forward to the destination. The main limitation of AF relay is noise amplification which can diminish the system performance. Therefore, AF is mainly useful in the high-SNR environment. Moreover, AF relaying may offer worse performance than QF relaying since the noise is amplified along with the useful signal. The system performance of AF can be improved by choosing an appropriate amplification factor which is less than one. These benefits are adopted in AQF relay and provide the solution for AF limitation such the noise amplification can be reduced by quantization process, the performance can be improved by choosing the appropriate amplification value. Furthermore, the benefit of QF relay is also no required to decode the signal of the source, but the signal is quantized before it is transmitted to the destination in digital form. So, it can be used as a digital relay. However, the transmitted signals may contain estimation errors. Therefore, a large number of quantization codebooks is needed to negligible error [28]. The QF relay is the most efficient scheme when the source-relay and relay-destination links are good conditions. QF could provide a good performance due to low SNR on the source-relay (SR) and relay-destination. In contrary, the AF is not very effective at low SNR. Based on the benefits of AF and QF relay, AQF relay has two adjustable parameters, the amplification factor as in AF relay and the quantization levels as in the QF. This means that the benefit of AF and QF relays are combined in the proposed AQF relay. Moreover, the noise amplification in AF relay can be reduced in AQF because it has the quantization process as in a conventional QF relay. The error estimations in QF relay can be solved in AQF since the received signal by the relay is firstly amplified and then quantize. Based on the fact, AQF relay has not only benefited by combining the benefit of AF and QF relays but also has solved the disadvantage of AF and QF relays.

This paper evaluates the performance of multi-relay cooperative networks using the AQF protocol. In order to evaluate the network performance, the AQF multi-relay network system model is proposed, in which included all mathematical expressions for each part of the model. Based on the model, performance of multi-relay AQF cooperative network in terms of outage probability and its network throughput is analyzed. The performance of this network is influenced by some parameters of AF and QF relay protocol, which are amplification and quantization level, respectively. Based on the reason, the performance of multi-relay AF and QF based networks are also analyzed in this paper. In the AQF protocol, a relay node amplifies the received signal before quantizing and forwarding it. The amplification is designed to counteract the weakening of the signal during transmission from source to relay, while the quantization is used to reduce noise in the signal. The parameters evaluated in this paper include the number of relays, the amplification values, the quantization levels, the outage probability, throughput, and channel capacity. Afterward, the performance of the proposed multi-relay AQF network is also compared with the performance of AF and QF network protocol.

The contributions of this paper can be summarized as follows. Firstly, we propose the hybrid cooperative relay AQF by combining the conventional AF and QF relay schemes. The hybrid AQF relay has the relaxing parameters in the performance since its performance can be improved by considering the appropriate amplification value as in AF and the quantization levels as in the QF. Then, we evaluate the performance of AQF relay in terms of outage probability, throughput, and channel capacity and compare its performance with the performance of AF and QF relays as well. We believe that the proposed AQF is important in the cooperative networks since it provides several benefits as follows:

- AQF relay can be implemented as a digital relay in which the limitation of AF relay as an analog relay can be solved for the practical issue. Moreover, the impact of noise amplification of AF relay can be reduced in AQF since it has a quantization process at relay as in a conventional QF relay.

- AQF relay can reduce the quantization noise as in a conventional QF relay since the received signal at relay will firstly amplified and then quantized.

2. SYSTEM MODEL

The system model of a multi-relay AQF cooperative network is shown in Fig. 1, in which the source (S) sends information to the destination (D) through several intervening relays. A cooperative transmission system can be divided into 2 phases. In the first phase, the source (S) sends information directly to the destination and to the k relays (S, R_i), where $i = 1, 2, ..., k$. The added AWGN noise in the received signals in the i relay and the direct path are calculated as follows:

$$\mathrm{y}_{\mathrm{SR_i}} = h_{SR_i} x_s + n_{R_i}, \tag{1}$$

$$\mathrm{y}_{\mathrm{SD}} = h_{SD} x_s + n_D, \tag{2}$$

where, y_{SRi} is the received information signal at relay i, h_{SRi} is the channel coefficient between source and relay i, x_s is the transmitted information signal from source, n_{Ri} is the AWGN noise generated between source and relay i, y_{SD} is the information signal received at the destination, h_{SD} is the channel coefficient for the direct path between source and destination, and n_D is the AWGN noise generated over the direct path.

In the second phase, k relays (R_i, D) receive the signal and forward those signals to the destination (D). Cooperation in this phase is a function to perform the processing of the information signal by the relay protocol during transmission over the k relays. As the AQF is a hybrid relay method that combines the AF and QF protocols, the signals received by the relay node will be amplified with a fixed average power before the quantization process is carried out [15]. Fig. 1 shows the model of the AQF relay used in a multi-relay network. Two important processes are performed by the relay before the signal is forwarded to the destination node:

Amplification

AF amplification process is a basic operation performed in the relay. The process is simple where each received signal will be multiplied with amplification value of relay and send the amplified signal to the destination. The amplification process will include both signal and noise. Thus, it will impact the performance of overall network performance.

The information signal is broadcasted from the source to the destination (D) node through several relays (R_i) on the network. The relay first amplifies the received signal. The amplified signal can be expressed as [6]

$$\hat{y}_{SRi} = h_{SR_i} \beta_i x_s + n_{SR_i} \tag{3}$$

where n_{SR_i} is the noise generated between source and relay i and β_i is the amplification coefficient in relay i defined by

$$\beta_i = \sqrt{\frac{P_{R_i}}{\left|h_{SR_i}\right|^2 P_S + N_0}} \tag{4}$$

where P_{R_i} is the average transmission power from the relay i, P_S is the transmitted power of source and N_0 isnoise variance of the channel. The noise is assumed to be Gaussian with $n(0, 1)$ and i.i.d [17].

Quantization

The amplified signal at the relay i is then a quantized process. Uniform quantization is used, because of its simple implementation [18]. The quantizer has an interval of $[\hat{\mathrm{y}}_{\mathrm{SR_i,max}}, \hat{\mathrm{y}}_{\mathrm{SR_i,min}}]$ of an amplified signal $\hat{y}_{SR_i}$ with L level of quantization, which is obtained by

$$L = 2^M, \tag{5}$$

where M is the number of quantization bits. The quantizer is similar to an analog to digital converter (ADC) structure with L levels of quantization and M resolution bits, where $M = log_2 L$. Based on the process in quantizer, the quantized signal in (3) can be expressed as

$$\tilde{y}_{SR_i} = \mathrm{Q}\left(\hat{y}_{SR_i}\right) = \hat{y}_{SR_i,\min} + \frac{\Delta}{2} + \Delta . j, \tag{6}$$

where Q(.) is a uniform quantizer for each $\tilde{y}_{SR_i}$ and $j = 1, 2, , L$. The quantized intervals of constant width Δ is [19]

$$\Delta = \frac{\left(\hat{y}_{SR_i,\max} - \hat{y}_{SR_i,\min}\right)}{L}, \tag{7}$$

where $\hat{y}_{SR_i,\max}$ and $\hat{y}_{SR_i,\min}$ are maximum and minimum value of $\hat{y}_{SR_i}$, respectively,

The signal received at the destination can be expressed as follows:

$$y_{R_i D} = h_{R_i D} \tilde{y}_{SR_i} + n_{R_i D}, \tag{8}$$

where, $h_{R_i D}$ is the channel coefficient between relay i and destination, and $n_{R_i D}$ is the noise generated between relay i and the destination.

Maximal ratio combining (MRC) is one of many combining techniques that can be used in wireless relay networks. MRC is applied on the receiving side, in which the receiver antenna receives signals that have experienced multipath fading with variation of phase and amplitude. It takes advantage of the spatial diversity provided by two independent paths. Signals from each path are weighted with respect to their instantaneous SNR. The channel coefficient can be modeled as the independent zero mean of circularly symmetric complex Gaussian random variables with $\sigma^2_{SD}, \sigma^2_{SRi}$, and $\sigma^2_{R_i D}$. The channel model follows a Rayleigh distribution, and is known as a Rayleigh flat-fading model [18]. The signals received in each

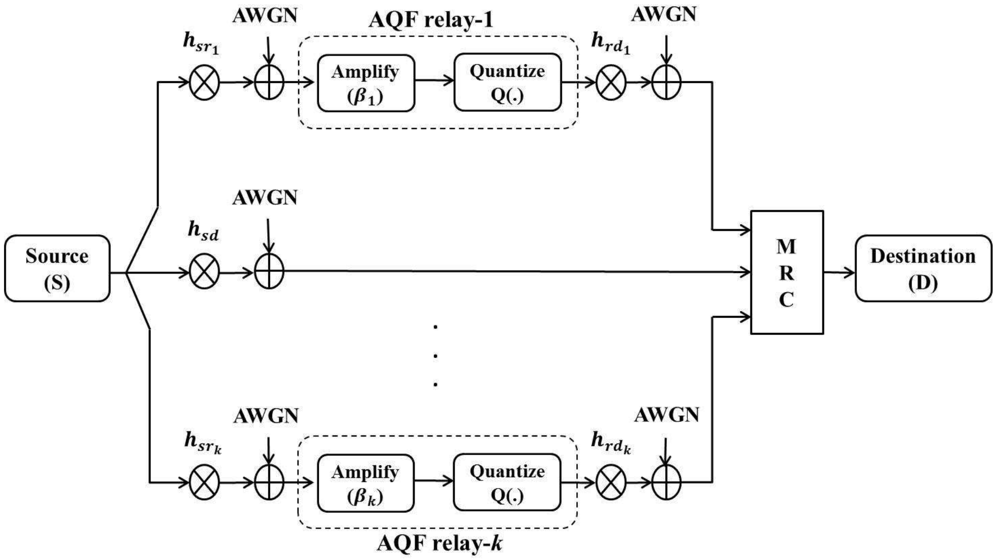

Fig. 1: *Model of multi-relay AQF cooperative network.*

phase can be combined by using Maximum Ratio Combining (MRC), where the output signal of the MRC is as follows [20], [21]:

$$y = \alpha_{SD} y_{SD} + \sum_{i=1}^{k} \alpha_{R_i} y_{R_i D}, \tag{9}$$

where α_{SD} and α_{SR_i} are the MRC coefficients for the direct path transmission and the cooperative transmission. These are calculated as follows:

$$\alpha_{SD} = \frac{\sqrt{P_{\mathrm{S}}} h_{SD}}{N_0,} \tag{10}$$

and

$$\alpha_{R_i} = \frac{\sqrt{P_{\mathrm{S}}} h_{SR_i} h_{R_i D}}{\left[N_0 \left(1 + |h_{R_i D}|^2\right)\right]}, \tag{11}$$

where P_S is the transmitted power of source and N_0 is noise variance of the channel.

3. PERFORMANCE ANALYSIS

3.1 Outage Probability

Outage probability (P_{out}) is defined as the probability that the system will fail when sending information to the destination. It is a standard criterion for characterizing the performance of communication systems operating in fading environments, and is one of the parameters used to determine the performance of a wireless relay network system. In general, P_{out} can be expressed as [22]

$$P_{\mathrm{out}} = \int_{0}^{\gamma_{th}} P_{\gamma}(\gamma)\, d\gamma, \tag{12}$$

for a slow independent identically distributed Rayleigh fading channel. It is stated as the probability that the mutual information from the channel is below a given SNR threshold:

$$P_{\mathrm{out}} = \mathrm{P_r}\left[\gamma < \gamma_{\mathrm{th}}\right]. \tag{13}$$

For the AF protocol, the average mutual information for multi-relay can be calculated by the following expression:

$$I_{\mathrm{AF}} = \frac{1}{2} \log_2 \left(1 + \gamma_{\mathrm{SD}} + \sum_{i=1}^{k} \gamma_{SR_i}\right), \tag{14}$$

where

$$\gamma_{SD} = \frac{P_s \left|h_{SD}\right|^2}{\sigma_{SD}^2} \tag{15}$$

and

$$\gamma_{SR_i} = \frac{P_s \left|h_{SD} \beta_i h_{SR_i}\right|^2}{\left|h_{sR_i} \beta_i\right|^2 \sigma_{SR_i}^2 + \sigma_{SD}^2}. \tag{16}$$

Hence, the outage probability for the multi-relay AF protocol can be expressed as [22-24]

$$P_{\mathrm{out}}^{\mathrm{AF}} = P\left\{I_{\mathrm{AF}} < R\right\} = P\left\{\gamma^{\mathrm{AF}} < \left(\frac{2^{(k+1)R} - 1}{\gamma_{\mathrm{th}}}\right)\right\}. \tag{17}$$

For the QF protocol, mutual information for multi-relay can be calculated by the following expression [3], [25], [26]:

$$I_{\mathrm{QF}} = \frac{1}{2} \log_2 \left(1 + \gamma_{\mathrm{SD}} + \sum_{i=1}^{k} \frac{\gamma_{\mathrm{SR}_i}}{1 + N_{qi}}\right), \tag{18}$$

where γ_{SD} is equal to that in the AF protocol, as in (15), while γ_{SR_i} can be expressed as

$$\gamma_{\mathrm{SR}_i} = \frac{P_s \left|h_{SR_i}\right|^2}{\sigma_{SR_i}}. \tag{19}$$

Therefore, the outage probability for the multi-relay QF protocol [26] is

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{QF}} &= P\left\{I_{\mathrm{QF}} < R\right\} \\ &= P\left\{\gamma^{\mathrm{QF}} < \left(2^{(k+1)R} - 1 - \sum_{i=1}^{k} \frac{\gamma_{SR_i}}{(1+N_{qi})}\right)\right\}, \end{aligned} \tag{20}$$

where N_{qi} is a quantization noise at relay i which can be calculated by

$$N_{qi} = \frac{\gamma_{\mathrm{SR}_i}\sigma_{\mathrm{SD}}^2}{\sigma_{\mathrm{R}_i\mathrm{D}}^2}. \tag{21}$$

For the AQF protocol, mutual information for multi-relay can be obtained by

$$I_{\mathrm{AQF}} = \frac{1}{2}\log_2\left(1 + \gamma_{\mathrm{SD}} + \sum_{i=1}^{k} \frac{\tilde{\gamma}_{\mathrm{SR}_i}}{1+N_{qi}}\right). \tag{22}$$

Then, the outage probability of a hybrid AQF multi-relay protocol can be expressed as

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{AQF}} &= P\left\{I_{\mathrm{AQF}} < R\right\} \\ &= P\left\{\gamma^{\mathrm{AQF}} < \left(2^{(k+1)R} - 1 - \sum_{i=1}^{k} \frac{\tilde{\gamma}_{\mathrm{SR}_i}}{(1+N_{qi})}\right)\right\}, \end{aligned} \tag{23}$$

where

$$\tilde{\gamma}_{\mathrm{SR}_i} = 1 + \frac{P_s \left|h_{SR_i}\right|^2}{\sigma_{\mathrm{R}_i\mathrm{D}}^2}. \tag{24}$$

3.2 Throughput

Throughput is one of the parameters that define network performance. Throughput measures the amount of information that can be transmitted by the source to the destination for each unit of time. It is defined as the number of data packets successfully transmitted to the receiver in each second. By using a defined outage probability, the network throughput can be calculated by [27], [28]

$$T_h(r) = r\left(1 - P_{\mathrm{out}}(r)\right), \tag{25}$$

where r is the rate of data transmission and $1 - P_{out}$ is the probability of successful information transmission. The outage probability, P_{out}, refers to the used relay protocol in the multi-relay networks. The P_{out} of AF, QF, and AQF multi-relay networks are as derived in the previous sub-section. Based on the system model in Fig. 1, it assumes that a source can transmit the data to the direct and relay links at r bits/second.

3.3 Simulation Settings

The performance of the proposed scheme is evaluated by computer simulation using Matlab programming. The simulation parameters and their values are presented in Table 1. In the simulation, a source generates 10^5 bits as data input for the target BER of 10^{-5}. The data input is modulated by BPSK scheme. The modulated signals send to 3 or 4 relays in the network. The processed signals at relays are forwarded to a destination. The network is simulated based on the use of relay protocol that is AF or QF or AQF. The simulation results are combined in a graph for a comparison purpose. To obtain outage probability and throughput analysis, SNR values are set from 0 to 30 dB.

The range of SNR is good enough to obtain the target BER of 10^{-5}. The noise variance N_0 is assumed to 1 [29]. While, the coefficient of Rayleigh fading is generated randomly between the relay link by a computer simulation. The maximum ratio combining (MRC) is used to combine the direct link signal and the relay link signals at the destination because it provides the best performance among the other combining techniques [2].

In the performance analysis, the outage probability is defined as the probability that he instantaneous bit error rate (BER) exceeds a certain target BER [30], [31]. So, in a wireless communication system, in general, there will be a trade-off between the BER performance and the outage probability. In our simulation, the target BER is 10-5, then the system specifies the minimum SNR required for the acceptable performance of the target BER which is depend on the used relay protocol and the type network such as a three-relay network. Different values of amplification at relay are considered to analyse the performance of AF and AQF networks. However, amplification value is assumed to be equal for each relay in simulated network. Meanwhile, the different quantization levels are also simulated only for QF and AQF network performance. Hence, the performance of AQF networks is influenced by both amplification value and quantization level. Moreover, the simulation of throughput performance is conducted based on the outage probability of AF, QF, and AQF networks with the assumption using a fixed data rate of 50 Mbps.

4. RESULTS AND DISCUSSION

4.1 Outage Probability

In this study, the outage probability of a multi-relay cooperative network was evaluated by considering several parameters that affect P_{out}, such as the number of relays, the amplification value of AF, and the quantization level of QF. The influence of these parameters was analyzed using computer simulations. Theoretically, in a multi-relay cooperative network an increase in the number of relays will significantly af-

Table 1: *Simulation parameters*

Parameter	Value
Data input	$10^5 bits$
Target BER	10^{-5}
Channel Model	Rayleigh Fading
Modulation scheme	BPSK
Number of source	1
Number of relays	3 and 4
Relay protocols	AF, QF, and AQF
Amplification values	0.1, 0.2, and 0.3
Quantization levels	2, 4, and 8
Number of destination	1
SNR vector	0 - 30 dB
Data rate	50 Mbps
Combining Technique	MRC

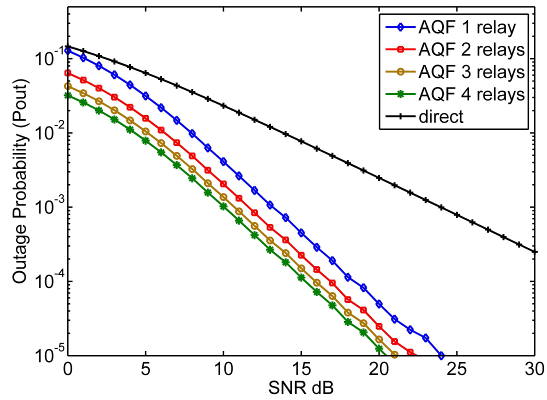

Fig.2: *Comparison of outage probability of AQF relay protocol by varying number of relays*

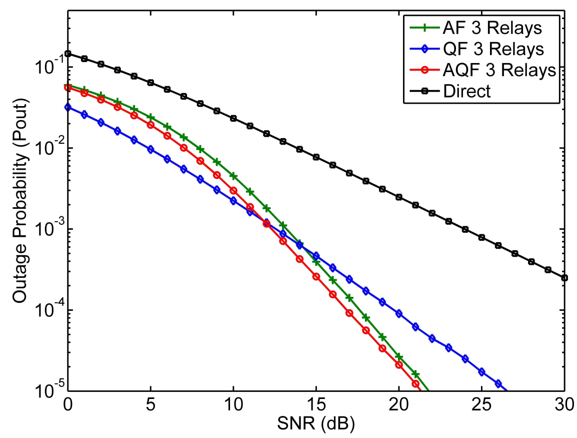

Fig.3: *Comparison of outage probability among AF, QF, and AQF relay protocol with 3 relays*

fect the P_{out} performance. We demonstrated this using computer simulations. Fig. 2 shows that the number of relays was directly proportional to the network performance of a multi-relay system using the AQF protocol. The outage probability (P_{out}) decreased as active relays were added to the network. For example, when SNR $=$ 10 dB, the P_{out} for AQF network with one relay was 4.5×10^{-3}. When two relays were active in the network, P_{out} decreased to 2.5×10^{-3}. In this case, the addition of a relay improved the network performance by $1.8 \times P_{out}$ performance compared when it only using one relay. Thus, the network gained $5 \times P_{out}$ for$P_{out} = 9 \times 10^{-4}$ when four relays were forwarding the information from source to destination. This effects the principle of diversity techniques, in which increasing the number of relays used increases the number of combinations of replicated signals at the receiver, which increases the probability of the information signal being received at the destination. The increase in the number of relays in a multi-relay network significantly affected the performance of the system, improving the performance as the number of relays increased.

As discussed earlier, the AQF protocol combines the AF and QF protocols. In evaluating the performance of the AQF protocol, we compared its performance with those of AF and QF when using the same number of relays. The results of our simulation are given in Fig. 3.

It can be seen that the overall performance of the network using the AQF protocol was better than the networks using the AF or QF protocol, especially when the SNR$>$11 dB. However, at SNR$<$11 dB, QF performance was better than AQF, because QF quantization was more effective in mitigating the effects of fading. The quantization process at AQF was effective in dealing with fading when the SNR was high and increasing. The amplification process under AQF performed better than the AF protocol at the same amplification value. Overall, the P_{out} performance of AQF showed significant improvement by exploiting the amplification process of AF and the quantization process of QF. Based on the result, it can be seen that AF relay protocol are mainly used in high SNR network environment. Contrarily, the QF relay protocol is more appropriate for the low SNR region network environment. The proposed AQF relay protocol can considerably be reduced the performance gap between AF and QF relay performance, where AQF relay protocol are able to reduce the P_{out} performance if compared with AF at high SNR region and improved the P_{out} performance if compared with QF at low SNR region. The P_{out} performance of AQF 3 relays is better than the P_{out} performance of AF 3 relays because the noise amplification in AF relay can be reduced by quantization process in the proposed AQF relay. Therefore, the P_{out} of AF 3 relays and AQF 3 relays look comparable. Furthermore, this is proved that the proposed AQF relay be able to combine the benefit of a quantization process of the QF relay in order to reduce the effect of noise amplification in the AF relay and also improves the performance compared to the AF performance.

The amplification factors used in the AF protocol also affected the P_{out} performance of the AQF protocol. In the AQF performance evaluation, we therefore examined the effect of the amplification. In the simulation, the amplification value was set to three different values for both protocols: $\beta = 0.1, 0.2$ and 0.3. The simulation results show that the cooperative network with the AQF protocol performed better than the network using the AF protocol (Fig. 4). The P_{out} performance dropped as the amplification value at the relay increased. However, an interesting result from simulation was that the performance of both protocols decreased when the amplification value was changed from 0.1 to 0.2. For the simulated amplification value, the performance under both protocols was optimal at an amplification value of 0.3. The performance of a cooperative network using the AQF protocol can be optimized by choosing the optimal amplification value. The amplification value is non-linear, so the optimal value is in the range $0.1 < \beta < 1.0$. Generally, the amplification factors have the impact to the performance of AF and AQF relaying. The low amplification value decreases the system performance because the detection probability at destination also decreased. In other words, the detection probability increases with an increase of the amplification values as shown in the Fig. 4. However, the amplification value should not very high (less than 1) because it's also gained the noise as in the AF relay. If the amplification value is greater than one, the power of noise signal within the received signal is increased, which amplifies the noise. Based on that, this paper was considered the amplification values are 0.1 to 0.3. The AQF protocol uses the QF quantization process. The simulation results showed that the P_{out} performance of both protocols increased as the quantization level at the relay increased (Fig. 5). As shown from the result, for $P_{out} = 10^{-3}$, the SNR requirements for L= 2, 4, and 8 are 14, 13.2 and 13 dB, respectively. There is a performance gain of 0.8 dB between L=2 and L=4. However, a performance gain between L=4 and L=8 is only 0.2 dB. So, changes in performance were less significant at high quantization levels. The higher the quantization levels used will give the better network performance. But, it will increase computation complexity in the process at the relay. Hence, the quantization levels should be selected moderately by considering the suitable performance and low computational complexity. Based on the simulation result in Fig. 5, the quantization level L=4 is suitable to apply in the multi-relay AQF network. Both QF and AQF relays have the quantization process before forwards the information to the destination. At the quantization process, the quantization level influences the system performance in which the more quantization levels, the better quality the system will deliver. Moreover, quantization noise is inversely proportional to the number of quantization levels. Increasing L from 4 to 8 leads to better performance mainly because with a higher quantization level, the quantization error, which cannot be recovered, is smaller.

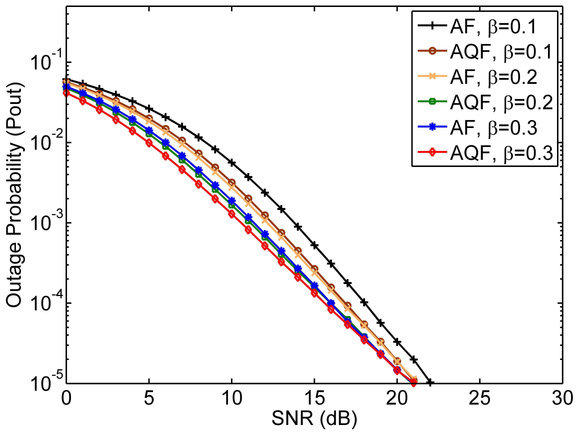

Fig.4: *Comparison of outage probability between AF and AQF relay protocol with different amplification values*

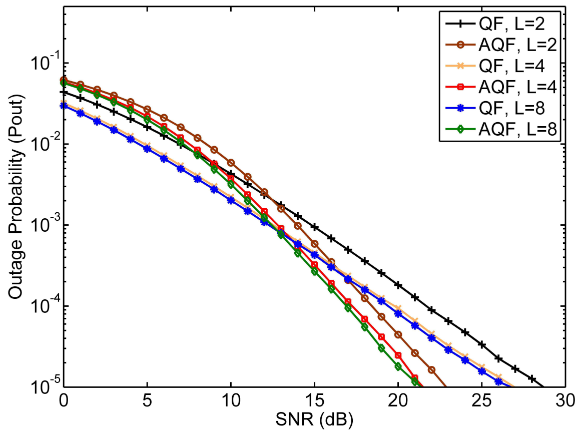

Fig.5: *Comparison of outage probability between QF and AQF relay protocols with different quantization levels*

4.2 Throughput

In a multi-relay cooperative network using the AQF protocol, the number of relays will affect the throughput of the system. This was demonstrated by the results shown in Fig. 6, where the data rate was set to 50 Mbps. In this simulation, network throughput increased as the SNR value and number of relays increased. Throughput reached its maximum at 50 Mbps at an SNR of 15 dB and remained at that value as the SNR level increased to 30 dB. For exam-

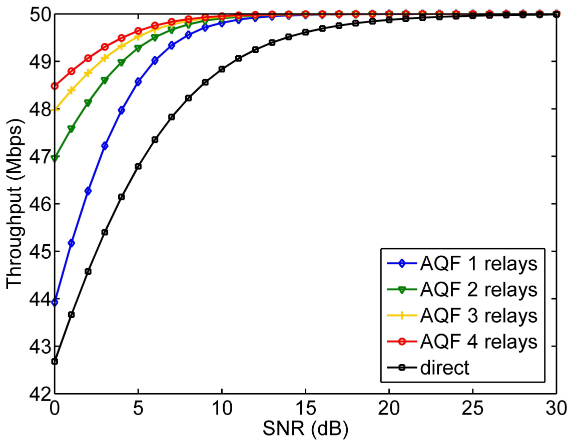

Fig.6: *Comparison of network throughput for AQF protocol with different number of relays*

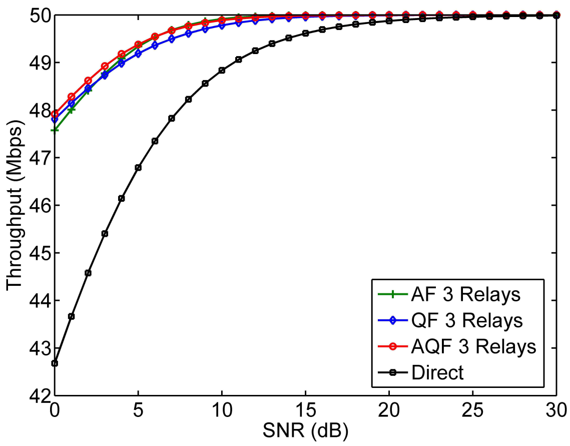

Fig.7: *Comparison of network throughput of AF, QF, and AQF relay protocols with 3 relays*

ple, at an SNR of 5 dB, the throughput of the network with one relay was about 1.75 Mbps higher than the throughput of the direct network with no relays. The network throughput with four relays increased by 4 Mbps compared with the direct network, and by 1 Mbps compared with the single relay network.

Fig. 7 compares the throughput in our simulations of the cooperative network with three relays, using the AF, QF, and AQF protocols. Overall, the throughput of the three protocols was similar at some levels of SNR, though the throughput of the network using AQF protocol was slightly better than that of the networks using the AF and QF protocols. However, at an SNR of 5 dB, the throughput for all three protocols improved significantly. This demonstrated that the use of relays, together with a cooperative protocol increased the efficiency of the telecommunication channel.

In this research, we also compared relay networks using the AF and AQF protocol by varying the amplification value with the same number of relays. The simulation results showed that the relay network using the AQF protocol provided better throughput than the relay network using the AF protocol for the same amplification value, under both low and high SNR regimes as shown in Fig. 8. The network throughput is affected by the amplification value for both relay protocols in which the higher amplification value the higher throughput is achieved in the networks. The network reached its maximum of 50 Mbps when the SNR was greater than 15 dB. The comparison between the relay networks using the QF and AQF protocols is performed by varying the quantization levels L between 2, 4, and 8. The results are shown in Fig. 9, and show that the network throughput increased as the quantization levels increased. For SNR>5 dB, the throughput of the relay network using the AQF protocol was higher than the network throughput when using the QF protocol at all quantization levels. We conclude that a relay network using the QF protocol will work better for systems with low SNR regimes. A maximum throughput of 50 Mbps will be reached when the SNR is greater than 15 dB. Hence, with the increased of quantization levels, will increase the relay channel capacity. Moreover, it will also increase the amount of data received by the relay that should be forwarded to the destination. Both processes have influenced to the multi-relay network throughput.

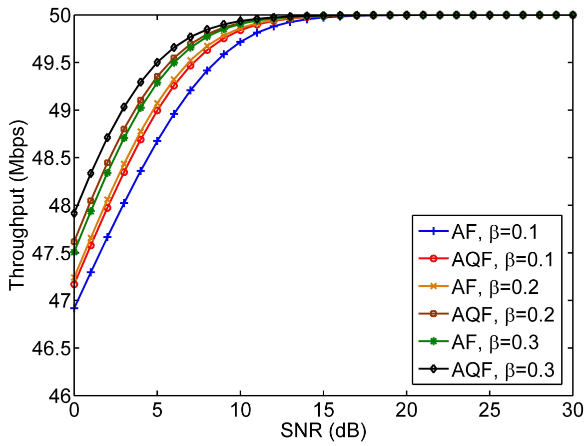

Fig.8: *Comparison of network throughput of AF and AQF protocol with different amplification values*

4.3 Channel Capacity

Channel capacity was simulated based on the maximum average mutual information of AF, QF, and AQF in the Eqs. (14), (18), and (22), respectively. The simulation was conducted by considering 3 relays in the networks, the quantization level of 2 for QF and AQF relay, while the amplification value for AF and AQF relay is according to the Eq. (4). The

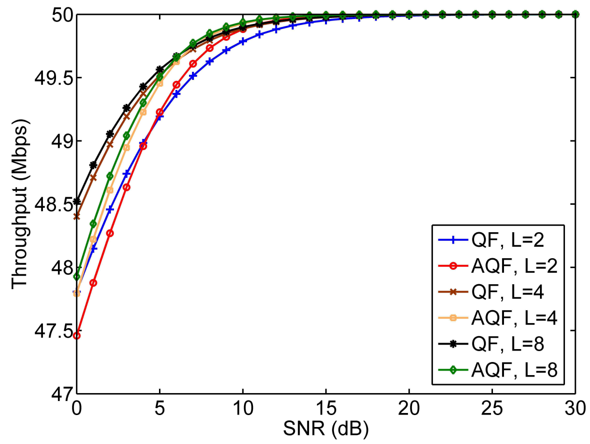

Fig.9: *Comparison of network throughput of QF and AQF protocols with different levels of quantization*

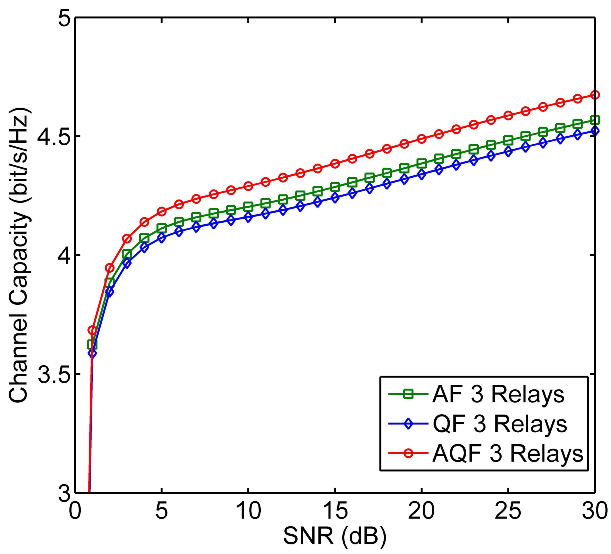

Fig.10: *Comparison of channel capacity of AF, QF, and AQF protocols with 3 relays*

other parameters are the same as in Table 1. The simulation result is shown in the Fig. 10, where the channel capacity of the proposed AQF is higher than those of AF and QF relays due to the link capacity relay-destination can be maximized by amplifying the input signal prior to quantization. Moreover, the capacity of AF relays obtains higher than that of QF relays because low delay of AF relay. Nevertheless, the difference of channel capacity between AF and QF relays is less significant. On the other hand, the channel capacity of the proposed AQF relays increases significantly compare with both AF and QF relays. Generally, the channel capacity for the three relay schemes increases as the SNR value increased.

4.4 Comparison of AF, QF, and AQF relay

In order to obtain the benefit of the proposed AQF relay, it needs to compare with several parameters of both AF and QF relays that are summarized in Table 2. Based on Table 2, the complexity of AQF is increased but it could increase the channel capacity as well. Both AF and QF relay are influenced by noise and distortion, respectively. The problems are solved in the AQF relay, where noise amplification is reduced by the quantization process while the distortion is minimized by signal amplification at relay before the quantization process. AF relay needs nothing. Moreover, AQF relay needs only one codebook, but QF relay needs channel distributions (codebooks). Today, many communication systems are used digital transmission, therefore AF relay cannot be used for such systems. But, AQF relay can be useful for digital

Table 2: *Comparison parameters of AF, QF, and AQF relays*

Parameters	AF	QF	AQF
Complexity	Very low	Low	Moderate
Channel capacity	Moderate	Low	High
Noise at relay	Information plus noise	Information plus distortion	Partially information
Relay needs	Nothing	Channel distribution (codebooks)	One codebook
Relay type	Analog	Digital	Digital
Performance factor	Amplification value	Quantization level	Amplification value and quantization levels

transmission as QF relay. In the case of the performance parameter, AF and QF relay are only based on amplification and quantization levels, respectively. But, AQF performance can be adjusting of both parameters. By the facts that it believes the AQF relay has several benefits as in Table 2.

5. CONCLUSIONS

This paper evaluated the performance of multi-relay amplify-quantize and forward (AQF) cooperative networks. We have analyzed the outage probability and throughput of multi-relay AQF networks. Computer simulations were conducted using several parameters known to impact on the performance of AQF multi-relay networks. We also investigated the performance of AQF using both AF and QF relays. The simulation results showed that the outage probability was improved by increasing the number of relays in the network. The AQF relay network performed better than AF and QF at high SNRs. The amplification values and quantization levels in the AQF protocol affected the outage probability, while the throughput of the AQF network increased as the number of relays was increased. The throughput of the AQF network was higher than those of the AF and QF networks, and was affected by the amplification values and the number of quantization levels. Moreover, the channel capacity of AQF network was higher than those of the AF and QF networks. We conclude that the AQF relay network can provide better outage probability performance, higher network throughput and higher channel capacity. The hybrid AQF is therefore a promising relay protocol for use in digital communications, taking advantage of the lower complexity of the AF and QF protocols.

6. ACKNOWLEDGEMENT

This work is partly supported by the research grant of "Tim Pascasarjana", Ministry of Research, Technology and Higher Education of the Republic of Indonesia.

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