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Energy-Efficient Multiple-Relay Cooperative Networks Using Hamming Coding

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***Abstract*—Using a multiple-relay cooperative communication network is one of the most effective methods for reducing the impact of fading on wireless channels. In such a network, a source sends information to a destination via several nearby nodes, which form virtual antennas regardless of the size and cost of the mobile equipment. The network is also required to transmit multimedia and allow access to high-speed data, thus requiring significant energy consumption. Until now, mobile devices have only been able to store a limited amount of energy, leading to rapid battery depletion in relay and mobile user devices. Moreover, the Base Station (BS) itself consumes considerable energy and the number of BSs continues to grow. Therefore, the development of an energy-efficient cooperative communication network that reduces energy consumption while maintaining the highest possible level of performance is urgently required. To this end, this paper proposes the application of Hamming coding to a multiple-relay cooperative communication network for Energy Efficiency (EE) analysis. Then, the relay protocol aspect is also determined to increase the level of EE. This study considers two practical protocol relays, Amplify-and-Forward (AF) and Quantize-and-Forward (QF), for a more in-depth analysis of EE. The results show that the multiple-relay QF network demonstrates EE when compared to a multiple-relay AF network.**

***Index Terms*—Energy efficiency, hamming coding, multi-relay, amplify and forward, quantize and forward**

I. INTRODUCTION

Recently, wireless communication systems have become increasingly widespread owing to their advantages such as flexibility, high mobility, high data rate, and access to multimedia services [1], [2]. However, some of these features increase the rate of battery consumption on users' mobile devices. Regarding the network, a Base Station (BS) consumes considerable power, and there are 4 million BSs, consuming an average of 25 MWh per year, spread globally and serving mobile users [3]. As a result, wireless communication systems contribute to up to 2% of the world's total carbon emissions, impacting the environment significantly [4]. Fading and interference result in additional energy consumption needs for wireless channels of mobile devices and BSs. Based on the aforementioned, the two main problems faced by next-generation communication networks are their energy consumption and the influence of fading on the transmission link. Therefore, many researchers have focused on investigating energy-saving strategies in wireless communications systems, one of which is the cooperative method, which permits efficient power usage [5]–[7]. One approach to improving Energy Efficiency (EE) in the proposed cooperative network is modeling the joint behavior of cell users in the relay selection decision-making process [8]. This is so that the network nodes have sufficient incentive to establish and maintain the cooperative network's reliability with lower transmission power and different power consumption characteristics. Another study proposed achieving energy-savings through the exploration of network resources and protocols in cooperative systems [9]. The proposed cooperative communication protocol is based on a system of clustering and cooperative transmission of data by utilizing the nodes (cluster relays) that lie between the source and destination clusters. During the routing stage, the relay nodes with the lowest energy consumption are selected; thus, the source node is enabled to use the least amount of power while maintaining performance.

Cooperative communication is a process whereby a source sends an information signal to a destination via one or more relays [10]. Cooperative communication networks have continued to evolve to be applied to next-generation wireless networks; spatial diversity can be achieved using a single antenna that functions as a virtual multi-input-multi-output [11]. Furthermore, the application of relay selection techniques to cooperative communication is an important aspect of next-generation wireless networks. In previous studies, the cooperative networks under consideration used only a single relay, although a source can transmit signals through several adjacent relays. The performance of cooperative communication networks can be improved with the addition of multiple relays between the source and destination, in which the higher of the system performance is achieved whereas the number of relays is increased in the cooperative network [12]. Nevertheless, multiple-relay networks do not entirely reduce the effects of noise and fading on wireless channels. One way to further minimize these effects is to apply channel coding techniques to multiple-relay cooperative networks [13]. Network performance is, thus, improved by not only the

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incorporation of multiple relays but also the reinforcement from channel coding. The development of future communication technology (e.g., modern 5G) depends on the reduction of energy consumption, longer battery life, and the application of cooperative systems [14]. To these ends, several types of channel coding have been applied to cooperative communications [15]–[17]. In [15], the Fountain code was applied to cooperative communication for LTE-A, which increased the performance of data transmission. Polar codes have also been used in cooperative systems to improve the bit error rate (BER) performance of decode-and-forward (DF) relays [16], [17]. Channel coding can also increase system security [18].

This study aims to analyze the EE of multiple-relay cooperative networks using channel coding, namely Hamming codes, which are simple to construct and can be easily adjusted for quantized-and-forward (QF) [19] and Amplify-and-Forward (AF) [20] relay protocols. A previous paper [19] proposed a two-way QF protocol with a minimally complex single-relay network. The authors in [20] examined multi-hop cooperative networks using AF protocols with efficient routing methods to achieve high connective probability. However, this paper focuses solely on QF and AF relay protocols for a one-way multiple-relay cooperative network, as neither of these protocols involves encoding mechanisms. In a QF relay, a source transmits information via one or more relays; the signal received by these relays is quantized before being forwarded to its destination. In an AF relay, the information signal received by the relays from a source is first amplified, and then forwarded to the destination. DF is yet another protocol that requires a signal to be encoded before being forwarded to its destination [21], [22]. To the best of our knowledge, there has been no investigation into the effects of applying Hamming codes to the EE of cooperative networks, particularly neither QF nor AF relays. Therefore, the current study considers these relay protocols and how the levels of energy consumption and network efficiency are affected by energy sources of Hamming codes. Cooperative networks are, thus, given the ability to detect and correct errors via Hamming coding, which can improve the performance and minimize energy consumption [23]. This paper also analyzes the level of EE that can be provided by applying Hamming codes in multiple-relay AF (MR-AF) and multiple-relay QF (MR-QF) cooperative networks. A cooperative network with energy-efficient relay protocols and enhanced performance is expected to result from this analysis. Thus, it is believed that cooperative communication will meet the requirements for use in future 5G technology [24]. The main contributions of this paper can be summarized as follows:

1) The application of Hamming coding to a multiple-relay cooperative network using AF and QF relays.
2) The analysis and simulation of the EE of multiple-relay cooperative networks that use AF and QF relays with Hamming coding.

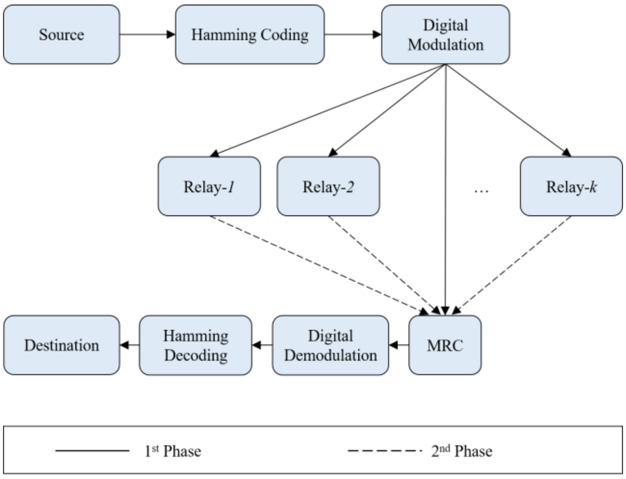

Fig. 1. System model.

II. SYSTEM MODEL

Fig. 1 illustrates the network model of the proposed multiple-relay cooperative system using Hamming coding. This network model comprises a source, multiple relays, and a destination. At the source, the information data are encoded by a Hamming encoder, and then digitally modulated. The coding technique used in this study is a relatively simple linear code that is easy to implement. The Hamming code is a type of linear coding channel that meets the criteria for multi-path or multiple-relay communication [22].

Hamming code is a simple linear code used for error detection and correction. It has a small bandwidth expansion and is commonly denoted by (n, k), where n is the codeword length and k is the number of message bits. They can be defined as follows [13]:

$$n = 2^m - 1 \tag{1}$$

$$k = 2^m - 1 - m \tag{2}$$

where m is the number of redundancy bits. The code rate can then be obtained as

$$r = \frac{k}{n} \tag{3}$$

Hamming codes can provide a minimum distance of $d_{\min} = 3$, meaning that this code can detect errors of $d_{\min} - 1 = 2$ bits and can correct $t = |(d_{\min} - 1)/2| = 1$ error bit in a codeword. For the proposed network, the data source (x_s) is encoded by directly applying the generator matrix to the Hamming encoder. The encoding data based on the Hamming code can be expressed as [13]

$$\bar{x}_s = x_s \times G \tag{4}$$

where G is a generator matrix that is formed as

$$G = |\mathrm{I}_k : \mathrm{P}| \tag{5}$$

The encoded data are then modulated with binary phase-shift keying. The cooperative process is performed in the following two stages.

Step A: In the first stage, the source sends the modulated data directly to the destination (*S*, *D*) and to several relays (*S*, R_i), where i=1, 2, ⋯, *k*. Noise, which is added to the received signals at the relays and the destination, occurs during the transmission process as the wireless channel is not ideal. Therefore, the signals received by the relays and the direct path can be expressed as follows [13]:

$$y_{SR_i} = h_{SR_i}\bar{x}_s + n_{R_i} \tag{6}$$

$$y_{SD} = h_{SD}\bar{x}_s + n_D \tag{7}$$

where y_{SR_i} is the received signal at relay *i*, h_{SR_i} is the channel coefficient at the link source and relay *i*, $\bar{x}_s$ is an encoded signal from the source, and n_{R_i} is the noise produced at the link source and relay *i*. Furthermore, y_{sd} is the data received from the direct path, h_{SD} is the channel coefficient of the direct link, and n_D is the direct path's noise.

Step B: The signal received by the relays is then forwarded to its destination by a protocol relay mechanism. Generally, signals from relay *i* to destination (R_i, *D*) can be obtained as

$$y_{R_iD} = h_{R_iD}\bar{x}_s + n_{R_iD} \tag{8}$$

where y_{R_iD} is the received signal at the destination, sent by relay *i*, h_{R_iD} is the channel coefficient at link relay *i* and destination (R_i, *D*), and n_{R_iD} is the noise generated between relay *i* and the destination. In this study, the AF and QF protocols are used for the amplification. Therefore, y_{R_iD} is generated via the mechanisms of the given relay protocols, as follows:

A. AF Relay Process

In the AF relay, the receipt of the signal by the relay, as in (8), is expressed as follows:

$$y_{R_iD} = h_{R_iD}\beta_i\hat{x}_s + n_{R_iD} \tag{9}$$

with

$$\beta_i = \sqrt{\frac{P_{R_i}}{\left|h_{SR_i}\right|^2 P_S + N_0}} \tag{10}$$

where β_i is the amplification factor at AF relay *i*, P_{R_i} is the power at relay *i*, P_S is the transmitted power at the source, and N_0 is an additive white Gaussian noise.

B. QF Relay Process

Using the QF relay, the received signal is quantized at some stage of the process, as follows [13]:

$$\varDelta = (y_{R_iD,\max} - y_{R_iD,\min})/L \tag{11}$$

$$L = 2^b \tag{12}$$

$$j = \text{round}\left(y_{R_iD} - \frac{y_{R_iD,\min}}{\varDelta}\right) \tag{13}$$

$$\tilde{y}_{R_iD} = y_{R_iD,\min} + j\varDelta,\ \ j = 0,1,\cdots,L-1 \tag{14}$$

where $\varDelta$ is the quantization level interval, *L* is the quantization level, *b* is the number of quantization bits, and y_{R_iD} is the quantized signal in relay *i*.

At the receiving end, signals from either direct or multiple transmissions are combined via maximum ratio combining (MRC). Further demodulation and decoding are then performed to obtain the signal information received at the destination. The channel coefficients are usually modeled as independent zero means of circularly symmetric, complex Gaussian random variables using σ_{SD}^2, σ_{SRi}^2, and $\sigma_{R_iD}^2$. The channel model is assumed to be a Rayleigh distribution, which is well-known as a flat-fading Rayleigh channel. Signals received at each stage are combined using the MRC technique, whereby the output signal from MRC is expressed as

$$y = \alpha_{SD}y_{SD} + \sum_{i=1}^{k}\alpha_{SR_i}\tilde{y}_{R_iD} \tag{15}$$

where α_{SD} and α_{SR_i} are the MRC coefficients for direct link and cooperative link transmissions, respectively. The MRC coefficient can be obtained as follows:

$$\alpha_{SD} = \frac{\sqrt{P_S}\,h_{SD}}{N_0} \tag{16}$$

$$\alpha_{SR_i} = \frac{\sqrt{P_S}\,h_{SR_i}h_{R_iD}}{[N_0(1+\left|h_{R_iD}\right|^2)]} \tag{17}$$

where P_S is the source power and N_0 is the noise channel variant. The output signal from MRC, *y*, is passed to the demodulator and decoder to recover the data bits as input bits from the source. In the decoder, the syndrome of the data bits (*S*) is obtained for error detection and the correction of the bit error in a codeword, which is obtained as

$$S = y \cdot H^T \tag{18}$$

where *y* is the possibility of the error bit and H^T is the transpose parity-check matrix. Assuming that *S*= 0, no bit error occurs and data should be reconstructed well. Conversely, where *S*=1, an error has occurred in the output signal of MRC.

III. EE ANALYSIS

An EE analysis was performed in the direct and cooperative system links to determine the rates of energy-saving. The total energy consumption of the system was assumed to comprise power consumption by power amplification, as well as other circuitry, on each component (i.e., source, relay, and destination). The loss factor of power gain δ was subsequently determined in the range of $0<\delta<1$.

A. Direct Path

Energy is a vital factor in wireless communications since the devices in the system consume so much power. For direct communication, energy is required to send data to the destination. The amount of energy is dependent on the amount of data sent, at what rate it is sent, and power gain. Therefore, the total energy consumption of the direct path can be expressed as follows:

$$E_{\mathrm{SD}} = \left(P_t(1+\delta) + P_{ct} + P_{cr}\right)\left(n/R_b\right) \tag{19}$$

where P_t is the power transmitted, P_{ct} is the power consumed by the transmitter, P_{cr} is the power consumed by the receiver, and R_b is the bit rate. Here, we assume that the power transmission (P_t) is the same as the power source (P_S) for the cooperative path.

In wireless channels, BER a crucial parameter of the receiver, which ensures system quality or performance. BER can be determined from the following equation:

$$BER_{SD} = \frac{\text{Total of transmitted bits } S-D}{\text{Total of error bits}} \tag{20}$$

Following is a basic definition of EE [26]:

$$EE\left(\text{bit/Joule}\right) = \frac{\text{Data rate }\left(\text{bit/s}\right)}{\text{Energy consumption }\left(\text{Joule/s}\right)} \tag{21}$$

Therefore, the EE of the direct path can be calculated as

$$\varepsilon_{\text{direct}} = n(1-BER_{\mathrm{SD}})/E_{\mathrm{SD}}\,. \tag{22}$$

B. Cooperative Paths

The cooperative system used in this paper comprises a source, several relays, and a destination. The total power consumption rates for the multiple-relay cooperative networks with AF and QF protocols can be expressed with discrete random variables. For a three-relay cooperative system, the total power consumption can be calculated as

$$P_{coop} = \begin{cases} P_t\left(1-\delta\right) + P_{ct} + 2P_{cr},\ (1-BER_{SD}) \\ P_t\left(1-\delta\right) + P_{ct} + 2P_{cr},\ (BER_{SD}BER_{SR}) \\ 2P_t\left(1-\delta\right) + 2P_{ct} + 3P_{cr},\ (BER_{SD}(1-BER_{SR})) \\ 3P_t\left(1-\delta\right) + 3P_{ct} + 4P_{cr},\ (BER_{SD}BER_{SR}(1-BER_{SR})) \end{cases} \tag{23}$$

where BER_{SR} is the BER of the source to the relay path, which can be calculated as follows:

$$BER_{SR} = \frac{\text{Total of transmitted bits } S-R}{\text{Total of error bits}} \tag{24}$$

The total energy consumption for either MR-AF or MR-QF is

$$\begin{aligned} E_{\text{coop}} = {} & \frac{(1-BER_{\mathrm{SD}})(P_t\left(1-\delta\right) + P_{ct} + 2P_{cr})n}{R_b} + \\ & \frac{\left(BER_{\mathrm{SD}}BER_{SR}\right)\left(P_t\left(1-\delta\right) + P_{ct} + 2P_{cr}\right)n}{R_b} + \\ & \frac{(BER_{\mathrm{SD}}(1-BER_{SR}))(2P_t\left(1-\delta\right) + 2P_{ct} + 3P_{cr})n}{R_b} + \\ & \frac{(BER_{\mathrm{SD}}BER_{SR}(1-BER_{SR}))(3P_t\left(1-\delta\right) + 3P_{ct} + 4P_{cr})n}{R_b} \end{aligned} \tag{25}$$

Based on the obtained energy consumption value, EE can be obtained as

$$\varepsilon_{\text{coop}} = \frac{n(1-BER_{\text{coop}})}{E_{\text{coop}}} \tag{26}$$

IV. RESULTS AND DISCUSSIONS

In carrying out the EE analysis per the previous section, several system parameters were considered during the computer simulations, including distance ratio, several Hamming codes, quantization level, and the relay amplification factor. The distance from the source to the relay, and from the relay to the destination, was considered in the distance ratio, where the distance ratio from the source to the destination was 1. Table I lists the fixed parameters that were used in the computer simulations. The length of a given codeword depends on the coding channel used as well as the bit rate.

TABLE I: SIMULATION PARAMETERS

Description	**Remarks**
Source	1
Number of relays	3
Destination	1
Data input	10^5 bits
Distance ratio	0.1–1.0
The MRC coefficient ($\propto$)	3
Loss factor of power gain (δ)	0.3
Power transmit (P_t) or power source (P_S)	10 mW
Power consumption of transmitter (P_{ct})	10^{-4} W
Power consumption of receiver (P_{cr})	5×10^{-5}W
Signal-to-noise ratio (SNR)	0–15 dB
Hamming codes	HC(7, 4), HC(15, 11), and HC(31, 26)
Level quantization of QF relay	2, 4, and 8

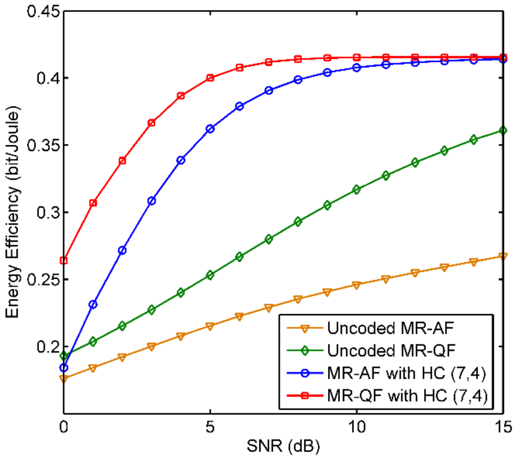

Fig. 2. Comparison of EE levels for coded and un-coded MR-AF and MR-QF.

Based on the simulation model and its parameters, the EE with SNR for multiple-relay networks with AF and QF protocols, with and without Hamming coding, was simulated, as seen in Fig. 2. The results of this simulation show that an increase in EE accorded an increase in SNR value. Moreover, the EE of the multiple-relay network with Hamming coding was higher than that without for both the AF and QF relay protocols. Furthermore, the MR-QF networks achieved higher EE compared to the MR-AF networks both with and without the use of Hamming codes. More energy was consumed by the AF relay network owing to the power amplification being applied to the signal before being forwarded to the destination. However, the quantization process involved with the QF protocol minimized the bit error, leading to energy being consumed more efficiently. The AF relay's level of complexity was found to be lower than that of the QF relay.

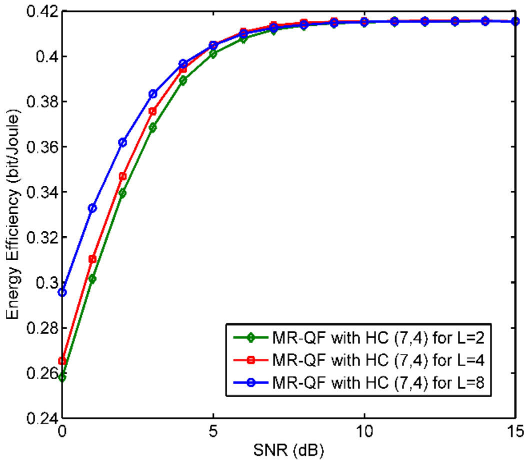

Fig. 3. Impact of quantization levels on the EE of multiple-relay QF with Hamming coding (7, 4).

Fig. 3 presents the results of the simulation of the MR-QF network's EE using Hamming coding (7, 4), based on the quantization levels. At the QF relays, the given level of quantization can improve the network's performance and EE. In other words, the higher the level of quantization used, the lower will the error rate be, lowering the network's energy consumption. Thus, the EE at a high level of quantization is higher than that for systems with low levels of quantization. However, this level of quantization only yields higher EE for SNR < 10 dB; the EE will remain the same when SNR > 10 dB, regardless of the quantization level. With the input bits in the simulation set to 10^5, the smallest BER of HC (7, 4) can be achieved at 10^{-5}, theoretically, at an SNR of approximately 9.5 dB, meaning that an increase in SNR of >10 dB would have no further influence on the system's BER performance.

The rate of energy consumption in the QF relay was nearly identical for all quantization levels because the link performance was similar at SNR > 10 dB. Thus, the EE level for HC (7, 4) at different quantization levels overlapped each other, as shown in Fig. 3.

The use of different Hamming codes for the MR-AF and MR-QF networks was simulated to obtain the levels of EE. A general characteristic of channel coding is that increasing the code length can reduce the BER. The simulation results of this are shown in Fig. 4, where the Hamming code with more bits resulted in a higher level of EE. Because a longer Hamming code has a more flexible minimum distance among the codewords and is robust against noise during transmission, it can be used in a cooperative network to reduce the BER. As an example, the EE achieved using the Hamming code (31, 26) was higher than the Hamming code (7, 4) for both the MR-AF and MR-QF networks.

The EE for MR-QF was higher than that for MR-AF for all simulated Hamming codes. The performance of a Hamming code can be characterized by the SNR value, where the performance of the HC will improve with an increase in the SNR. In general, a low SNR range produces a high BER, implying that it consumes considerable energy. Therefore, the EE was low, as shown in Fig. 3, for SNR ranges between 0 and 10 dB. Conversely, when the SNR was >10 dB, the MR-AF and MR-QF with HC (31, 26) demonstrated the lowest BER performances achieved with the two codes, resulting in a roughly identical level of EE for both networks.

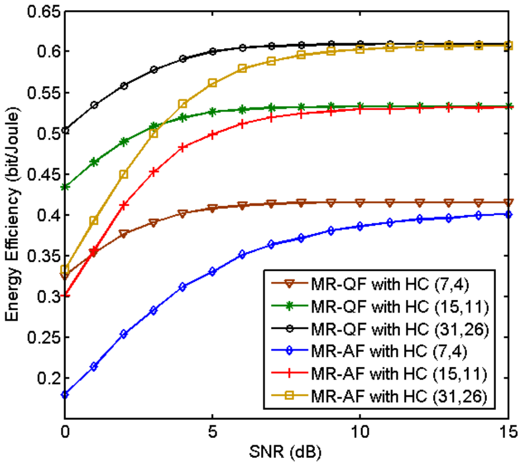

Fig. 4. Comparison of EE for MR-AF and MR-QF with different Hamming codes.

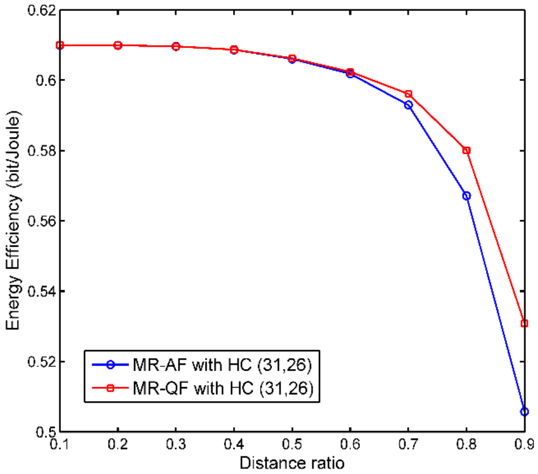

Fig. 5. Comparison of EE with relay distance ratio for MR-AF and MR-QF with Hamming code (31, 26).

Fig. 5 shows a comparison of EE with the relay distance ratio for the MR-AF and MR-QF networks with the same Hamming code (31, 26). In this context, EE generally tends to decrease as the distance to the relay increases. The EE in the MR-QF network was still better than that in the MR-AF network. However, at a distance ratio of up to 0.5, the EE for both networks was similar. However, when the relay distance ratio was increased to >0.5, the EE decrease in MR-AF was more significant than that in MR-QF. This is because the AF network requires higher reinforcement power as the relay distance ratio increases, or else the power consumption level in the AF will increase with the relay distance ratio.

V. CONCLUSION

This paper presented an analysis of the EE of multiple-relay cooperative networks using Hamming codes. The multiple-relay networks to be considered included the AF and QF relay protocol mechanisms. Three types of Hamming codes were applied to the multiple-relay networks. To determine the EE, the network model and system parameters need to be considered for energy consumption in each network, which were simulated using a computer. The simulation results showed that the EE for the MR-AF and MR-QF protocols was enhanced using Hamming coding. The application of the Hamming codes to the MR-QF network resulted in higher EE than that in the MR-AF network. Furthermore, the quantization level of the MR-QF network was found to impact the EE, where higher quantization levels resulted in higher levels of EE. Moreover, longer Hamming codes provided higher EE than shorter ones. The distance to the relay in the network also affected the EE of the networks with both relay protocols. However, the EE of MR-QF was still higher at the same relay distance ratio. Thus, the application of Hamming coding to the MR-QF protocol is a promising method for enhancing performance while improving EE.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Nasaruddin Nasaruddin conducted the research, performed simulation, and wrote the paper; Ramzi Adriman and Afdhal Afdhal verified simulation data and reviewed the paper; Nasaruddin Nasaruddin and Afdhal Afdhal analyzed data and revised the paper. All authors had approved the final version.

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