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Video multicast cooperative communication in 5G systems with radio frequency energy harvesting

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ABSTRACT

In this paper, the performance of radio frequency energy harvesting cooperative multicast communication is analyzed in terms of outage probability. The multicast communication between base station (BS) and multiple destinations is assisted by one energy harvesting relay chosen from multiple energy harvesting relays. The relays harvest energy from the BS transmissions to be able to transmit for cooperation. We propose two power splitting approaches at the relays for energy harvesting. The first approach splits the received signal at the relays into two portions and send them to decoding/energy harvesting circuitry, simultaneously. In the second approach, the received signal during any receiving time is either sent to the information decoding circuitry or energy harvesting circuitry depending on the strength of the received signal. Analytical expressions of outage probability for these two power splitting approaches are derived. The derived expressions are validated by comparing them with the simulation results. Further, the outage probability of our proposed energy harvesting cooperative multicast system is almost equal to the non-energy harvesting cooperative multicast system.

1. Introduction

The advancement in display technology of the mobile devices has resulted in exponential rise in the mobile video communication. The video communication is also an integral part of the 5G communication standard. It is believed that the video communication traffic will comprise 75 percent of the overall mobile communication traffic in 2020. Therefore, it is of immense importance to make the video communication spectrum efficient in order to meet the spectral efficiency goals of the 5G standards. One way to increase spectral efficiency is through multicasting. This is possible when multiple mobile users are interested in watching same video content e.g. a sport event or news. The basic idea of multicasting utilizes the broadcast nature of the wireless communication. Although, spectrally efficient the mutlicasting is not always energy/power efficient. This is explained with the help of following example. Assume two mobile users, u_1, u_2, send request for same video content to the base station (BS). Further, assume that the channel condition of u_1 is better than the channel condition of u_2. In this situation the transmit power of the BS must be adjusted according to the worst user so that both users can decode successfully. The main problem in the above scenario is that the BS may not have good channel conditions with all of the mobile users. This problem can be dealt with the help of cooperative communication. Essentially, in cooperative communication the multicast communication between the BS and mobile users is assisted by some helping nodes. The helping nodes are termed as relays. Increasing the number of relays results in higher probability of finding a relay that has good channel conditions with all the mobile users thanks to the increased degrees of freedom provided by the cooperative communication. The communication between BS and destinations is accomplished in two transmission phases. During the first transmission phase the BS transmit the signal to relays and destinations. While during the second transmission phase one of the relays is selected for retransmitting the received signal to all the destinations. The destinations combines the signals received from the BS in first transmission phase and that received from the selected relay during the second transmission phase. In conventional cooperative multicast communication, the relays use their own energy to assist the communication between the BS and mobile users. However, the video multicast communication may last over several minutes and therefore may result is exhaustion of the relay batteries. Due to this reason, it is reasonable to consider the possibility of providing energy/power to the relays for their trans-

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missions. Although there has been lot of research efforts carried out to study the cooperative mulitcast system however the study of energy harvesting (EH) cooperative video mulitcast system is not present in the existing literature. Due to the aforementioned characteristic (longer communication) of video multicast, it becomes very crucial to study the performance of energy harvesting cooperative video multicast system.

Among various energy harvesting techniques, the energy harvesting efficiency of the radio frequency (RF) energy harvesting is the highest [1]. In RF energy harvesting cooperative communication the relays harvest energy from the received signal in addition to retrieving information from the received signal. This is accomplished by splitting the received signal at the relay into two portions. One portion is sent to the energy harvesting circuitry while the remaining portion is used for information decoding. The splitting of the received signal at the relays raises following questions: (i) How much portion of the received signal should be sent to the EH circuitry and information decoding circuitry? This is because if higher portion of the received signal is sent to the EH circuitry then decoding may fail, on the contrary a higher portion sent to information decoding circuitry may result in very small power for transmission purpose at the relay. (ii) How the splitting of the received signal affects the performance of the video multicast communication?

To answer the above questions, we study the outage probability of EH cooperative multicast system. The relays use dynamic power splitting protocol for energy harvesting. The main benefit of dynamic power splitting is that it allocates the power to information decoding and energy harvesting circuitry according to the strength of received signal. The decoding result at the relays and the amount of harvested energy at the relays depend on the channel conditions between BS and relays. Further, the channel conditions between different relays and different destinations are independent. Since, the success of multicast communication depends on the success of all the destinations. Therefore, we define the outage event when no relay can support the communication between BS and all the destinations in the presence of direct connection between BS and all the destinations. We study two power splitting approaches at the relays for energy harvesting and information decoding. The contributions of this paper can be summarized as follows.

- We propose an RF energy harvesting cooperative video multicast system where a selected relay, among multiple relays, assist the communication between BS and all the video user (VU) destinations. In contrast to conventional cooperative multicast system, the relay in our proposed system uses RF energy harvesting from the BS to power its transmission.
- We consider two power splitting approaches for energy harvesting at the relays. The power splitting approaches are termed as first transmission phase dependent (FPD) and average of first transmission phase dependent (APD). In addition, we provide an analytical expression for the suboptimal transmit power for FPD approach.
- We analyze the outage probability of the proposed system and provide novel analytical expressions for the outage probability.
- We compare the analytical results with the results achieved through extensive simulations.

The rest of the paper is organized as follows. Section 2 presents a comprehensive literature review and our motivation. System model is discussed in Section 3. Outage probability analysis of the proposed system is carried out in Section 4. Section 5 presents simulation results and the conclusions of the paper are presented in Section 6.

2. Related work

There has been a lot of research effort put into the study of cooperative multicast systems. A power allocation scheme based on outage probability minimization is proposed in [2]. In their work, the authors have assumed that a single relay assist the communication between source and multiple destinations. In [3], the optimum relay location strategies and power allocation of multiple relays are proposed for cooperative multicast system. Their proposed power allocation and relay location schemes are based on the average outage probability of all the destinations. A two stage cooperative multicast with optimized power consumption and guaranteed coverage is proposed in [4]. It is shown that the two stage cooperative scheme outperforms the conventional one stage scheme with respect to the power consumption at the BS. The same authors have proposed an energy efficient two stage cooperative multicast system [5] which is preferable when the user density is sufficiently high. A social aware device to device based video multicast system is proposed in [6]. They have proposed a group formation solution based on the coalitional game theory and further proposed a resource allocation scheme for BS to handle the resource requests. The performance of a multicast scheme depends on the availability of the channel state information among different communicating entities. In this regard, an efficient time allocation scheme is proposed in [7] to obtain the channel state information at the source and to find the optimal time duration of the BS/relay transmission. It is shown that considerable improvement in the outage probability and average transmit power of the relays can be achieved by using their optimal time allocation scheme. A spectrum allocation algorithm to improve the performance of video traffic while satisfying the voice traffic constraints is proposed in [8]. Their proposed algorithm satisfy the voice traffic QoS constraints by allocating a higher priority to the voice traffic with comparison to the video traffic. The exact outage probability analysis of cooperative multicast communication is carried out in [9]. It is shown that the diversity order of the best relay selection scheme is the same as of that achieved by all relay cooperation scheme. A similar analysis is carried out in [10] except that the effect of cochannel interference is also considered while analyzing the outage probability of the Nth best relay selection scheme. A successive relaying based cooperative multicast system is proposed in [11]. Analytical expression for the outage probability of the quantize-map-forward relays is provided. However, the authors of [11] assumed no direct connection between the source and all the destinations.

None of the above works discuss energy harvesting at the relays. Multicasting with energy harvesting is discussed in [12–18]. A renewable energy based energy harvesting cooperative multicast system is proposed in [12]. The optimal transmit powers of the relays and their on-off operation with respect to energy efficiency are found through line search. The energy harvesting efficiency for radio frequency energy harvesting is the highest as compared to other renewable sources. With this consideration, the remaining works have advanced the application of RF energy harvesting in multicast systems. A method for maximizing the secrecy rate of the energy harvesting multicast system is proposed in [13]. A similar study is provided in [14] in which the secrecy is maximized when energy receivers try to eavesdrop on the signal that is intended for information receivers. This work is extended in [15] to consider the possibility of imperfect channel state information at the BS. A transmit power minimization scheme at the BS is proposed in [16]. The transmit power minimization at the BS is achieved by using efficient beamforming at the BS and adjusting the power splitting at the receiver for energy harvesting. A low complexity implementation of [16] is provided in [17] to make it feasible for massive MIMO systems. The above works consider single group of receivers where each receiver is interested in same

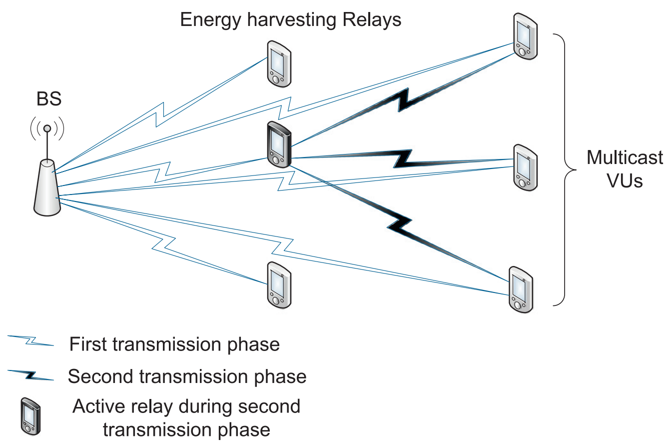

Fig. 1. System model comprising of BS, energy harvesting relays and multicast destinations.

content. In reality it is possible that receivers can be grouped according to their requested content. In this context, an antenna selection scheme for multigroup multicasting system is proposed in [18]. The goal of their proposed algorithm is to minimize the transmission power of the BS while satisfying the QoS constraints with respect to information and energy transfer.

Although there is a lot of literature available for cooperative multicasting and energy harvesting however, to the best of our knowledge, there is no existing work that study the performance of cooperative multicast communication when the relays use energy harvesting for their transmissions. The energy harvesting at the relays is crucial specially when the communication has to be carried out for longer periods e.g. video communication. Therefore, in this paper we propose an energy harvesting based cooperative video multicast system and analyze its performance in terms of outage probability.

3. System model

We consider a cooperative downlink video multicast system. The system model comprises of a BS, K energy harvesting decode-and-forward relays and J VU destinations. A pictorial depiction of the system model is presented in Fig. 1. The relays work in half duplex manner. We assume that all the VUs are interested in same video content. The video multicast comprise of two transmission phases. In first transmission phase, the BS transmit the video signal to all the relays and VUs. Some of the relays will be able to decode the information sent by the BS in first transmission phase. These relays are termed as successful relays. One of these successful relays will transmit during the second phase of transmission to all the VUs. The VUs combine the received signal from BS and the selected relay with maximum ratio combining (MRC). The channel between any two communicating nodes are Rayleigh distributed. The channel between a BS and ith relay is represented by h_i while the channel between the BS and ith VU is represented by g_i. Similarly the channel between ith relay and jth VU is represented by $f_{i,j}$. We assume that the average values of $|h_i|^2$, $|g_i|^2$, $|f_{i,j}|^2 \quad \forall \quad i, j$ are equal to λ_h, λ_g and λ_f, respectively. Assuming that BS transmits at power P_B, the received signal at the ith relay (y_i) and jth VU (z_j) during the first transmission phase can be written as follows

$$\begin{aligned} y_i &= \sqrt{P_B} h_i x + n_i, \\ z_j^{1st} &= \sqrt{P_B} g_j x + n_j, \end{aligned} \tag{1}$$

where x is the transmitted symbol of the BS. n_i, n_j are the AWGN noises at the ith relay and jth VU with variance N_0. The superscript $1st$ denotes the reception during the first transmission phase. The mutual information between BS and jth VU during first transmission phase is

$$I_j^{VU,1st} = \frac{1}{2}\log\left(1 + \frac{P_B|g_j|^2}{N_0}\right), \tag{2}$$

where the factor $\frac{1}{2}$ accounts for the fact that transmission is accomplished in two transmission phases. The relays use energy harvesting to power the transmission to VUs. Power splitting protocol is used at the relays due to its simplicity. In power splitting protocol, the ith relay splits the received signal into two portions. One portion α_i $(0 < \alpha_i < 1)$ is fed to the energy harvesting circuitry while the remaining portion $1 - \alpha_i$ $(0 < 1 - \alpha_i < 1)$ is fed to the information processing circuitry for decoding. α_i is termed as the power splitting factor. The signal fed to information processing circuitry at the ith relay is given as follows

$$y_i^{inf} = \sqrt{(1 - \alpha_i)P_B} h_i x + n_i. \tag{3}$$

The outage performance of the energy harvesting cooperative system depends on α and hence its value should be adjusted accordingly. From (3) we can find the mutual information (data rate) between the BS and ith relay as follows

$$I_i^R = \frac{1}{2}\log\left(1 + \frac{(1-\alpha_i)P_B|h_i|^2}{N_0}\right). \tag{4}$$

As we have assumed decode-and-forward relaying protocol at the relays therefore the relaying operation will only be required if the decoding at the relay is successful. This consideration can result in two power splitting approaches. In the *first* approach we use the harvested power, the power that remains after successful decoding, in the first transmission phase for retransmission during second transmission phase. Since the channel conditions between BS and relays may vary over time hence the harvested power may also vary with time. We assume that a successful transmission from a relay can only take place if the harvested power in the first transmission phase is higher than a given threshold (P_{th}^{1st}). The transmit power of the relay is set to P_{th}^{1st} and the extra harvested power is used by the relay for its own purposes. We denote this power splitting approach as first phase dependent (FPD). In the *second* power splitting approach, if the relay is able to decode the received signal correctly then the whole received signal is sent to information decoding circuitry and no signal part is sent to the energy harvesting circuitry. On the other hand, if the signal cannot be decoded correctly then whole received signal is fed to the energy harvesting circuitry. The transmit power of the relay is equal to the average harvested power during the first transmission phase. We denote this power splitting approach as average of first phase dependent (APD).

For the FPD approach, assuming that the required data rate is R that is $I_i^R = R$ then the value of α_i can be obtained as follows

$$\alpha_i = 1 - \frac{N_0(2^{2R} - 1)}{P_B|h_i|^2}. \tag{5}$$

On the other hand, if $|h_i|^2 < \frac{N_0(2^{2R}-1)}{P_B}$ then α_i will be negative according to above relation. Therefore, to avoid such situation we set the optimal value of α_i to be

$$\alpha_i^* = max\left(0, 1 - \frac{N_0(2^{2R} - 1)}{P_B|h_i|^2}\right). \tag{6}$$

With this power splitting factor, the harvested power at ith relay during the first transmission phase can be written as follows

$$P_h^i = \eta\alpha_i^* P_B|h_i|^2,$$

$$P_h^i = max(0, \eta(P_B|h_i|^2 - (2^{2R} - 1)N_0)), \tag{7}$$

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where η is the energy harvesting efficiency and for simplicity of exposition we assume its value to be 1 however the rest of the analysis is applicable to any value of η. It can be noted that we have not considered the AWGN noise in our expression for harvested power. This is done to avoid the complexity of the analysis [19,20].

For the APD approach, assuming that the required data rate is R that is $I_i^R = R$ then the value of α_i can be obtained as follows

$$\alpha_i = \begin{cases} 0 & \text{if} \quad |h_i|^2 \geq \frac{N_0(2^{2R}-1)}{P_B}, \\ 1 & \text{if} \quad |h_i|^2 < \frac{N_0(2^{2R}-1)}{P_B}. \end{cases} \tag{8}$$

The corresponding harvested power during the first transmission phase given that $|h_i|^2 < \frac{N_0(2^{2R}-1)}{P_B}$ is

$$P_h^i = \eta P_B |h_i|^2. \tag{9}$$

The average value of P_h^i is as follows

$$E[P_h^i] = \underbrace{\frac{\eta P_B}{\lambda_h}\left(1 - \frac{1+\lambda_h \frac{N_0(2^{2R}-1)}{P_B}}{e^{\lambda_h \frac{N_0(2^{2R}-1)}{P_B}}}\right)}_{E\left[P_h^i \middle| |h|^2 < \frac{N_0(2^{2R}-1)}{P_B}\right]} \underbrace{\left(1 - e^{-\lambda_h \frac{N_0(2^{2R}-1)}{P_B}}\right)}_{P\left(|h_i|^2 < \frac{N_0(2^{2R}-1)}{P_B}\right)}. \tag{10}$$

The APD scheme is less complex for implementation at the relay since it can be implemented with the help of a switch that directs the whole received signal towards energy harvesting or information decoding circuitry depending upon the strength of the received signal. However, more complex circuitry will be required to implement the FPD power splitting scheme. Since, the received signal should be splitted into two portions within every receiving time.

If i^*th relay is selected to transmit during the second phase of transmission and if the transmission power of the i^*th relay is P_{i^*} then the received signal at the jth destination can be written as follows

$$z_j^{2nd} = \sqrt{P_{i^*}} f_{i^*,j} x + n_j, \tag{11}$$

where the superscript $2nd$ denotes the reception during the second transmission phase. As described above the destination will combine the signals received during the first transmission phase and second transmission phase for decoding. Therefore, the mutual information at the jth destination can be written as follows

$$I_j^{VU,2nd} = \frac{1}{2}\log\left(1 + \frac{P_B|g_j|^2}{N_0} + \frac{P_{i^*}|f_{i^*,j}|^2}{N_0}\right). \tag{12}$$

Since, the data rate in the multicast communication depends on the data rate of the worst destination therefore the mutual information for the multicast communication can be written as follows

$$I_{MC}^{i^*} = \min_{l\in(1\cdots J)} \frac{1}{2}\log\left(1 + \frac{P_B|g_l|^2}{N_0} + \frac{P_{i^*}|f_{i^*,l}|^2}{N_0}\right), \tag{13}$$

where the subscript MC means multicast and superscript i^* indicates the selection of i^*th relay. Since, there are K number of total relays therefore we consider that an outage occurs when none of the K relays can provide the desired data rate. Mathematically, the outage event can be written as

$$I_{MC}^1 < R, I_{MC}^2 < R \cdots I_{MC}^K < R \tag{14}$$

$$\max_{i^*\in(1\cdots K)}\left(\min_{l\in(1\cdots J)} \frac{1}{2}\log\left(1 + \frac{P_B|g_l|^2}{N_0} + \frac{P_{i^*}|f_{i^*,l}|^2}{N_0}\right)\right).$$

Our aim is to find the probability of the event described in (14). This probability is defined as the outage probability and it is a very important parameter to gauge the performance of a communication system.

T_{BS}	T_{R1}	NA_1	T_{R2}	NA_2	First transmission phase	Second transmission phase

Fig. 2. Relaying scheme for two relay case.

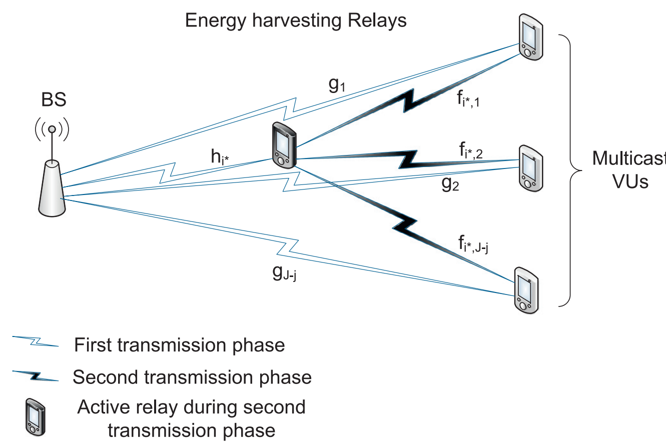

Fig. 3. Simplified system model with one energy harvesting relay.

Remark 1. From (14) it can be easily noted that we are considering the outage probability of famous Max-Min relay selection scheme. This scheme requires the exact channel state information between all the communicating entities at the source [9]. The availability of this information at a central node (for example at source) results in excessive communication overhead especially when the number of communicating entities are large. Therefore, in the following we provide a relaying scheme that achieves same outage probability as the Max-Min relay selection scheme without requiring the channel state information at any central node.

3.1. Relaying scheme

It is widely known that communication between any nodes will not be successful if the received signal to noise ratio is lower than a certain threshold. In our proposed relaying scheme, we divide the whole transmission time into $2K+3$ time slots. A simplified version for two relay case is shown in Fig. 2. The first transmission phase and second transmission phase discussed above occur in the last two time slots and hence the above discussion is still valid. During the first time slot (labeled T_{BS}) the BS transmits a pilot signal. With the help of this pilot signal the relays and VU destinations can find their channel states with the BS. If the channel between relay $R1$ and BS is such that $P_B|h_1|^2 \geq N_0(2^{2R}-1)$ then the relay $R1$ transmits a pilot signal during the second time slot (labeled T_{R1}). All of the VU destinations can find their respective channel conditions ($|f_{i,j}|^2$) with the help of this pilot signal from $R1$. On the other hand, if $P_B|h_1|^2 < N_0(2^{2R}-1)$ then no transmission takes place from relay $R1$. After T_{R1} all the VU destinations combine the received signal from BS and relay $R1$ and if for any of the VU destinations $P_B|g_j|^2 + P_1|f_{1,j}|^2 < N_0(2^{2R}-1)$ then that VU destination sends its negative acknowledgment in NA_1 time slot. If no VU destination sends a negative acknowledgment then we conclude that relay $R1$ can support the multicast communication and nothing is transmitted during T_{R2}. Otherwise, this procedure is repeated for relay $R2$ also and if a negative acknowledgment is received in NA_2 time slot then it means relay $R2$ also cannot support the desired data rate between BS and VU destinations. This procedure can be repeated for K number of times if we have K relays in the system and hence an outage event will occur only if no relay can support the multicast communication between BS and all the VU destinations at data rate R. Therefore, the outage probability of this scheme is the probability of the event described by (14). Hence, we conclude that this relaying scheme achieves same outage probability as achieved by the Max-Min scheme however without the need of exact channel states information at the source.

3.2. Signaling overhead

For the Max-min relay selection we need to know all the g_i's and $f_{i,j}$'s according to (14) at source. This required information increases with the increase in number of relays and VU destinations. On the other hand, the relaying scheme described in Section 3-A does not require all channel states information at source. Instead, it requires transmission of pilots from the successful relays, and negative acknowledgment in case of decoding failure at the VU destinations. This results in increase in signaling overhead. However, this overhead is dependent on the number of successful relays and number of failing VU destinations. The number of successful relays are generally less than the number of destinations and it is also highly likely that some of the destinations decode correctly. Therefore, the signaling overhead for the relaying scheme will be less than that needed for Max-min relay selection.

4. Outage probability analysis

In order to analyze the outage probability of multicast system presented in Fig. 1 we consider the outage probability of the system in which there is single energy harvesting relay. We denote this outage probability as P^1_{out}. The simplified system with single energy harvesting relay is shown in Fig. 3. The outage event **j** occurs if $0 \le j < J$ VU destinations decode the BS signal correctly during the first transmission phase and at least one of the remaining $J - j$ VU destinations fails to decode the received signal at the end of second transmission phase. The outage probability P^1_{out} can be found by summing the probabilities of event **j** for $0 \le j < J$. In the following we find the analytical expression for P^1_{out} for different transmit power schemes discussed above.

4.1. FPD power splitting approach

To find P^1_{out} the successful transmission probability of the relay, the probability that the relay transmit during the second phase of transmission, is required. In conventional cooperative commnunication, with decode-and-forward relay, the successful transmission probability of the relay is equal to the successful decoding probability of the relay. In FPD transmit power splitting scheme, the relay will transmit only when the harvested power in the first transmission phase is higher than a particular value P^{1st}_{th}. In this situation, even if the relay has decoded the BS signal correctly the transmission from the relay in the second transmission phase is not guaranteed because the harvested power may be lower than P^{1st}_{th}. Therefore, the probability of successful transmission from the relay during second transmission phase in our energy harvesting system is different than the conventional cooperative multicast system. We denote the probability of successful transmission from the relay during second transmission phase as $P_{r,ST}$. The successful transmission from the relay will occur if

$$\underbrace{P_B\alpha_i^*|h|^2}_{\text{harvesting part}} + \underbrace{P_B(1-\alpha_i^*)|h|^2}_{\text{decoding part}} \ge \underbrace{N_0(2^{2R}-1)}_{\text{successful decoding threshold}} + \underbrace{P^{1st}_{th}}_{\text{harvest power threshold}}. \tag{15}$$

hence we can write the probability of successful transmission from the relay as follows

$$P_{r,ST} = P\left(|h|^2 \ge \frac{P^{1st}_{th} + N_0(2^{2R}-1)}{P_B}\right),$$
$$P_{r,ST} = e^{-\lambda_h \frac{P^{1st}_{th} + N_0(2^{2R}-1)}{P_B}}. \tag{16}$$

Assuming that $0 \le j < J$ VU destinations decode the BS signal correctly during the first transmission phase we can write the outage probability of the multicast communication as follows

$$P^{1,FPD}_{out,j} = \binom{J}{j} \underbrace{P^j_{VU,1st}}_{\text{j VUs successful}} E_{\text{J-j direct links}}\Bigg[\underbrace{(1-P_{r,ST})}_{\text{relay fails}} + \underbrace{P_{r,ST}}_{\text{relay successful}} \underbrace{(1 - P_{VU_1,2nd}P_{VU_2,2nd}\cdots P_{VU_{J-j},2nd})}_{\text{at least one of J-j VUs fails}}\Bigg],$$
$$P^{1,FPD}_{out,j} = \binom{J}{j} P^j_{VU,1st} E_{\text{J-j direct links}}\Bigg[1 - P_{VU_1,2nd}P_{VU_2,2nd}\cdots P_{VU_{J-j},2nd}P_{r,ST}\Bigg], \tag{17}$$

where $P_{VU,\,1st}$ is the probability that a VU is able to decode the message correctly during the first transmission phase, $P_{VU,\,2nd}$ is the probability that a VU is able to decode the message correctly after combining the signals received during first and second transmission phases. Further, $E_{\text{m direct links}}[x]$ in (17) denotes the expectation of x over m direct links. The binomial operator appears in (17) because there are $\frac{J!}{j!(J-j)!}$ number of ways in which j successful VU destinations can be selected from a total of J VU destinations. Since, we have assumed i.i.d. channel characteristics therefore indexing of the users in (17) will only result in complexity of notation without any useful insights. The value of $P_{VU,\,1st}$ can be obtained using (2) as follows

$$P_{VU,1st} = P(I^{VU,1st}_j \ge R) = e^{-\frac{\lambda_g N_0(2^{2R}-1)}{P_B}}. \tag{18}$$

Similarly, we can find $P_{VU_i,2nd}$ with the help of (12) as follows

$$P_{VU_i,2nd} = P(I^{VU,2nd}_j \ge R) = e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P^{1st}_{th}} - \frac{P_B|g_i|^2}{P^{1st}_{th}}\right)}, \tag{19}$$

where we have assumed that the value of direct channel between the BS and ith VU destination is $|g_i|^2$. Putting (18), (19) into (17) and using the following definition of expectation

$$E_{x_1,\cdots x_n}[f(x_1,\cdots x_n)] = \int\cdots\int f(x_1,\cdots x_n) \times p(x_1)\cdots p(x_n)dx_1\cdots dx_n, \tag{20}$$

we can write (17) as

$$P^{1,FPD}_{out,j} = \binom{J}{j} e^{-j\lambda_g \frac{N_0(2^{2R}-1)}{P_B}} (\lambda_g)^{J-j} \int_0^{\frac{N_0(2^{2R}-1)}{P_B}} \cdots \int_0^{\frac{N_0(2^{2R}-1)}{P_B}} \Bigg[1 - e^{-\lambda_f(\frac{N_0(2^{2R}-1)}{P^{1st}_{th}} - \frac{P_B|g_1|^2}{P^{1st}_{th}})} \cdots e^{-\lambda_f(\frac{N_0(2^{2R}-1)}{P^{1st}_{th}} - \frac{P_B|g_{J-j}|^2}{P^{1st}_{th}})} \times e^{-\lambda_h(\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B})}\Bigg] e^{-\lambda_g|g_1|^2}\cdots e^{-\lambda_g|g_{J-j}|^2} d|g_1|^2\cdots d|g_{J-j}|^2, \tag{21}$$

where we have used $\lambda_g e^{-\lambda_g |g_i|^2}$ as the probability density function of $|g_i|^2$. The limit for direct channels ($|g_i|^2$'s) is taken from $0 \to \frac{N_0(2^{2R}-1)}{P_B}$ because we have assumed that $J-j$ VU destinations have not decoded correctly during the first transmission phase. Since all the channels are independent from each other therefore we can write the $P^{K,FPD}_{out,j}$ as follows

$$P^{K,FPD}_{out,j} = \binom{J}{j} e^{-j\lambda_g \frac{N_0(2^{2R}-1)}{P_B}} \lambda_g^{J-j} \int_0^{\frac{N_0(2^{2R}-1)}{P_B}} \cdots \int_0^{\frac{N_0(2^{2R}-1)}{P_B}} \Bigg[\Bigg\{1 - e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P^{1st}_{th}} - \frac{P_B|g_1|^2}{P^{1st}_{th}}\right)} \cdots e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P^{1st}_{th}} - \frac{P_B|g_{J-j}|^2}{P^{1st}_{th}}\right)} \times e^{-\lambda_h\left(\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}\right)}\Bigg\}^K\Bigg] e^{-\lambda_g|g_1|^2} \cdots e^{-\lambda_g|g_{J-j}|^2} d|g_1|^2 \cdots d|g_{J-j}|^2. \quad (22)$$

Using the binomial theorem and carrying out the integration we can write

$$P^{K,FPD}_{out,j} = \binom{J}{j} e^{-\lambda_g j\left(\frac{N_0(2^{2R}-1)}{P_B}\right)} \sum_{k=0}^{K} \binom{K}{k} (-1)^k e^{-k\lambda_h \frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}} \times e^{-k(J-j)\lambda_f \frac{N_0(2^{2R}-1)}{P^{1st}_{th}}} (\lambda_g)^{J-j} \zeta, \quad (23)$$

where $\zeta = \left(\int_0^{\frac{N_0(2^{2R}-1)}{P_B}} e^{-|g|^2\left(\lambda_g - k\lambda_f \frac{P_B}{P^{1st}_{th}}\right)} d|g|^2\right)^{J-j}$ which simplifies to

$$\zeta = \begin{cases} \left(\frac{N_0(2^{2R}-1)}{P_B}\right)^{J-j}, & \text{if } \quad k\lambda_f \frac{P_B}{P^{1st}_{th}} = \lambda_g \\ \left(\frac{1-e^{-\frac{N_0(2^{2R}-1)}{P_B}\left(\lambda_g - k\lambda_f \frac{P_B}{P^{1st}_{th}}\right)}}{\lambda_g - k\lambda_f \frac{P_B}{P^{1st}_{th}}}\right)^{J-j} & \text{if } \quad k\lambda_f \frac{P_B}{P^{1st}_{th}} \neq \lambda_g, \end{cases} \quad (24)$$

and $P^{FPD}_{out} = \sum_{j=0}^{J-1} P^{K,FPD}_{out,j}$.

Remark 2. From (23) it can be observed that $P^1_{out,j}$ is convex function of P^{1st}_{th} and therefore there exists an optimal value of P^{1st}_{th} for which the overall outage probability P^{FPD}_{out} is minimum. The convexity of outage probability with respect to P^{1st}_{th} can be explained as follows. For very small values of P^{1st}_{th} the probability that the relay successfully transmits increases however the probability that the transmission is correctly received at the VU destination reduces due to the reduction in transmit power from the relay. On the other hand, the situation is reversed for higher values of P^{1st}_{th} because in this case the probability of successful transmission from the relay reduces albeit the probability of correct decoding has improved owing to the increased transmit power of the relay. The optimal value of P^{1st}_{th} can be obtained by differentiating $P_{out,\ FDF}$ and solving for P^{1st}_{th}. Although we can find the optimal value of P^{1st}_{th} using numerical techniques however it is difficult to get a mathematical form of the solution. Due to this reason we consider a suboptimal solution for P^{1st}_{th} in the following Lemma.

Lemma 1. *The optimal value of P^{1st}_{th} when there is no direct connection present between BS and any of the destinations is given as follows*

$$P^{*1st}_{th} = \sqrt{P_B J N_0 (2^{2R}-1)}. \quad (25)$$

Proof. In the absence of direct connection between BS and VU destinations the outage probability for a single energy harvesting relay case can be obtained from (22) by putting all the $g_i = 0$ and $j = 0$. After these adjustments the outage probability for a K energy harvesting relay system can be written as follows

$$P^{K,FPD}_{out,NDC} = \left(P^1_{out,NDC}\right)^K = \left(1 - e^{-\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}} e^{-\frac{JN_0(2^{2R}-1)}{P^{1st}_{th}}}\right)^K. \quad (26)$$

Minimizing $P_{out,\ NDC}$ is equivalent to minimizing

$$1 - e^{-\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}} e^{-\frac{JN_0(2^{2R}-1)}{P^{1st}_{th}}}. \quad (27)$$

The product $e^{-\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}} e^{-\frac{JN_0(2^{2R}-1)}{P^{1st}_{th}}}$ is a concave function since $e^{-\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}}$ is a decreasing function of P^{1st}_{th} and $e^{-\frac{JN_0(2^{2R}-1)}{P^{1st}_{th}}}$ is an increasing function of P^{1st}_{th}. Further

$$\lim_{P^{1st}_{th}\to 0} e^{-\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}} e^{-\frac{JN_0(2^{2R}-1)}{P^{1st}_{th}}} \to 0$$
$$\lim_{P^{1st}_{th}\to \infty} e^{-\frac{P^{1st}_{th}+N_0(2^{2R}-1)}{P_B}} e^{-\frac{JN_0(2^{2R}-1)}{P^{1st}_{th}}} \to 0. \quad (28)$$

Hence we conclude that $P^1_{out,NDC}$ is a convex function. After taking the derivative of $P^1_{out,NDC}$ with respect to P^{1st}_{th} and equating it to zero we can get the result presented in (25). □

4.2. APD power splitting approach

In this scheme, the outage probability analysis can be carried out in a similar way as done for the FPD scheme case. Therefore, we consider the single energy harvesting relay case first and then we consider the multiple relay case. By using the value of power splitting factor in (8) and received signal at the relay in (3) the probability of successful decoding at the relay can be written as follows

$$P_{suc,R} = e^{-\frac{\lambda_h N_0(2^{2R}-1)}{P_B}}. \quad (29)$$

The relay will be able to transmit during the second transmission phase with probability 1 if the transmission power of the energy harvesting relay is equal to the average of the harvested power [21]. Since, we have assumed that the relay will transmit at the average of the harvested power therefore the probability of successful transmission from the relay is equal to the probability of successful decoding at the relay and therefore

$$P_{r,ST} = e^{-\frac{\lambda_h N_0(2^{2R}-1)}{P_B}}. \quad (30)$$

Now we need to find the transmit power of the relay. If we have a single relay then the transmit power of the relay is equal to the average harvested power during the first transmission phase provided in (10). However if we have multiple energy harvesting relays then the transmit power of the relay will be a multiple of (10) because the probability that a particular relay gets selected, among multiple successful decoding relays, for second transmission phase is less than 1 and hence harvested power may accumulate over multiple number of first transmission phase before a transmission occurs from that particular relay. On an average the harvested power will be accumulated $Ke^{-\frac{\lambda_h N_0(2^{2R}-1)}{P_B}}$ (= average number of successful decoding relays during the first transmission phase) times. Therefore, the transmit power of the relay, P^R_t, is given as follows

$$P^R_t = \frac{\eta K P_B}{\lambda_h}\left(1 - \frac{1+\lambda_h \frac{N_0(2^{2R}-1)}{P_B}}{e^{\lambda_h \frac{N_0(2^{2R}-1)}{P_B}}}\right)\left(1 - e^{-\lambda_h \frac{N_0(2^{2R}-1)}{P_B}}\right) \times e^{-\frac{\lambda_h N_0(2^{2R}-1)}{P_B}}. \quad (31)$$

Putting $P_{VU_i,2nd} = e^{-\lambda_f\left(\frac{2^{2R}-1}{P^R_t} - \frac{P_B|g_i|^2}{P^R_t}\right)}$ and $P_{r,ST} = e^{-\frac{\lambda_h N_0(2^{2R}-1)}{P_B}}$ in (16) we can write $P^1_{out,j}$ as follows

$$P^{1,APD}_{out,j} = \binom{J}{j} e^{-j\lambda_g \frac{N_0(2^{2R}-1)}{P_B}} \int_0^{\frac{N_0(2^{2R}-1)}{P_B}} \cdots \int_0^{\frac{N_0(2^{2R}-1)}{P_B}} \Bigg[1$$

Table 1
Simulation parameters.

Parameter	Value	Parameter	value
J	(5, 10)	K	(2, 4)
η	1	λ_f	.25
λ_h	.75	λ_g	1
P_B	5 – 40 watt	N_0	.001 watt
R	(1, 2) bps	P_{th}^{1st}	.01 – .5 watt

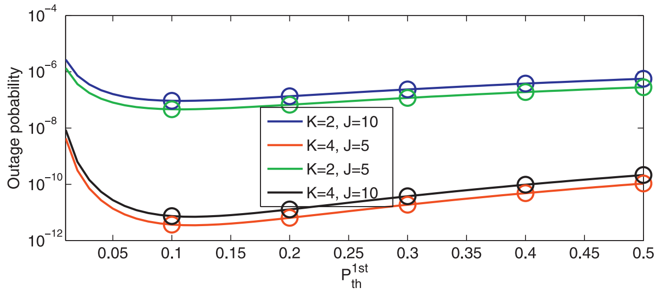

Fig. 4. Outage probability as a function of relay transmit power P_{th}^{1st} for FPD scheme with $R=1$ bps. The lines represent analytical results and circles represent simulation results.

$$-e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P_t^R}-\frac{P_B|g_1|^2}{P_t^R}\right)}\cdots e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P_t^R}-\frac{P_B|g_{J-j}|^2}{P_t^R}\right)}\times$$
$$e^{-\lambda_h\frac{N_0(2^{2R}-1)}{P_B}}\Bigg]\lambda_g e^{-\lambda_g|g_1|^2}\cdots\lambda_g e^{-\lambda_g|g_{J-j}|^2}d|g_1|^2\cdots d|g_{J-j}|^2, \qquad (32)$$

and for K number of relays $P_{out,j}^{K}$ becomes

$$P_{out,j}^{K,APD}=\binom{J}{j}e^{-j\lambda_g\frac{N_0(2^{2R}-1)}{P_B}}\int_0^{\frac{N_0(2^{2R}-1)}{P_B}}\cdots\int_0^{\frac{N_0(2^{2R}-1)}{P_B}}\Bigg[\Bigg\{1$$
$$-e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P_t^R}-\frac{P_B|g_1|^2}{P_t^R}\right)}\cdots e^{-\lambda_f\left(\frac{N_0(2^{2R}-1)}{P_t^R}-\frac{P_B|g_{J-j}|^2}{P_t^R}\right)}\times$$
$$e^{-\lambda_h\frac{N_0(2^{2R}-1)}{P_B}}\Bigg\}^K\Bigg]\lambda_g^{J-j}e^{-\lambda_g|g_1|^2}\cdots e^{-\lambda_g|g_{J-j}|^2}d|g_1|^2\cdots d|g_{J-j}|^2, \qquad (33)$$

which can be simplified using the binomial theorem. The overall outage probability will be $P_{out}^{APD}=\sum_0^{J-1}P_{out,j}^{K,APD}$ and is provided below

$$P_{out}^{APD}=\sum_{j=0}^{J-1}\binom{J}{j}e^{-\lambda_g j\left(\frac{N_0(2^{2R}-1)}{P_B}\right)}\sum_{k=0}^{K}\binom{K}{k}(-1)^k e^{-k\lambda_h\frac{N_0(2^{2R}-1)}{P_B}}$$
$$\times e^{-k(J-j)\lambda_f\frac{N_0(2^{2R}-1)}{P_t^R}}(\lambda_g)^{J-j}\zeta, \qquad (34)$$

where ζ can be obtained from (24) by replacing P_{th}^{1st} with P_t^R.

5. Simulation results

The simulations are carried out in MATLAB. The important simulation parameters are provided in Table 1 below. We show four types of simulation results. In the first result, we show the existence of optimal transmit power of the relay. The second result shows the variations of optimal transmit power with the number of available relays and desired data rate. The third result shows the outage probability of the FPD and APD power splitting approaches. Finally, we compare the outage probability of the proposed energy harvesting cooperative multicast system with the outage probability of the non-energy harvesting cooperative multicast system.

Fig. 4 shows the variation of outage probability for different number of relays and VU destinations as a function of the transmit power of the selected relay (P_{th}^{1st}). It can be seen that the results obtained through analytical expressions are in complete agreement

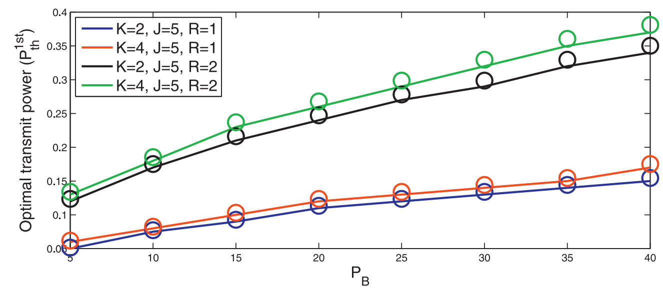

Fig. 5. Optimal transmit power P_{th}^{1st} as function of P_B and R for different number of relays. The lines represent optimal value of P_{th}^{1st} obtained from the exhaustive search of the analytical expression for the outage probability and circles represent the optimal transmit power obtained through simulations.

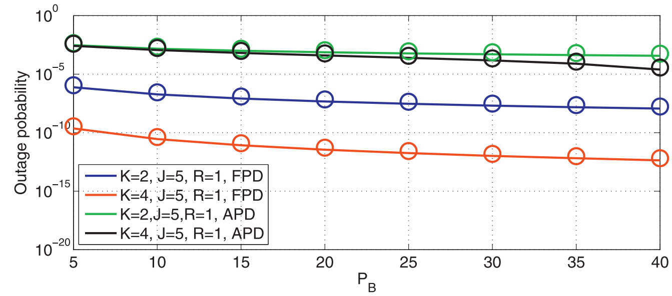

Fig. 6. Outage probability comparison of the FPD and APD scheme when $R=1$ bps. The lines represent the results obtained through analytical expressions and circles represent the results obtained through simulations.

with the results obtained through simulations. Further, it can be easily observed that the outage probability is a convex function of the P_{th}^{1st}. The optimal transmit power for higher number of relays is slightly higher than the optimal transmit power for smaller number of relays. This is because with increasing the number of relays the likelihood of finding a relay that can harvest higher power and has good channel conditions with all the destinations becomes more likely.

Fig. 5 shows the optimal transmit power as a function of the P_B and the desired data rate R. As R increases the optimal transmit power (P_{th}^{1st}) also increases for a fixed value of P_B. This is because higher signal to noise ratio is required at VU destinations to fulfill the data rate needs and hence higher transmit power from the selected relay is desirable. Further, it can be observed that for a fixed value of R the optimal transmit power increases with increase in P_B. This is explained as follows. As P_B increases the probability that the harvested power at the relays is greater than P_{th}^{1st} also increases even for higher values of P_{th}^{1st}. Hence, the transmission power of the selected relay can also be increased which subsequently results in higher chances of successful reception at all the VU destinations. Therefore, the optimal transmit power increases with the increase in P_B.

The outage probability comparison of FPD and APD approaches is presented in Figs. 6 and 7 for $R=1$ and $R=2$, respectively. It can be seen that the FPD scheme performs better than the APD scheme. This is because in APD approach the whole received signal is fed to either energy harvesting circuitry or information decoding circuitry. The energy harvesting from the received signal will only take place when the received signal cannot be decoded or in other words when the received signal is weak and hence smaller power is available for energy harvesting. Since, the transmit power is dependent on the average of the harvested power therefore the transmit power is also small. This results in poor outage performance of the APD approach as compared to the FPD approach.

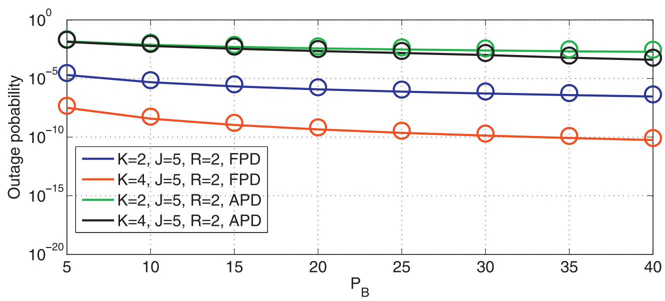

Fig. 7. Outage probability comparison of the FPD and APD scheme when $R = 2$ bps. The lines represent the results obtained through analytical expressions and circles represent the results obtained through simulations.

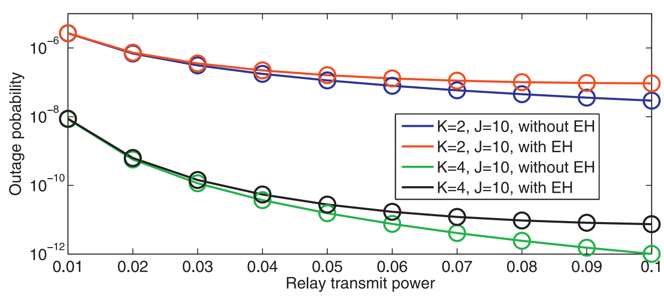

Fig. 8. Outage probability comparison of the energy harvesting relaying scheme and non-energy harvesting relaying scheme when $R = 1$ bps, $P_B = 20$ watt. The lines represent the results obtained through analytical expressions and circles represent the results obtained through simulations.

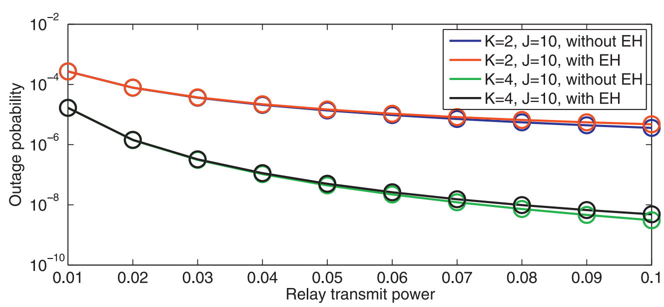

Fig. 9. Outage probability comparison of the energy harvesting relaying scheme and non-energy harvesting relaying scheme when $R = 2$ bps, $P_B = 20$ watt. The lines represent the results obtained through analytical expressions and circles represent the results obtained through simulations.

Now we compare the outage probability of the proposed EH cooperative multicast communication system with the non-EH cooperative multicast communication system. The simulation results are shown in Figs. 8 and 9 for $R = 1$ bps and $R = 2$ bps, respectively. It can be seen from the figures that the outage probability for the proposed EH system and non-EH system is almost same for smaller values of relay transmit power. However, it increases for proposed EH system as the relay transmit power increases. This is due to the convex nature of the outage probability for EH system. The loss is performance becomes almost negligible as the desired data rate (R) increases. As the video communication usually operate at higher data rates therefore we can say that the performance of the EH cooperative multicast communication system, where relays do not use any of their own energy, is identical to the non-EH cooperative multicast communication system, where relays use their own energy for transmissions, for video communication.

6. Conclusions

In this paper, we have analyzed the outage probability of energy harvesting cooperative multicast systems where one relay is selected to assist the communication between BS and multiple VU destinations. The relays use either FPD power splitting approach or APD power splitting approach for energy harvesting from the BS transmissions. In the FPD approach the harvested power at the relay is dependent on the instantaneous received power. On the contrary, in APD approach the harvested power is dependent on the average of the received power. For FPD approach it is concluded that outage probability can be optimized with respect to the transmit power of the selected relay. The optimal transmit power is observed to increase with the increase in the number of relays. Further, the APD approach is easy to implement at the relays however the performance of APD approach is inferior to the performance of FPD power splitting approach. The simulation results show that the outage probability of the proposed energy harvesting cooperative multicast system is almost identical to the non-energy harvesting cooperative multicast system for higher data rates. Therefore, we conclude that our scheme is more suitable for video communication where the data rates are comparatively higher than the voice or data communication.

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References

[1] R. Atallah, M. Khabbaz, C. Assi, Energy harvesting in vehicular networks: a contemporary survey, IEEE Wireless Commun. 23 (2) (2016) 70–77, doi:10.1109/MWC.2016.7462487.
[2] D. Li, Outage probability and power allocation for cooperative multicast systems, IEEE Commun. Lett. 16 (7) (2012) 1080–1083, doi:10.1109/LCOMM.2012.050112.120595.
[3] H.V. Zhao, W. Su, Cooperative wireless multicast: performance analysis and power/location optimization, IEEE Trans. Wireless Commun. 9 (6) (2010) 2088–2100.
[4] Y. Zhou, H. Liu, Z. Pan, L. Tian, J. Shi, G. Yang, Two-stage cooperative multicast transmission with optimized power consumption and guaranteed coverage, IEEE J. Sel. Areas Commun. 32 (2) (2014) 274–284.
[5] Y. Zhou, H. Liu, Z. Pan, L. Tian, J. Shi, Energy-efficient two-stage cooperative multicast: effect of user density, IEEE Trans. Veh. Technol. 65 (9) (2016) 7297–7307.
[6] Y. Cao, T. Jiang, X. Chen, J. Zhang, Social-aware video multicast based on device-to-device communications, IEEE Trans. Mob. Comput. 15 (6) (2016) 1528–1539.
[7] L. Yang, J. Chen, H. Zhang, H. Jiang, S.A. Vorobyov, D.T. Ngo, Cooperative wireless multicast: performance analysis and time allocation, IEEE Trans. Veh. Technol. 65 (7) (2016) 5810–5819.
[8] M. Li, L.-W. Chen, Spectrum allocation algorithms for wireless cellular networks supporting mobile IPTV, Comput. Commun. 99 (C) (2017) 119–127.
[9] I.H. Lee, H. Lee, H.H. Choi, Exact outage probability of relay selection in decode-and-forward based cooperative multicast systems, IEEE Commun. Lett. 17 (3) (2013) 483–486.
[10] P. Yang, Q. Zhang, J. Qin, Exact outage probability of n^{th}-best multicast relay networks with co-channel interference, IEEE Wireless Commun. Lett. 2 (6) (2013) 595–598.
[11] M. Fang, J. Li, Z. Wang, W. Li, Performance of quantize-map-forward based cooperative multicast systems with successive relaying, IEEE Commun. Lett. 20 (11) (2016) 2257–2260.
[12] S.Y. Lee, C.Y. Liu, M.K. Chang, D.N. Yang, Y.W.P. Hong, Cooperative multicasting in renewable energy enhanced relay networks expending more power to save energy, IEEE Trans. Wireless Commun. 15 (1) (2016) 753–768.
[13] M. Zhang, K. Cumanan, A. Burr, Secrecy rate maximization for MISO multicasting SWIPT system with power splitting scheme, in: 2016 IEEE 17th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Edinburgh, 2016, pp. 1–5.

[14] B. Zhu, J. Ge, Y. Huang, Y. Yang, M. Lin, Rank-two beamformed secure multicasting for wireless information and power transfer, IEEE Signal Process. Lett. 21 (2) (2014) 199–203.
[15] Z. Zhu, Z. Chu, Z. Wang, I. Lee, Robust beamforming design for MISO secrecy multicasting systems with energy harvesting, in: 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), Nanjing, 2016, pp. 1–5.
[16] M.R.A. Khandaker, K.K. Wong, SWIPT in MISO multicasting systems, IEEE Wireless Commun. Lett. 3 (3) (2014) 277–280.
[17] Z. Yue, H. Gao, C. Yuen, T. Lv, J. Zeng, Low complexity joint beamforming and power splitting for massive MIMO multicasting SWIPT, in: 2015 IEEE/CIC International Conference on Communications in China (ICCC), Shenzhen, 2015, pp. 1–6.
[18] O.T. Demir, T.E. Tuncer, Antenna selection and hybrid beamforming for simultaneous wireless information and power transfer in multi-group multicasting systems, IEEE Trans. Wireless Commun. 15 (10) (2016) 6948–6962.
[19] M. Ashraf, J.W. Jang, K.G. Lee, Outage probability analysis for energy harvesting cooperative relays in a clustered environment, Mobile Netw Appl (2017), doi:10.1007/s11036-017-0813-1.
[20] Z. Ding, S.M. Perlaza, I. Esnaola, H.V. Poor, Power allocation strategies in energy harvesting wireless cooperative networks, IEEE Trans. Wireless Commun. 13 (2) (2014) 846–860, doi:10.1109/TWC.2013.010213.130484.
[21] K. Huang, V.K.N. Lau, Enabling wireless power transfer in cellular networks: architecture, modeling and deployment, IEEE Trans. Wireless Commun. 13 (2) (2014) 902–912, doi:10.1109/TWC.2013.122313.130727.

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