

Performance Analysis of Opportunistic Relay Selection Cooperative Communication in Cascaded Fading Channels

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Abstract. Cooperative communication enables users to transmit information in a cooperative way, which is one of the key technologies used in wireless communication systems to improve spectral efficiency. A cascade Nakagami- m fading function is proposed to describe the fading characteristics of complex wireless channels, and a communication model of decoding-and-forward opportunistic relay selection (DF-ORS) cooperative communication under total power constraints is established. Theoretical analysis and simulation results show that DF-ORS cooperative communication can effectively reduce outage probability and improve spectrum efficiency under total power constraints and complex cascade Nakagami- m fading channels. The transmission power allocation of source node and relay node has an important impact on communication performance. Equal power allocation scheme cannot guarantee the optimal system performance, and the obtained conclusions have more general applicability.

1. Introduction

Multiple-Input and Multiple-Output (MIMO) wireless communication technology is one of the key technologies currently used to resist multipath fading and improve channel capacity. The cooperative communication technology developed in recent years makes full use of the broadcast characteristics of wireless channels, realizes "virtual MIMO" through mutual assistance among nodes, effectively overcomes the technical limitations of traditional MIMO and can retain its technical advantages to the greatest extent. Cooperative communication technology has been widely applied to wireless cognition communication, cellular networks and other fields [1,2].

The opportunistic relay selection (ORS) cooperative communication strategy proposed by Bletsas A. et al. is even better than the cooperative communication performance in which all relays participate under certain conditions[3]. ORS has many advantages, such as not requiring ideal synchronization, which greatly simplifies the physical layer design of the network. In recent years, the research on opportunistic relay selection cooperative communication is still one of the hot spots in the field of wireless cooperative communication, involving different channel environments, signal combining schemes, combining various existing specific communication technologies, showing the broad research and application space [4,5,6]. Different Channel fading characteristics are assumed to be Rayleigh, Nakagami- m and Rician, etc. by researchers. However, due to its simple form and few adjustable parameters, the accuracy of describing the fading characteristics of wireless signals in complex urban environments with many obstacles such as multiple diffraction, scattering, refraction and reflection is poor. In recent years, the cascade channel fading model proposed by some scholars overcomes the above problems and has been effectively applied [7,8,9,10,11].

In this paper, cascade Nakagami- m channel fading (N^* Nakagami- m) model is used to describe the urban fading channel with many obstacles and the fading caused by multiple diffraction, scattering,



refraction and reflection of wireless signals. The decoding-and-forward opportunistic relay selection (DF-ORS) cooperative communication model under the condition of total power is established and its communication performance is studied. on this basis, the node power allocation scheme is further studied, and a more general conclusion in line with the actual situation is obtained. Different cascade orders and fading parameters can be selected to be applied to different fading scenarios, and the conclusions have wider applicability.

2. System Model

As shown in Figure 1, a half-duplex dual-hop DF-ORS cooperative communication system model is established, where the direct path between the source and destination is blocked by an intermediate wall or obstacles, while relays are located at the periphery of the obstacle (around-the-corner). Because the most practical wireless communication situation in the urban environment is due to obstacles such as buildings, trees and the like blocking or experiencing strong signal attenuation, there is no possibility of direct communication between the source node S and the destination node D, and relay forwarding is required. In addition to the source node S and the destination node D, there are relay nodes R_k ($k = 1, \dots, K$).

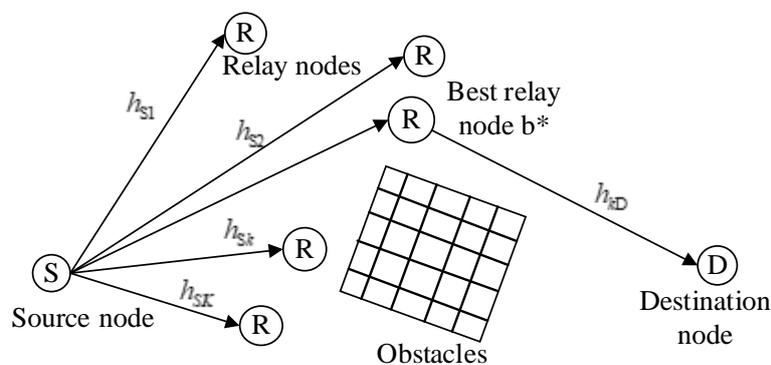


Figure 1. Schematic diagram of opportunistic relay selection cooperative communication

In Figure 1, h_{sk} and h_{kd} ($k = 1, \dots, K$) are the channel fading coefficients from the source node to the relay node and from the relay node to the destination node respectively. Distinguishing from the influence of additive noise, channel fading will cause random non-additive signal disturbance of received signal power in wireless communication. More reasonable mathematical models and statistical functions are needed to accurately analyse and describe it. When a wireless signal is transmitted between two stations (transmitter and receiver), if there is multiple scattering, modelling the actual fading conditions with cascade Nakagami- m fading is more practical than commonly used fading models such as Rayleigh, Nakagami- m and Rician, etc. For example, in urban and forest areas, it is extremely appropriate to describe the signals using cascade channels due to the diffraction, scattering, refraction and reflection of signals by a large number of trees and building edges, street corners, moving cars, and propagation of holes. Under special conditions, the model of cascade Nakagami- m fading is easily simplified to commonly used channel fading models, such as Rayleigh, Nakagami- m , Rician, etc.

3. Theoretical Derivation

Assuming that the channel characteristics in DF-ORS cooperative communication in Figure 1 obey quasi-static flat fading, channel state information (CSI) is known and remains unchanged in one transmission. In the node-to-node link $A \rightarrow B$, the signal received at the node B is

$$y_B = h_{AB} x_A + n_B \quad (1)$$

where x_A is the transmission signal at the node A, the channel gain factor h_{AB} is between links $A \rightarrow B$, and $n_b \sim CN(0, N_0)$ is the additional complex white Gaussian noise introduced at the node B, $CN(\mu, \sigma^2)$ means that the mean value is μ and the difference is σ^2 of the additive complex white Gaussian noise. $|h_{AB}|^2$ indicates instantaneous signal power gain. If the node A is the source node, $E\{|x_A|^2\} = P_s$ is the transmission power of the source node. Similarly, if the node A is a relay node, $E\{|x_A|^2\} = P_r$ is the transmission power of the relay node.

According to the DF-ORS cooperation strategy the source node S broadcasts code word to the relay nodes, and a set of successfully decoded relay nodes is generated. In the second phase, according to the criterion of minimum interruption probability, the best relay is chosen to forward the signal to the destination node D from the decoded successful relay set. Each relay in this set has the opportunity to become a forwarding relay. During the whole cooperative transmission period, the communication process of the two-phase relay forwarding through the relay nodes participating in the cooperation can realize the transmission efficiency because the same code word is transmitted twice. If the optimal relay is selected, the maximum channel capacity achieved between source node A and destination D is

$$C_{\max} = \frac{1}{2} \log_2 \left\{ 1 + \max \min \left(|h_{Sk}|^2 \frac{P_s}{N_0}, |h_{kD}|^2 \frac{P_r}{N_0} \right) \right\} \quad (2)$$

which means that the optimal relay node is selected according to the following principle

$$b^* = \arg \max \min_{k \in S_{\text{relay}}} \left\{ |h_{Sk}|^2 \frac{P_s}{N_0}, |h_{kD}|^2 \frac{P_r}{N_0} \right\} \quad (3)$$

For DF-ORS cooperative communication strategy, from the point of view of realizing complete cooperative diversity, wireless communication from source node S to destination D node can choose any path through relay node supporting the required transmission rate. The decoded successful relay set D_l formed by relays is empty, or when the link from any relay node of the decoded successful relay set D_l to destination node cannot realizing rate $2R$ (bps/Hz), interrupt occurs. Where D_l is the subset formed by l decoded successful relays, $D_l \subseteq S_{\text{relay}}$. The optimal relay node according to formula (3) can be selected in the relay set D_l according to the following principle

$$b^* = \arg \max_{k \in D_l} \frac{1}{2} \log_2 \left\{ 1 + |h_{kD}|^2 \frac{P_r}{N_0} \right\} = \arg \max_{k \in D_l} \left(|h_{kD}|^2 \right) \quad (4)$$

The probability of forming a correctly decoded relay set in the first phase is

$$\Pr(D_l) = \prod_{k \in D_l} \Pr \left\{ \frac{1}{2} \log_2 \left(1 + |h_{Sk}|^2 \frac{P_s}{N_0} \right) > R \right\} \prod_{k \notin D_l} \Pr \left\{ \frac{1}{2} \log_2 \left(1 + |h_{Sk}|^2 \frac{P_s}{N_0} \right) < R \right\} \quad (5)$$

If the link from the relay of the set D_l to the destination node is interrupted, it means the DF-ORS cooperative communication is interrupted, and the interruption probability is

$$P(\text{outage}) = \Pr \left\{ \frac{1}{2} \log_2 \left[1 + \max_{k \in D} \left(|h_{kD}|^2 \frac{P_r}{N_0} \right) \right] < R \mid D_l \right\} = \sum_{l=0}^K \sum_{D_l} \Pr(D_l) P_{D_l} = \sum_{l=0}^K \sum_{D_l} \left[\prod_{i \in D_l} \Pr \left\{ |h_{Si}|^2 \frac{P_s}{N_0} > 2^{2R} - 1 \right\} \right] \quad (6)$$

In this paper, we present single-selection opportunistic relaying with decode-and-forward strategy in cooperative communication network and analyze its outage probability under a source power

constraint $P_s = \zeta P_{\text{total}}$, where the total power P_{total} of the entire cooperative network is a fixed value, and the power P_s is allocated to the source node. $\zeta \in (0, 1]$ is the power allocation coefficient. An opportunistic relay power constraint $P_R = \sum_{k=1}^K P_k = (1 - \zeta) P_{\text{total}}$, where the power $P_R = (1 - \zeta) P_{\text{total}}$ allocated to the optimal relay node. The total signal-to-noise ratio of cooperative communication under a certain total power of the cooperative network is defined as $SNR = P_{\text{total}} / N_0$. The introduction of power constraints is also conducive to power allocation between source nodes and relay nodes, thus optimizing network performance. This opportunistic relay selection yields and minimizes the conditional outage probability in (6) as

$$P(\text{outage}) = \sum_{l=0}^K \sum_{D_l} \left[\prod_{i \in D_l} \Pr \left\{ |h_{Si}|^2 \xi SNR > 2^{2R} - 1 \right\} \right] \quad (7)$$

Next, let's consider the channel fading. If a wireless signal experiences multiple Nakagami- m fading (assuming N orders) during point to point transmission, the power of the received signal can be expressed as cascade products with the same probability density function independent of N orders

$$P = \prod_{k=1}^N P_k \quad (8)$$

where the probability density pdf of P_k satisfies Gamma distribution

$$f(P_k) = \frac{P_k^{m_k - 1}}{b_k^{m_k} \Gamma(m_k)} \exp(-\frac{P_k}{b_k}), k = 1, 2, \dots, N \quad (9)$$

where m is a parameter related to the channel fading degree, the average power $E\{p\} = mb_k$ of the signal can be obtained by the moment function of Gamma function.

When these random variables satisfy the independent and identically distributed (i.i.d.). The probability density function (PDF) of signals received by the receiver via cascade fading can be obtained from the product theory of multiple random variable pdf, transformed by Moment Generating Functions (MGFs) and Laplace, expressed as MeijerG function [9].

$$f(x) = \frac{1}{x \prod_{k=1}^N \Gamma(m_k)} G_{0,N}^{N,0} \left(\frac{x}{\prod_{k=1}^N \Gamma(b_k)} \middle| m_1, m_2, \dots, m_N \right), \quad k = 1, 2, \dots, N \quad (10)$$

where $G(\cdot)$ is MeijerG function [††††].

In actual communication environment, multi-order cascade N*Nakagami- m fading environment has good adaptability. It can be simplified as Nakagami- m channel fading as $N=1$ and can be further simplified as cascaded N*Rayleigh channel fading as $m=1$. It is simplified as $N=2$ and can be further simplified as double cascade Rayleigh fading channel when $m=1$. Double cascade Nakagami- m channel fading model is suitable for Next-generation wireless communication systems with high user mobility, where the fading effects are more severe than classical channel models including Rayleigh and Nakagami- m [§§§§]. The mixed Rayleigh and double Rayleigh fading channels as an adequate multipath fading channel model for vehicle-to-vehicle communication scenarios [*****].

Defines the instantaneous signal-to-noise ratio per symbol $\gamma = P/N_0$ of signals received through a two-point direct communication link, $\Omega = E\{p\}$ is average signal power, and $\bar{\gamma} = \Omega P/N_0$ is the average signal-to-noise ratio. By performing variable substitution and integration on equation (9) and using the integration characteristics of MeijerG function, it is obtained that the outage probability at the receiving end of point-to-point N*Nakagami- m cascade fading channel is

$$P_{\text{out}}(\gamma_{\text{th}}) = \int_0^{\gamma_{\text{th}}} f_{\gamma}(\gamma) d\gamma = \frac{1}{\Gamma^N(m)} G_{1,N+1}^{N,1} \left(m^N \frac{\gamma_{\text{th}}}{\bar{\gamma}} \left| \begin{matrix} 1 \\ m, m, \dots, m, 0 \\ N+1 \end{matrix} \right. \right) \quad (11)$$

where γ_{th} is the threshold of the signal-to-noise ratio.

Combining equation (7) with equation (11) and further simplifying, the outage probability of DF-ORS cooperative communication in asymmetric N^* Nakagami- m cascade channel fading environment under total power constraint is obtained as follows

$$P(\text{outage}) = \prod_{k=1}^K \left\{ 1 - \left[1 - \Pr \left(\frac{\gamma_{S_k}}{\bar{\gamma}_{S_k}} \leq k_1 \right) \right] \left[1 - \Pr \left(\frac{\gamma_{kD}}{\bar{\gamma}_{kD}} \leq k_2 \right) \right] \right\} = \prod_{k=1}^K \left\{ 1 - \left[1 - \frac{1}{\Gamma^{N_{S_k}}(m_{S_k})} \right] \right. \\ \left. \times G_{1,N_{S_k}+1}^{N_{S_k},1} \left(m_{S_k}^{N_{S_k}} k_1 \left| \begin{matrix} m_{S_k}, m_{S_k}, \dots, m_{S_k}, 0 \\ N+1 \end{matrix} \right. \right) \right] \right\} \quad (12)$$

where $k_1 = (2^{2R} - 1) / \zeta \Omega_{S_k} SNR$, $k_2 = (2^{2R} - 1) / (1 - \zeta) \Omega_{kD} SNR$ and $SNR = P_{\text{total}} / N_0$.

Note that (12) implies that the outage event happens only when all relays are in outage, and when N and m take different parameter values, equation (15) can equivalently describe various common and different fading functions. For example, when $N=2$ and $m=1$, it is reduced to double cascade Rayleigh channel fading.

4. Simulation Analysis

Figure 2 shows the numerical simulation results according to formula (10). Monte Carlo (MC) simulation method is used to ensure the correctness of theoretical analysis results, which counting times is in this paper. The MC simulation curve and the theoretical numerical simulation curve in the same figure have a good fit, indicating that the theoretical and practical modelling results are consistent. Overall, the curves in the figure show that the outage probability of DF-ORS cooperative communication under the total power constraint decreases with the increase of the total power SNR, that is to say, increasing the total power can reduce the outage probability and improve the cooperative communication performance.

Combined with the cascade fading channels of simulation curves, parameters $N=1$ and $m=1$ in Figure 2, the cooperative communication system model is simplified to an opportunistic relay selection cooperative communication system model in a single order Rayleigh channel fading environment. As parameter $N=2$ and $m=1$, the cooperative communication system model simplified to an DF-ORS in a two-order cascaded fading environment, written as 2^* Rayleigh. The simulation results in the figure show that even if the relay node and the destination node have the same average power of the received signal, the two-order cascade Rayleigh fading makes the power of the received signal of the wireless channel have greater randomness, the communication quality becomes poor, and the outage probability increases. When the cascade fading channel with parameters $N=1$ and $m=1.5$ are adopted, the cooperative communication model is simplified to a DF-ORS cooperative communication model in a fading environment representing Nakagami- m channel. When a cascade fading channel with parameters $N=2$, $m=1.5$ are adopted, the cooperative communication model represents the DF-ORS cooperative communication model under two cascade 2^* Nakagami- m fading environments. The curve in the figure shows that the two-order cascade 2^* Nakagami- m fading has greater randomness than Nakagami- m channel fading, which leads to poor communication quality and increased outage probability.

Figure 2 also shows the performance analysis curves of decode-and-forward selection combination (DF-SC) cooperative communication under cascade 2^* Rayleigh and cascade 2^* Nakagami- m fading environments. DS-SC and DF-ORS both depend on fading arises from the availability of several potential paths towards the destination to select the best one. This finding reveals that the cooperation process of DF-SC is similar to DF-ORS, except that under the constraint of total power of the whole

network, DF-ORS causes power to be distributed to each relay node, thus reducing the performance of the cooperative communication system. Under the same total power constraint and channel fading parameters, the performance of DF-ORS cooperative communication system is better than that of DF-ORS cooperative communication system. It can also be seen from the Figure 2 that different fading parameters m and cascade orders N mean different fading degrees of the channel, which has an important impact on the performance of DF-ORS.

Figure 3 shows the relationship between the outage probability of DF-ORS cooperative communication and the number of relay nodes under the total power constraint condition. As can be seen from the figure, with the increase of the number of relay nodes, cooperative diversity gain can be effectively realized, because more relay nodes provide more potential optimal paths for the implementation of opportunistic relay selection strategy. When DF-ORS cooperates under the condition of total power constraint, the optimal relay node selected from the K nodes participating in cooperation will use all relay power to send information in channel with the best quality, and its performance is obviously better than the traditional cooperation mode in which all relay nodes participate. The traditional cooperative mode in which all relays participate in cooperation and relay nodes evenly distribute relay power and transmit information to destination nodes in channels with different quality.

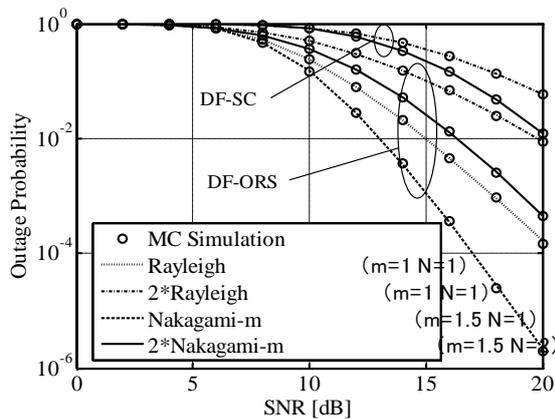


Figure 2. Relationship between outage probability and total power SNR

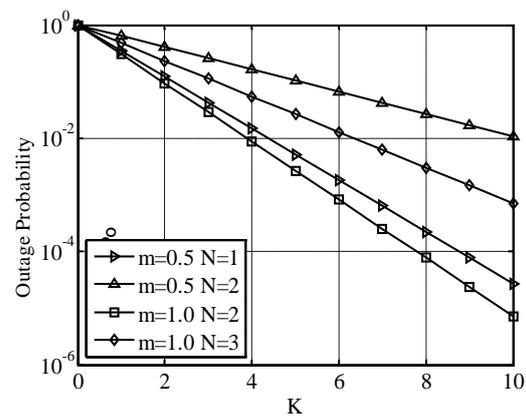


Figure 3. Relationship between outage probability and number of nodes

The simulation results in Figure 4 show the relationship between the outage probability of DF-ORS cooperative communication and the cascade order of cascade channels under total power constraint. It is shown in the figure that with the increase of cascade fading order, the outage probability of DF-ORS continues to increase and the communication performance decreases under the total power constraint of the whole network. When the channel cascade order increases, the wireless signal undergoes multiple diffraction, scattering, refraction and reflection in the path propagation process. The randomness of the signal increases and the quality of the received wireless signal decreases. It can also be seen from the Figure 4 that different fading parameters mean different fading degrees of the channel even if the cascade order is the same, which has an important impact on the performance of DF-ORS cooperative communication.

Figure 5 shows that the minimum outage probability occurs under asymmetric channel conditions is not the equal power allocation $\zeta \neq 0.5$ between source node and destination node. The value of allocation coefficient is restricted by the channel fading conditions. In the figure, the Nakagami- m parameter are set for channel fading as $m_{sk} = m_{kd} = 1$, $N_{sk} = 1$. By changing the cascade order N_{kd} , the wireless link from the relay node to the destination node meets different N *Nakagami- m cascade fading channel distribution conditions. When increasing the value of N_{kd} , the curve in the figure shows that the optimal power allocation coefficient ζ is decreasing while the outage probability is

increasing, which means that more power needs to be allocated to relay nodes to overcome the channel quality loss caused by cascade channel fading. It can also be seen from the Figure 5 that different channel fading parameters m and cascade orders N mean different fading degrees of the Nakagami- m fading channel, which have an important impact on the outage probability performance of DF-ORS cooperative communication.

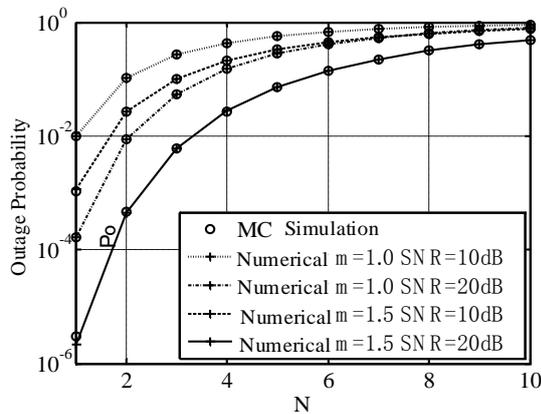


Figure 4. Relationship between outage probability and cascade channel order

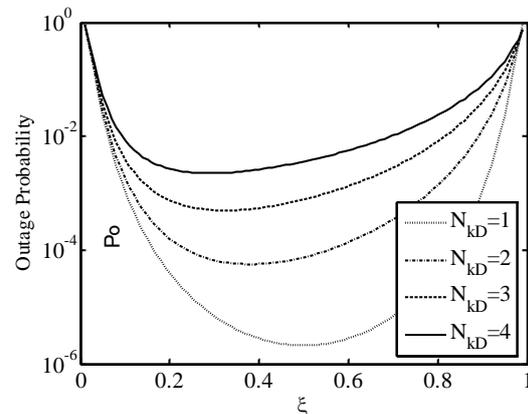


Figure 5. Relationship between outage probability and power allocation coefficient in asymmetric cascade fading channel

The main difficulty here is to have the network as a whole entity cooperate in order to rapidly discover the best path with minimal overhead. The source node and the relay node need to know the CSI of the whole network through feedback and other methods, and the best power allocation coefficient calculated will make the communication performance optimal. Although the unequal power distribution method can obtain the best performance, it will lead to increased overhead.

5. Conclusion

DF-ORS cooperative communication under total power constraint condition has been widely studied and applied due to its high diversity performance and easy physical implementation. A communication performance analysis model for DF-ORS cooperative communication strategy under total power constraint in cascade channel fading environment is proposed. The closed expression of outage probability theory is derived. The relationships between outage probability and total power signal-to-noise ratio, spectrum efficiency, number of nodes, different cascade orders of fading and power allocation coefficient are analysed, and general conclusions are obtained. It is further discussed that reasonable power allocation between source node and optimal relay node is beneficial to improve communication performance. The optimal power allocation coefficient minimizes the outage probability and optimizes the performance of DF-ORS cooperative communication under the condition of total power constraint, but it also requires some overhead.

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7. References

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