Abstract: In this paper, we propose a dual-hop decode-and-forward (DF) relaying network with beamforming for an unmanned aircraft system (UAS) over $\kappa-\mu$ fading channels. The $\kappa-\mu$ fading model is a general fading model that models wireless fading channel perfectly in line-of-sight (LOS) propagation environments and includes Nakagami-$m$, Rician, Rayleigh, and One-sided Gaussian fading channels as special cases. We consider an unmanned aircraft vehicle (UAV) as a moving relay for forwarding the data signals from a source ground station (GS) to a destination GS. Our proposed system considers multiple antennas at the source and destination, whereas the relay has a single antenna. We derive a closed-form expression for the outage probability in terms of the generalized Marcum Q-function. We carry out the performance analysis by means of derived expression for the various antenna arrangements, distinct values of radius, and different values of fading parameters. Our results show that the number of antennas and fading parameters, $\kappa$ and $\mu$, have a positive relation with system performance. The analytical results are validated through Monte Carlo simulations.

Keywords: Unmanned aircraft system, drone relay, dual-hop system, decode-and-forward relaying, outage probability, $\kappa-\mu$ fading channels.

1. Introduction

Recently, the deployment of unmanned aerial vehicles (UAVs) has increased tremendously in a vast range of applications such as military, weather monitoring, traffic control, forest fire detection, emergency search & rescue, and communicating relay, etc. due to their mobile nature and cost-effectiveness [1]. An unmanned aircraft system (UAS) is a control system that comprises a ground control station and a UAV node which is also known as a drone for establishing a communication link between ground stations (GSs). A typical UAV has a flight management system, propulsion system, energy storage, communication system, and autonomous/remote control system [2]. Hence, a UAV with communication capability can serve as a moving relay between the isolated networks present on the ground. There are two major categories of UAVs: fixed-wing and rotary-wing [11]. A fixed-wing UAV has the capability to operate for a long time due to the large capacity of the battery, which makes it suitable for power-limited wireless systems; whereas, a rotary-wing UAV consumes more power, but has a feature of hovering over fixed locations and thus provides the flexibility in position.

2. Related Work

During the last few decades, the cooperative dual-hop relaying technique has emerged as an effective in improving reliability/data rates as well as extending the radio coverage [3-7]. Dual-hop relaying techniques are classified into two major categories: amplify-and-forward (AF) and decode-and-forward (DF) [4], [7]. In an AF relaying method, a relay node sends the received signal after amplifying to a destination, whereas, in DF relaying technique, a relay node first decodes the received signal, then re-encodes, and retransmits that signal to a destination. Most of the current wireless systems employ the static relaying by considering the relays with limited-node mobility and wired backhauls [3-9]. In [8], the closed-form expressions for the spectral efficiency of dual-branch selection combining without diversity under optimal rate adaptation with constant power and channel inversion with fixed rate adaptation techniques have been derived and analyzed. The outage probability and average channel capacity expressions of dual-branch selection combining over uncorrelated Nakagami fading channels are obtained in [9]. This paper evaluates the outage probability and channel capacity under optimum power with rate adaptation and truncated channel inversion with fixed rate adaptive transmission schemes. A novel mobile relaying is studied in [10], where a relay is mounted on the moving UAV node. Mobile relaying offers several key benefits over the conventional static relaying. First, on-demand mobile relaying systems are more cost-effective and can be deployed quickly [11], which would make them suitable for unexpected or temporary events, i.e., emergency response and military operation, etc. Moreover, the high mobility feature laid the new foundation for performance improvement through the dynamic adjustment of relay position to best suit the communication environment, this technique is very promising for delay-tolerant (DTN) applications [12] - [14].

Wireless relaying systems that include the UAV/drone relays have received considerable attention in numerous research studies [15-22]. In [15], the authors studied an energy-efficient metric based on network capacity and power consumption ratio for a wireless system under Rician fading environments when a single antenna is installed at each node, i.e., the UAV relay and both GSs. The UAV-assisted
communications for uplink transmission have been investigated over Rayleigh fading channels in [16], here, a closed-form expression for the ergodic normalized transmission rate is derived. In [17], an uplink wireless system having UAV relay with multiple antennas was proposed and an algorithm was developed to maximize the data rates of the uplink channel by adjusting the position of the UAV, and system performance was analyzed over Rician fading channels. In [18], the authors proposed a wireless network with a mobile relay over random waypoint (RWP) mobility model and analyzed the optimal power allocation and time-varying data rate performances. A model-free trajectory optimization for wireless data ferries via a UAV is studied in [19]. A nonlinear model predictive control algorithm to optimize the location and trajectory of multiple UAVs for enhancing the connectivity of wireless network under Rayleigh fading environments was presented in [20]. In [21], a field experiment was conducted with a UAV relay to assist the data downloading from an autonomous underwater vehicle to a ground station. A wireless relay network was developed using fixed-wing UAV DF relaying in [22], where outage performance was analyzed over Rician fading channel and performance was optimized using variable-rate approach.

In this work, we propose a dual-hop DF relaying system with beamforming over $\kappa-\mu$ fading channels for UAS system, where a drone is acting as a moving relay and is responsible for forwarding data between two stationary GSs (source and destination). The $\kappa-\mu$ fading distribution is a more realistic and practical in nature and has potential to model the experimental data perfectly than conventional distributions (i.e., Rayleigh, Rician, and Nakagami-m) [23]. In our proposed system, the source and destination are equipped with multiple antennas, and relay has a single antenna. Firstly, we derive new and exact closed-form expression for the outage probability of our system model. Then, we analyze the system performance for the various antenna arrangements, distinct values of radius, and different values of fading parameters. Our result has some special cases such as $\kappa-\mu$-Rayleigh/Rayleigh, Rician/Rician, Nakagami-m/Nakagami-m, One-sided Gaussian/One-sided Gaussian, and mixed $\kappa-\mu$-Rayleigh, Rician, Nakagami-m, and One-sided Gaussian fading links. From above mentioned special cases, except Rayleigh/Rayleigh and Rician/Rician, all are new in the literature.

The remainder of this paper is arranged as follows: Section 3 presents the system model and $\kappa-\mu$ channel model with the derivations of CDF and PDF. New and exact closed-form expression for the outage probability is derived in Section 4. The performance of the proposed system is discussed through numerical results in Section 5. In last, Section 6 provides the conclusion of the paper.

3. System and Channel Models

3.1 System Model

A half-duplex dual-hop wireless communication system consists of a drone DF relay, $R$, equipped with a single antenna and a stationary source, $S$, with $N_1$ antennas and a destination, $D$, with $N_2$ antennas, is considered as depicted in figure 1. We assume that there is no direct communication link between $S$ and $D$ and data can be delivered only via drone relay $R$. For the simplicity, we consider the three-dimensional (3D) plane, shown in figure 2. Without loss of generality, we also consider a Cartesian coordinate system with $S$ and $D$ placed at $S(-L, 0, 0)$ and $D(L, 0, 0)$, respectively, i.e., $S$ and $D$ are apart by $2L$. It is assumed that the drone $R$ with a moving speed $v$ circles above at an altitude of $H > 0$ from the ground plane with the origin $O'(0, 0, H)$ as its center point and radius $r$. Hence, we can say that $R$ is located at $R(rcos\theta, rsin\theta, H)$, where $\theta$ relates to the angle of the circle along which the $R$ flies. In the 3D-plane, the distances between $S \rightarrow R$ and $R \rightarrow D$ are calculated using Euclidean distance formula, respectively, given by

$$d_1 = \sqrt{H^2 + L^2 + r^2 - 2r\cos\theta},$$  \hspace{1cm} (1)$$
$$d_2 = \sqrt{H^2 + L^2 + r^2 + 2r\cos\theta}. \hspace{1cm} (2)$$

Likewise, the Euclidean distances between $S \rightarrow O'$ and $D \rightarrow O'$ are equal and is given by

$$d_3 = \sqrt{H^2 + L^2}. \hspace{1cm} (3)$$

Figure 1. Dual-hop DF drone relay system with beamforming

Figure 2. 3D plane geometry of system model

We consider a scenario where $R$ employs DF protocol and communication takes place between $S$ and $D$ into two time-periods. The perfect channel state information (CSI) is available at $S$ and $D$. Moreover, the communication channels...
between $S-R$ and $R-D$ links are assumed to experience independent quasi-static block fading. In the first time period, the source sends data signal $x$ to the relay using $N_1 \times 1$ transmit beamforming, the received signal at the relay is given by [22],
\[ y_1 = b_1^H w_1 \sqrt{a_1} \sqrt{P_1} x + n_1, \]
where $b_1$ symbolizes the channel coefficient vector with $N_1 \times 1$ between $S$ and $R$, $a_1$ is the path loss attenuation factor, $P_1$ represents the source transmit power, $(\cdot)^T$ is the transpose operator, $n_1$ is additive white Gaussian noise (AWGN) having mean power $P_{N_1}$, $w_1 = h_0/\|h_0\|$ [26], and $\|\|$ symbolizes the Frobenius norm. In the second time period, the relay decodes the transmitted signal successfully, then re-encodes the data signal $\hat{x}$ and sends the signal with a $1 \times N_2$ receive beamforming to the destination. The received signal at $D$ is written as
\[ y_2 = h_2^H w_2 \sqrt{a_2} \sqrt{P_2} \hat{x} + n_2, \]
where $h_2$ designates the channel coefficient vector with $1 \times N_2$ between $R$ and $D$, $a_2$ is the path loss attenuation factor, $P_2$ represents the relay transmit power, $n_2$ is AWGN having mean power $P_{N_2}$, and $w_2 = h_2/\|h_2\|$ [26].

The path loss attenuation factors, $a_1$ and $a_2$, mentioned in (4) and (5), respectively, and $a_i$ are modeled as [22]
\[ a_i = K_i \frac{d_1}{d_0}, \quad a_2 = K_2 \frac{d_2}{d_0}, \]
where $K_1$, $K_2$, and $K$ are the constants that depend on environment and $a$ is the path loss exponent. The ratio of received signal power at $R$ during the first time period is expressed as [22]
\[ \zeta_1 = \frac{a_1}{a_0} = \left( \frac{d_1}{d_0} \right)^{a} \left( \frac{1 + \hat{H}^2}{1 + \hat{H}^2 + \hat{r}^2 - 2\hat{r}\cos\theta} \right)^{a/2}, \]
\[ (7) \]
where $\hat{H} = H / L$ and $\hat{r} = r / L$. It is apparent from the figure that $r$ should be less than $L$ for efficient relaying. Similarly, the ratio of received signal power at $D$ during the second time period is written by [22]
\[ \zeta_2 = \frac{a_2}{a_0} = \left( \frac{d_2}{d_0} \right)^{a} \left( \frac{1 + \bar{H}^2}{1 + \bar{H}^2 + \bar{r}^2 + 2\bar{r}\cos\theta} \right)^{a/2}. \]
\[ (8) \]
Throughout this paper, we consider that the total transmit power $P_T$ is given by $P_T = P_1 + P_2$ and the noise power is constant and we set as $P_{N_1} = P_{N_2} = P_{N_0}$. We define the ratio of the transmit power to the noise power normalized by $a_i$ path loss factor and can be defined as
\[ \gamma_i = \frac{P_i a_i}{P_N}, \]
\[ (9) \]
Then, using (9), we can determine the received SNRs of the first-hop and second-hop, respectively as
\[ \gamma_1 = \beta_1 \gamma_i (\theta) w_1 \gamma_T, \]
\[ (10) \]
\[ \gamma_2 = \beta_2 \gamma_i (\theta) w_2 \gamma_T, \]
\[ (11) \]
where $\beta_1 \neq P_1 / P_T$ and thus $\beta_1 + \beta_2 = 1$. With this normalization, we assume that the total transmission power is fixed relative to noise power for analyzing the system performance.

### 3.2 Channel Model

In this paper, we model the channel links using the large-scale path loss and $\kappa$-$\mu$ fading distribution. The large-scale path loss is the degradation in signal strength due to the transmitter and receiver distance [22]. The $\kappa$-$\mu$ is a generalized fading distribution that can model small-scale fading in line-of-sight (LOS) environments with fading parameters, $\kappa$ and $\mu$ [23]. This fading distribution considers a homogenous environment where a propagating signal composed of clusters of multipath waves. These clusters assume the scattered waves with same powers, however, each cluster has a dominant component with an arbitrary power.

If a link is experiencing a $\kappa$-$\mu$ fading model, then the PDF expression of an instantaneous SNR $\gamma_i$ ($i = 1, 2$), with parameters $\kappa$ and $\mu$, can be expressed as [23, 27]
\[ f_{\gamma_i} (\gamma) = \frac{\mu_i}{\kappa_i} \left( \frac{\kappa_i}{\kappa_i + \kappa_i} \right)^{\frac{\kappa_i}{\kappa_i + \kappa_i}} \exp \left( \frac{\mu_i}{\kappa_i} \left( 1 + \frac{\kappa_i}{\kappa_i} \right) \gamma \right) \]
\[ \times I_{\kappa_i, \mu_i} \left( 2N_i \mu_i \sqrt{\kappa_i \left( 1 + \frac{\kappa_i}{\kappa_i} \right) \gamma} / \gamma_i \right), \]
\[ (12) \]
and its associated CDF is given by
\[ F_{\gamma_i} (\gamma) = 1 - Q_{\kappa_i, \mu_i} \left( 2N_i \mu_i \sqrt{\kappa_i \left( 1 + \frac{\kappa_i}{\kappa_i} \right) \gamma} / \gamma_i \right), \]
\[ (13) \]
where $\kappa_i > 0$ designates the ratio of the total power of the dominant component and scattered waves, $\mu_i > 0$ defines the number of multipath clusters, $\gamma_i$ denotes the average SNR of $i$-th hop, $I_i (\cdot)$ is the $i$-th order modified Bessel function of the first kind, and $Q_{\kappa_i, \mu_i} (\cdot, \cdot)$ is the generalized Marcum Q-function with $n$-th order [23].

As mentioned earlier, the $\kappa$-$\mu$ fading distribution includes some particular cases, such as, Nakagami-$m$ ($\kappa = 0$ and $\mu = m$), Rician ($\kappa = 0$ and $\mu = 1$), and One-sided Gaussian ($\kappa = 0$ and $\mu = 1/2$) distributions, for which $m$ and $K_0$, respectively, represent the Nakagami-$m$ and Rician fading parameters.

### 4. Outage Probability

The outage probability can be defined as the probability when the instantaneous end-to-end SNR of a communication link falls below a predefined threshold value $\gamma_{th}$. Mathematically, it can be given by $\Pr(\gamma < \gamma_{th})$ [7].

Here, we derive the outage probability of the proposed system by considering that each communication link follows independent $\kappa$-$\mu$ fading in conjunction with path loss effect. The probability when the data transmission fails during first time period is given by
\[ \Pr(\gamma_1 < \gamma_{th}) = F_{\gamma_1} (\gamma_{th}) \]
\[ = 1 - Q_N(\sqrt{2N_1 \mu_1 K_1} \sqrt{2\mu_1 (1 + K_1)} / \gamma_{th} / \gamma_{th}), \]
\[ (14) \]
In a similar way, the outage probability during second time period is given by
\[ \Pr(\gamma_2 < \gamma_{th}) = F_{\gamma_2} (\gamma_{th}) \]
\[ = 1 - Q_N(\sqrt{2N_2 \mu_2 K_2} \sqrt{2\mu_2 (1 + K_2)} / \gamma_{th} / \gamma_{th}), \]
\[ (15) \]
The outage probability of the proposed system is obtained with respect to the total end-to-end SNR $\gamma_{eq}$ as
where $F_{\gamma_1}(\gamma_a)$ and $F_{\gamma_2}(\gamma_a)$ are the CDFs of the first-hop and second-hop SNRs, respectively. By substituting (14) and (15) into (16), we get

$$ \begin{align*}
F_{\gamma_n}(\gamma_a) &= 1 - Q_{N_1,\mu_1}(\sqrt{2N_1\mu_1\kappa_1}, \sqrt{2\mu_1(1 + \kappa_1)\gamma_a / \bar{T}_1}) \\
& \quad \times Q_{N_2,\mu_2}(\sqrt{2N_2\mu_2\kappa_2}, \sqrt{2\mu_2(1 + \kappa_2)\gamma_a / \bar{T}_2}).
\end{align*} 
$$

(17)

5. Numerical Results and Discussions

In this section, we present the numerical analysis of our proposed system model in terms of the outage probability over $\kappa$–$\mu$ fading channels. The performance results are obtained with the various configurations of the antennas, $N_1$, $N_2$, distinct values of radius $r$, and different values of fading parameters, $\kappa$ and $\mu$. We set the simulation parameters as $H = 0.05$, $\alpha = 2$, $K_1 = K_2 = K_3 = 10$, and $R = 1$ bit/sec/Hz. We also provide the Monte Carlo simulations to verify the correctness of the analytical results.

Figure 3 shows the outage performance against average SNR per hop for different values of radius $r$. It is observed that the outage probability improves with the decrease in $r$ values. In addition, when the radius $r = 0$, this case shows the performance of rotary-wing drone that can stay at a fixed location.

Figure 4 shows the outage performance for various antenna configurations ($N_1$, $N_2$) and different values of radius $r$ as a function of the average SNR per hop. From figure 4, it is seen that the beamforming techniques improve the outage performance remarkably. We see that the significant improvement in outage performance when the number of antennas ($N_1$, $N_2$) increase. Furthermore, the performance gain is enhanced for the respective values of $r$ as the number of antennas is increased.

Figure 5. Outage probability versus average SNR for different fading models and with numerous antenna arrangements ($N_1$, $N_2$) when $\theta = 90^\circ$, $\kappa_1 = \kappa_2 = 0.5$, and $\mu_1 = \mu_2 = 1$.

We investigate the outage performance with respect to the angle $\theta$ of the proposed system in figure 6. It is observed that outage probability diminishes when the $\theta$ ranges from $0^\circ$–$90^\circ$ and from $180^\circ$–$270^\circ$, and raises when the $\theta$ ranges from $90^\circ$–$180^\circ$ and from $270^\circ$–$360^\circ$. Moreover, the significant improvement in the outage performance is noticeable at a large number of antennas.
6. Conclusions

We proposed a wireless DF relaying network with beamforming for a UAS under κ–μ fading environments, where a fixed-wing drone serves as a moving relay between the source and destination GSs. We derived the closed-form expression for the outage probability of the proposed system. Using that closed-form expression, the system performances for various antenna configurations, several values of radius, and different values of the fading parameters, are evaluated and compared. The analysis results reveal that the outage performance has a direct relation with the number of antennas \((N_1, N_2)\) and fading parameters, \(\kappa\) and \(\mu\), and has an inverse relation with the radius \(r\).

7. Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science, ICT & Future Planning) (No. 2016R1A2B4013118).

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