Chapter 6
Conclusion

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UAVs have become increasingly prevalent in various industries and applications, ranging from military and surveillance operations to commercial and humanitarian uses. Efficient and reliable communication is critical to UAV operations, enabling control, data transmission, and situational awareness.

Over the years, significant advancements have been made in UAV communication systems, resulting in improved range, bandwidth, security, and reliability. Several communication technologies, including RF, satellite, and cellular networks, are commonly used for UAV operations. Each technology has advantages and limitations; the choice depends on the mission's requirements.

RF communication remains the primary UAV control and telemetry method, particularly in the form of dedicated data links. It offers low latency, high bandwidth, and LOS operation, making it suitable for short-range and real-time applications. However, RF communication has a limited range and can be affected by interference and signal degradation.

Satellite communication provides global coverage and is ideal for long-range UAV operations, remote sensing, and BLOS applications. It offers high bandwidth and reliable connectivity but may suffer from higher latency due to the longer transmission distances. Satellites equipped with high-frequency bands, such as Ka-band, can provide even greater data rates for UAV communication.

Cellular networks, specifically 4G and emerging 5G networks, are being increasingly explored for UAV communication. They offer extensive coverage in urban and populated areas, allowing UAVs to leverage existing infrastructure. Cellular networks provide high data rates, low latency, and advanced features like network

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slicing and edge computing. However, their coverage is limited to areas with cellular infrastructure, and signal quality may vary depending on the location.

To ensure robust and secure communication, UAVs often employ encryption techniques and protocols to protect data integrity and confidentiality. Additionally, measures like frequency hopping, anti-jamming mechanisms, and redundancy in communication links are implemented to enhance reliability and mitigate interference.

In conclusion, UAV communications have witnessed significant advancements, enabling more sophisticated and complex operations. RF communication, satellite communication, and cellular networks play vital roles in different scenarios, providing UAVs with diverse options for reliable and efficient communication. As technology continues to evolve, we can expect further improvements in UAV communication systems, enabling even more advanced and innovative applications in the future.

In this book, we mainly elaborated the following content.

6.1 UAV-Terrestrial Communications

6.1.1 Secure UAV Systems with Linear Trajectory

The mentioned section investigates the secrecy outage performance of a UAV system with a linear trajectory. In this system, a UAV, denoted as S, flies in a straight line and transmits its information over the downlink to a legitimate receiver, D, on the ground. However, there is also an eavesdropping UAV denoted as E that attempts to overhear the data being transmitted between S and D. Additionally, there is information being transmitted over the uplink from D to S, such as commanding messages to control S's detecting operations, which can also be eavesdropped by E. The locations of S, D, and E are randomly distributed.

The first step in the investigation is to characterize the statistical characteristics, such as CDFs and PDFs, of the received SNR for both the downlink and the uplink. The SNR is a critical parameter that determines the quality of the communication links. By analyzing the statistical characteristics of the SNR, the researchers can gain insights into the system's performance and vulnerability to eavesdropping attacks.

Next, closed-form analytical expressions are derived for the lower boundary of the SOP for both the downlink and the uplink. SOP represents the probability that eavesdropper E successfully decodes the transmitted information, compromising the system's security. By deriving these analytical expressions, the researchers can evaluate the system's secrecy performance and assess the effectiveness of countermeasures to protect against eavesdropping.

To validate the proposed analytical models, Monte Carlo simulations are conducted. Monte Carlo simulations involve using random sampling to estimate the behavior and performance of a system. By comparing the simulation results with the derived analytical expressions, the researchers can verify the accuracy and effectiveness of their proposed models.

In summary, the secrecy outage performance of a UAV system with a linear trajectory has been investigated while considering the presence of an eavesdropping UAV. The statistical characteristics of the SNR are analyzed, and closed-form analytical expressions for the lower boundary of the SOP are derived for both the downlink and the uplink. Monte Carlo simulations are performed to validate the proposed analytical models. This research contributes to understanding secure communication in UAV systems with linear trajectories and provides analytical tools to evaluate the system's secrecy performance.

6.1.2 Secure UAV-to-Vehicle Communications

This work investigates the secrecy performance of a UAV-to-vehicle (UAV-2-V) communication system, addressing the security concerns associated with UAV communications. In this system, communication occurs between a UAV denoted as S, acting as a temporary aerial BS, and a legitimate vehicle denoted as D, which moves along a road. However, an eavesdropping vehicle denoted as E, also on the same road, attempts to overhear the information transmitted between S and D.

The locations of S, D, and E are assumed to be uniformly distributed. S is in the sky, while D and E are on the highway. The statistical characteristics of the received SNR, including the CDF and PDF, are characterized separately for both the downlink and uplink. Understanding the statistical characteristics of the SNR is crucial for assessing the system's performance and vulnerability to eavesdropping attacks.

For the downlink, closed-form expressions are derived for both the approximate and asymptotic SOP. SOP represents the probability that the eavesdropper E successfully decodes the transmitted information, compromising the system's security. The downlink channels are assumed to experience Rician fading, a common model for wireless channels that includes a LOS component. The derived expressions provide insights into the system's secrecy performance under Rician fading conditions.

Furthermore, the secrecy outage performance of the uplink is investigated. The uplink refers to the communication from D to S. Closed-form expressions for the exact and asymptotic SOP are derived for two cases: when the eavesdropping channel experiences Rician fading and when it follows a Weibull fading model. Weibull fading is a more generalized fading model that encompasses various fading environments.

Monte Carlo simulations are conducted to validate the proposed analytical models. By comparing the simulation results with the derived analytical expressions, the researchers can assess the accuracy and effectiveness of their models in representing the system's secrecy performance.

In summary, this work investigates the secrecy performance of a UAV-2-V communication system, considering the presence of an eavesdropping vehicle. The statistical characteristics of the SNR are analyzed, and closed-form expressions for the SOP are derived for both the downlink and the uplink under different fading conditions. Monte Carlo simulations are performed to validate the proposed models. This research enhances the understanding of secure communication in UAV-2-V systems and provides analytical tools for evaluating the system's secrecy performance.

6.1.3 Power Adaptation Schemes in Aerial-Terrestrial Communications

This part focuses on studying the transmission capacity performance of an aerial-terrestrial communication system. In this system, an unmanned aerial vehicle denoted as S transmits information bits to a terrestrial receiver denoted as D. The transmit power of S is adaptively controlled based on the instantaneous CSI to optimize the transmission capacity.

Three adaptive transmission schemes are considered in this work. The first scheme is optimal simultaneous power and rate adaptation, where S adjusts its transmit power and transmission rate based on the channel conditions. The second scheme is optimal rate adaptation with constant transmit power, where S adapts only the transmission rate while keeping the transmit power constant. The third scheme is truncated channel inversion with a fixed rate, where S adjusts the transmit power using channel inversion while maintaining a fixed transmission rate.

Closed-form expressions for the EC are derived under these adaptive transmission schemes, taking into account the randomness of the location of the terrestrial receiver D. The EC represents the average achievable transmission capacity over multiple channel realizations. By deriving closed-form expressions, the researchers can gain insights into the system's capacity performance under different adaptive transmission schemes and random location scenarios.

Furthermore, asymptotic expressions for the EC are derived to obtain additional insights into the system's performance. Asymptotic analysis allows for understanding the system's behavior as specific parameters, such as the SNR or the number of antennas, tend to infinity or approach extreme values.

Numerical results are presented to compare the performance of the considered power adaptation methods and to validate the accuracy of the proposed analytical models. These numerical results provide quantitative assessments of the different adaptive transmission schemes and confirm the effectiveness of the derived closed-form expressions.

In summary, the transmission capacity performance of an aerial-terrestrial communication system with adaptive transmission schemes has been studied. Closed-form expressions for the EC are derived, considering the randomness of the terrestrial receiver's location. Asymptotic expressions are also obtained to gain further insights. Numerical results are provided to compare power adaptation methods and validate the proposed analytical models. This research contributes to understanding and optimizing the capacity performance of aerial-terrestrial communication systems.

6.2 UAV-to-UAV Communications

In the mentioned work, the focus is on investigating the secrecy performance of a UAV-to-UAV system. In this system, one UAV is the source (S) transmitting information to a legitimate UAV receiver. At the same time, a group of other UAVs attempts to eavesdrop on the information being transmitted between S and the legitimate UAV receiver. The locations of both the legitimate UAV receiver and the eavesdropping UAVs are randomly distributed within the coverage space of S.

The first step in the investigation is to characterize the statistical characteristics of the SNR over the links from S to the legitimate UAV receiver. The SNR is an essential factor that determines the quality and reliability of the communication link. By analyzing the statistical characteristics of the SNR, the researchers gain insights into the system's performance and vulnerability to eavesdropping attacks.

Next, we present closed-form analytical expressions for the SOP and the average secrecy capacity. SOP represents the probability that the eavesdroppers successfully decode the transmitted information, breaching the system's security. On the other hand, the average secrecy capacity quantifies the average amount of secure data that can be reliably transmitted from S to the legitimate UAV receiver while keeping it confidential from the eavesdroppers.

To validate the proposed analytical models, Monte Carlo simulations are conducted. Monte Carlo simulations involve using random sampling to estimate the behavior and performance of a system. By comparing the simulation results with the derived analytical expressions, the researchers can verify the accuracy and effectiveness of their proposed models.

In summary, we investigate the secrecy performance of a UAV-to-UAV system, considering the presence of eavesdropping UAVs. The statistical characteristics of the SNR are analyzed, and closed-form analytical expressions for the SOP and the average secrecy capacity are derived. Monte Carlo simulations are performed to validate the proposed analytical models. This research contributes to understanding secure communication in UAV systems and provides analytical tools to evaluate the system's secrecy performance.

6.3 Satellite-UAV Communications

The investigation of the impacts of small-scale fading over the aerial-terrestrial channel and the randomness of the position of the terrestrial terminal on the capacity performance of a SISO aerial-terrestrial system under three different adaptive transmission schemes (OSPRA, ORA, and TIFR) can provide valuable insights into the system's efficiency and reliability.

Small-scale fading refers to the rapid fluctuations in the received signal strength caused by multipath propagation and interference effects in wireless communication channels. It can significantly impact the quality and reliability of the received signal.

Small-scale fading can affect the system's capacity in the context of the aerial-terrestrial system, where signals are transmitted between an aerial UAV or drone and a terrestrial terminal.

The randomness of the position of the terrestrial terminal introduces spatial variability into the channel characteristics. As the terrestrial terminal moves within its coverage area, the received signal strength and quality can vary due to changes in the channel conditions. This randomness adds another layer of complexity to the system's capacity performance.

The three adaptive transmission schemes, OSPRA, ORA, and TIFR schemes, are likely designed to mitigate the effects of small-scale fading and adapt the transmission parameters to optimize capacity. OSPRA (Optimal Spatial Random Access) is a scheme that aims to maximize the system capacity by dynamically selecting the best transmission mode based on channel conditions. ORA (Opportunistic Relaying Algorithm) is a relaying scheme that exploits the available relay nodes to improve the overall system capacity. TIFR (Time-Invariant Feedback Rate) is a scheme that adapts the feedback rate based on channel quality, optimizing the system capacity under varying channel conditions.

By studying the capacity performance under these adaptive transmission schemes, the investigation can provide insights into how these schemes cope with small-scale fading and the randomness of the terrestrial terminal's position. It can evaluate their effectiveness in maximizing capacity, adapting to changing channel conditions, and maintaining reliable communication in the aerial-terrestrial system.

The findings of this investigation can be used to enhance the design and optimization of future aerial-terrestrial communication systems. It can guide the development of adaptive transmission schemes that better handle small-scale fading and spatial variability in the terrestrial terminal's position. Additionally, the results can help understand the limitations and potential trade-offs associated with each adaptive transmission scheme, allowing for informed decision-making in system design and deployment.

The mentioned work also focuses on improving the accuracy and analytical modeling of interfering signals in a three-dimensional (3D) space within the context of CH-UAV RF and S-CH FSO links. The previous approach approximated the statistical randomness of interfering signals using the Gamma distribution, a commonly used approximation based on the central limit theorem. However, the current work aims to provide a more accurate representation by deriving the moment-generating function of the summation of interfering signals while considering the randomness of the 3D locations of CHs (Cluster Heads).

By considering the randomness of the 3D locations of CHs, the work accounts for the spatial variability of the interference signals in a more precise manner. This approach provides a more realistic representation of the interfering scenarios in 3D space. Furthermore, the work goes beyond presenting non-closed-form analytical expressions for performance indices. It achieves closed-form analytical expressions for the coverage probability over S-CH FSO and CH-UAV RF links.

The derived closed-form analytical expressions for the coverage probability are valuable as they allow a more straightforward evaluation of the system's performance under different interference scenarios. The coverage probability is a critical performance metric that indicates the probability of achieving a reliable connection or communication link in the presence of interference.

The closed-form expressions presented in this work cover various interference scenarios, including interference-free, interference-dominated, and interference-and-noise cases. This comprehensively analyzes the system's performance under different interference conditions.

Overall, this work contributes to the understanding and analysis of CH-UAV RF links and S-CH FSO links by incorporating accurate modeling of interfering signals in 3D space and deriving closed-form analytical expressions for the coverage probability. The improved modeling and analytical expressions enhance the evaluation and optimization of these communication links, enabling better design and deployment decisions in practical scenarios.

6.4 UAV Relay Communications

The first contribution is the proposal of a mixed RF and underwater optical communication network, where a UAV acts as a mobile source to transmit a signal to an underwater terminal. This transmission is achieved through a surface relay. Integrating RF and underwater optical communication allows for communication between aerial and underwater nodes, which can be useful in various applications.

Furthermore, the analytical expressions of OP were derived for both amplified-and-forward and DF protocols in this mixed RF-underwater optical communication network. OP is a performance metric representing the probability of a communication link failing to meet a certain quality-of-service requirement. The system's performance can be evaluated, optimized, and compared under different protocols and scenarios by deriving analytical expressions for OP.

The second contribution is proposing a resource optimization scheme for a UAV-NOMA network. This scheme aims to enhance the EE and spectrum efficiency of the system. EE refers to the system's achievable throughput ratio to energy consumption, and spectrum efficiency refers to the data transmitted over a given bandwidth. By optimizing resource allocation in the UAV-NOMA network, the scheme aims to improve the system's energy and spectrum utilization, leading to more efficient and effective communication.

In summary, the contributions include the proposal of a mixed RF-underwater optical communication network with a UAV as a mobile source, the derivation of analytical expressions for OP under different protocols, and the development of a resource optimization scheme for a UAV-NOMA network to enhance energy and spectrum efficiency. These contributions advance the understanding and optimization of communication systems in challenging environments and pave the way for more efficient and reliable communication in aerial, underwater, and NOMA networks.

6.5 Future of UAV Communications

UAVs have already revolutionized industries such as agriculture, construction, logistics, and delivery services. In the future, we can expect to see further advancements in these areas, with drones becoming more efficient, autonomous, and capable of carrying heavier payloads. This could lead to increased adoption of UAVs for tasks like aerial inspections, crop monitoring, and last-mile deliveries. Moreover, Urban Air Mobility (UAM) refers to using drones for personal transportation within cities. In the future, we might witness the development of advanced drone taxis and air shuttles, enabling convenient and efficient transportation. These autonomous aerial vehicles could help alleviate traffic congestion, reduce commuting times, and enhance urban mobility. What's more, UAVs will continue to evolve with improved autonomous capabilities. Future drones might possess advanced computer vision systems and machine learning algorithms. Here are also a few key areas that are likely to shape the future of UAV communication:

1. BLOS Communication: Currently, UAVs are often limited to operating within the line of sight (LOS) of the operator or a ground station. However, future advancements in communication technology, such as satellite links, high-frequency radio waves, and advanced networking protocols, can enable UAVs to communicate beyond the LOS, expanding their operational range and capabilities.
2. Swarm Communication: Swarm technology, where multiple UAVs operate cooperatively and coordinated, is gaining traction. In the future, enhanced communication systems will allow for seamless coordination and communication among swarm members, enabling them to effectively perform complex tasks, share information, and adapt to dynamic environments.
3. Improved Data Transmission: UAVs generate vast amounts of data through various sensors, cameras, and other onboard systems. Future communication systems must support high-speed data transmission and low-latency links to facilitate real-time data analysis, remote control, and command and control operations.
4. Security and Privacy: As UAVs become more prevalent in various industries, ensuring secure and private communication will be crucial. Advanced encryption techniques, authentication protocols, and anti-jamming technologies will significantly protect UAV communications from cyber threats.
5. Integration with Existing Communication Infrastructure: Integrating UAV communications seamlessly into existing communication infrastructure, such as cellular networks or dedicated UAV communication networks, will be essential. This integration will allow UAVs to leverage existing infrastructure for communication, enhancing their reliability and enabling efficient airspace management.
6. Spectrum Management: With the increasing number of UAVs in operation, efficient spectrum management will become critical to avoid interference and congestion. Regulatory bodies and communication authorities must develop frameworks to allocate dedicated frequency bands or implement dynamic spectrum-sharing mechanisms to support UAV communication.

7. Artificial Intelligence (AI) and Machine Learning (ML): AI and ML technologies will play a crucial role in UAV communications by enabling autonomous decision-making, adaptive communication protocols, and intelligent routing algorithms. These technologies can enhance communication efficiency, optimize network resources, and improve overall UAV mission performance.

It's important to note that advancements will influence the future of UAV communications in communication technology, regulatory frameworks, industry requirements, and the evolving needs of various sectors, such as agriculture, logistics, emergency response, and surveillance.