

UNIVERSITY OF TECHNOLOGY SYDNEY
Faculty of Engineering and Information Technology

**Performance analysis of Unmanned Aerial
Vehicles-enabled Wireless Networks**

by

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Certificate of Authorship/Originality

I, Xin Yuan declare that this thesis, is submitted in fulfilment of the requirements for the award of doctor of philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney. This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text. This thesis is the result of a research candidature jointly delivered with Beijing University of Posts and Telecommunications as part of a Collaborative Doctoral Research Degree. This research is supported by the Australian Government Research Training Program.

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ABSTRACT

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As an indispensable part of mobile communication systems, Unmanned Aerial Vehicles (UAVs) can be leveraged to complement terrestrial networks by providing coverage to areas where infrastructures are scarce. Equipped with self-navigation and strong automation, UAVs have extensive applications to environmental monitoring, disaster recovery, search and rescue, owing to their excellent agility and autonomy. As a result, an increasing demand arises for ubiquitous connectivity and reliable communication for data exchange between UAVs, and between UAVs and ground stations. Since UAVs operate in three-dimensional (3D) space with strong manoeuvrability, random trajectories and wireless propagation environment can pose significant challenges to the study on coverage and capacity of UAV networks. On the other hand, UAVs are increasingly posing threats to information security. UAVs can be potentially used to eavesdrop and jam wireless transmissions between legitimate terrestrial transceivers. It is of practical interest to understand the robustness of terrestrial wireless communications under exposure to new threats from aerial adversaries. This thesis studies the coverage and capacity, including secure coverage and secrecy capacity, of UAV-enabled wireless networks with UAVs flying under 3D random trajectories based on stochastic geometry and measure convergence theory. The detailed contributions of this thesis are summarised as:

- Capacity analysis of UAV networks under random trajectories. We geometrically derive probability distributions of UAV-to-UAV distances and closed-form bounds for the capacity can be obtained by exploiting the Jensen's in-

equality. We extrapolate the idea to dense UAV networks and analyse the impact of network densification and imperfect channel state information on the capacity.

- Connectivity analysis of uncoordinated UAV swarms. New closed-form bounds are derived for the outage probability of individual UAVs, and broadcast connectivity of each UAV which evaluates the reliability of broadcast across the swarm. The qualifying conditions of the bounds on 3D coverage and impact of ground interference on the outage are identified.
- Secure connectivity analysis in UAV networks. We propose a trust model based on UAVs' behaviour and mobility pattern and characteristics of inter-UAV channels. We derive analytical expressions of both physical and secure connectivity probabilities with/without considering Doppler shift.
- Secrecy capacity analysis against aerial eavesdroppers. We analyse ergodic and ϵ -outage secrecy capacities of ground link in the presence of cooperative aerial eavesdroppers. The "cut-off" density of eavesdroppers under which the secrecy capacities vanish is identified. By decoupling the analysis of random trajectories from random channel fading, closed-form approximations with almost sure convergence to the secrecy capacities are devised.

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List of Publications

Journal Papers

- J-1. **X. Yuan**, Z. Feng, W. Ni, R. P. Liu, J. Zhang, and W. Xu, "Secrecy Performance of Terrestrial Radio Links under Collaborative Aerial Eavesdropping," *IEEE Transactions on Information Forensics and Security*, June 2019.
- J-2. **X. Yuan**, Z. Feng, W. Ni, Z. Wei, R. P. Liu, and J. Zhang, "Secrecy Capacity Analysis against Aerial Eavesdropper," *IEEE Transactions on Communications*, July 2019.
- J-3. **X. Yuan**, Z. Feng, W. Xu, W. Ni, J. Zhang Z. Wei, and R. P. Liu, "Capacity Analysis of UAV Communications: Cases of Random Trajectories," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 8, pp. 7564-7576, Aug. 2018.
- J-4. **X. Yuan**, Z. Feng, W. Xu, Z. Wei, and R. P. Liu, "Secure Connectivity Analysis in Unmanned Aerial Vehicle Networks," *Frontiers of Information Technology & Electronic Engineering*, 19, 409-422, 2018.
- J-5. Z. Wei, H. Wu, **X. Yuan**, S. Huang and Z. Feng, "Achievable Capacity Scaling Laws of Three-Dimensional Wireless Social Networks," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 3, pp. 2671-2685, March 2018.
- J-6. S. Huang, Z. Wei, **X. Yuan**, Z. Feng and P. Zhang, "Performance Characterization of Machine-to-Machine Networks With Energy Harvesting and Social-Aware Relays," *IEEE Access*, vol. 5, pp. 13297-13307, 2017.
- J-7. Z. Wei, Z. Wang, **X. Yuan**, H. Wu and Z. Feng, "Information Density-based Energy-limited Capacity of Ad Hoc Networks," *International Journal of Distributed Sensor Networks*, 2018, 14(4): 1550147718773242.

Conference Papers

- C-1. **X. Yuan**, Z. Wei, Z. Feng, Q. Zhang and W. Li, “Throughput Scaling Laws of Hybrid Wireless Networks with Proximity Preference,” *IEEE Wireless Communications and Networking Conference*, Doha, 2016, pp. 1-6.
- C-2. **X. Yuan**, Z. Wei, Z. Feng and W. Xu, “Trust Connectivity Analysis in Overlaid Unmanned Aerial Vehicle Networks,” 17th International Symposium on Communications and Information Technologies (ISCIT), Cairns, QLD, 2017, pp. 1-6.
- C-4. Z. Wei, Z. Feng, **X. Yuan**, X. Feng, Q. Zhang and X. Wang, “The Achievable Capacity Scaling Laws of 3D Cognitive Radio Networks,” *IEEE International Conference on Communications (ICC)*, Kuala Lumpur, 2016, pp. 1-6.
- C-5. S. Liu, Z. Wei, Z. Guo, **X. Yuan** and Z. Feng, “Performance Analysis of UAVs Assisted Data Collection in Wireless Sensor Networks,” *IEEE 87th Vehicular Technology Conference (VTC Spring)*, Porto, 2018, pp. 1-5.
- C-6. J. Shang, W. Xu, C. Lee, **X. Yuan**, P. Zhang, and J. Lin “Delay Estimation of UAV Communications Based on Fountain Codes,” *IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2019.

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Abbreviation

a.s. - Almost sure

i.i.d. - Independent and identically distributed

CDF - Cumulative distribution function

PDF - Probability of Density

2DPSK - Binary DPSK

2D: Two-dimensional

3D: Three-dimensional

5G - The 5th Generation mobile communication system

6G - The 6th Generation mobile communication system

A2A - Air-to-air

A2G - Air-to-ground

AA - Azimuth angle

AWGN - Additive white Gaussian noise

BER - Bit error rate

BS - Base station

BPP - Binomial point process

BPSK - Binary Phase Shift Keying

CDMA: Code Division Multiple Access

CoMP: Coordinated Multi-Point

CSMA/CA - Carrier-sense multiple access with collision avoidance

CSI: Channel State Information

CQI: Channel Quality Indicator

D2D: Device to Device

DoF - Degree-of-freedom
DPSK - Differential Phase Shift Keying
M2M: Machine to Machine
MIMO: Multi input multi output
E2E: End-to-end
EA - Elevation angle
EHTM - Efficient hierarchical trust model
FDD: Frequency Division Duplex
FDMA: Frequency Division Multiple Access
G2G: Ground-to-ground
G2U: Ground-to-UAV
JP: Joint Processing
LTE: Long Term Evolution
LTE-A: Long Term Evolution-Advanced
LoS: Line-of-sight
MAC: Medium access control
MANET: Mobile Ad Hoc Network
MIMO: Multiple Input Multiple Output
MISO: Multiple Input Single Out
MMSE: Minimum Mean Square Error
MRC: Mobile Ad Hoc Network
NLoS: Non line-of-sight
PER: Packet error rate
PMF: Probability Mass Function
PGF: Probability Generating Functional
PLL: Phase-locked loop
PLR: packet loss rate

PPP: Poisson Point Process
PRR: Packet Receiving Ratio
QoS: Quality of Service
RF: Radio Frequency
RMS: Root-mean-square
RSRP: Reference Signal Received Power
RSSI: Received Signal Strength Indicator
SC: Selection combining
SINR: Signal to Interference plus Noise Ratio
SNR: Signal-to-noise ratio
SON: Self-Organized Network
SRCM: Semi-Random Circular Movement
ST:Smooth Turn
SVD: Singular value decomposition
TDD: Time Division Duplex
TDMA: Time Division Multiple Access
MTC: Machine Type Communication
ICIC: Inter-Cell Interference Coordination
WiMAX: Worldwide Interoperability for Microwave Access
WSN: Wireless Sensor Networks
U2G: UAV-to-Ground
UAV: Unmanned Aerial Vehicles
VANET: Vehicular Ad hoc Network
ZF: Zero Forcing

Nomenclature and Notation

Capital letters denote matrices.

Lower-case alphabets denote column vectors.

$(\cdot)^T$ denotes the transpose operation.

$(\cdot)^*$ denotes the complex conjugate operation.

$(\cdot)^H$ denotes the conjugate transpose operation.

I_n is the identity matrix of dimension $n \times n$.

0_n is the zero matrix of dimension $n \times n$.

\mathbb{R} , \mathbb{R}^+ denote the field of real numbers, and the set of positive reals, respectively.

$(\cdot)^+$ denotes $\max\{\cdot, 0\}$.

$|\cdot|$ denotes the modulo operation.

$\mathbb{E}[\cdot]$ denotes the expectation operation.

$f(\cdot)$ denotes the probability distribution function.

$F(\cdot)$ denotes the cumulative distribution function.

$\Pr(\cdot)$ denotes the probability function.

$\frac{\partial y}{\partial x}$ denotes the first order partial derivative of y to x .

$\frac{\partial^2 y}{\partial x^2}$ denotes the second order partial derivative of y to x .

$\mathbf{1}(\cdot)$ denotes the indicator function.

$B(a, b)$ denotes the Beta function with parameter a and b .

$\beta(\cdot; \cdot, \cdot)$ denotes the incomplete beta function.

$\Gamma(\cdot)$ denotes the Γ function.

$\gamma(a, b) = \int_0^b e^{-t} t^{a-1} dt$ denotes the incomplete gamma function.

${}_2F_1(a, b; c; z) = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n} \cdot \frac{z^n}{n!}$ denotes the Gaussian hypergeometric function.