UNIVERSITY OF TECHNOLOGY SYDNEY
Faculty of Engineering and Information Technology

Performance analysis of Unmanned Aerial Vehicles-enabled Wireless Networks

by

Xin Yuan

A Thesis Submitted
in Partial Fulfillment of the
Requirements for the Degree

Doctor of Philosophy

Sydney, Australia

2020

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.

Signature: Production Note:
Signature removed prior to publication.

Date: 02/02/2020

ABSTRACT

Performance analysis of Unmanned Aerial Vehicles-enabled Wireless Networks

by

Xin Yuan

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.

Dissertation directed by Professor Ren Ping Liu, Associate Professor Andrew Zhang, and Dr. Wei Ni
School of Electrical and Data Engineering

Acknowledgements

Throughout the writing of this thesis, I have received a great deal of support and assistance. I would first like to thank my principal supervisor, Prof. Ren Ping Liu, whose expertise was invaluable in the formulating of the research topic and methodology in particular. I appreciate all his contributions of time, ideas, and funding to make my PhD experience productive.

I owe my deepest gratitude to my co-supervisor, Dr. Wei Ni, for his scientific advice and knowledge and many insightful discussions and suggestions. He is my primary resource for getting my science questions answered and was instrumental in helping me crank out this thesis. I also would like to thank my co-supervisor A/Prof. Andrew Zhang, for his patience, encouragement and insightful comments on my research.

I especially thank my supervisor, Prof. Zhiyong Feng, from Beijing University of Posts and Telecommunications (BUPT), for her support, guidance, encouragement, and technical comments through all years of my research. Special thanks to BUPT, Beijing, China, and University of Technology Sydney (UTS) for providing a scholarship and other financial support for my study and research.

I also thank my friends for providing a happy distraction to rest my mind outside of my research. Finally, I would like to express my deep and sincere gratitude to my parents for their encouragement, constant support and unconditional love, they have kept me moving forward even in tough times. This journey would not have been possible if not for them, and I dedicate this milestone to them.

Xin Yuan

Sydney, Australia, 2020.

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.

Contents

List of Figures

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.

$(\cdot)^{\mathrm{H}}$ 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.