Wireless Communications and Job Selection in Networked Drone Systems

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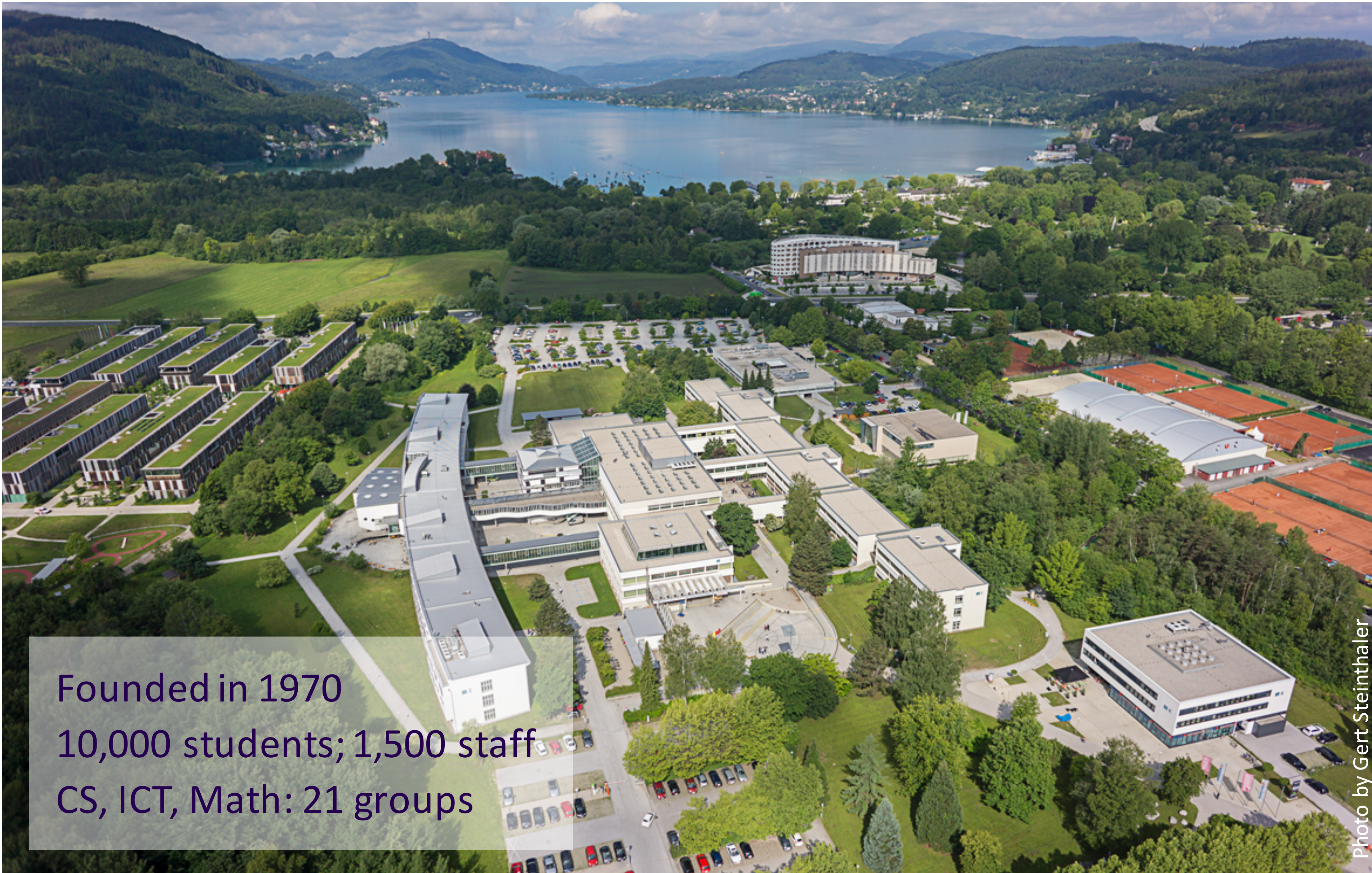
University of Klagenfurt and Lakeside Labs
Talk at CARRE, U of Toronto, April 27, 2017

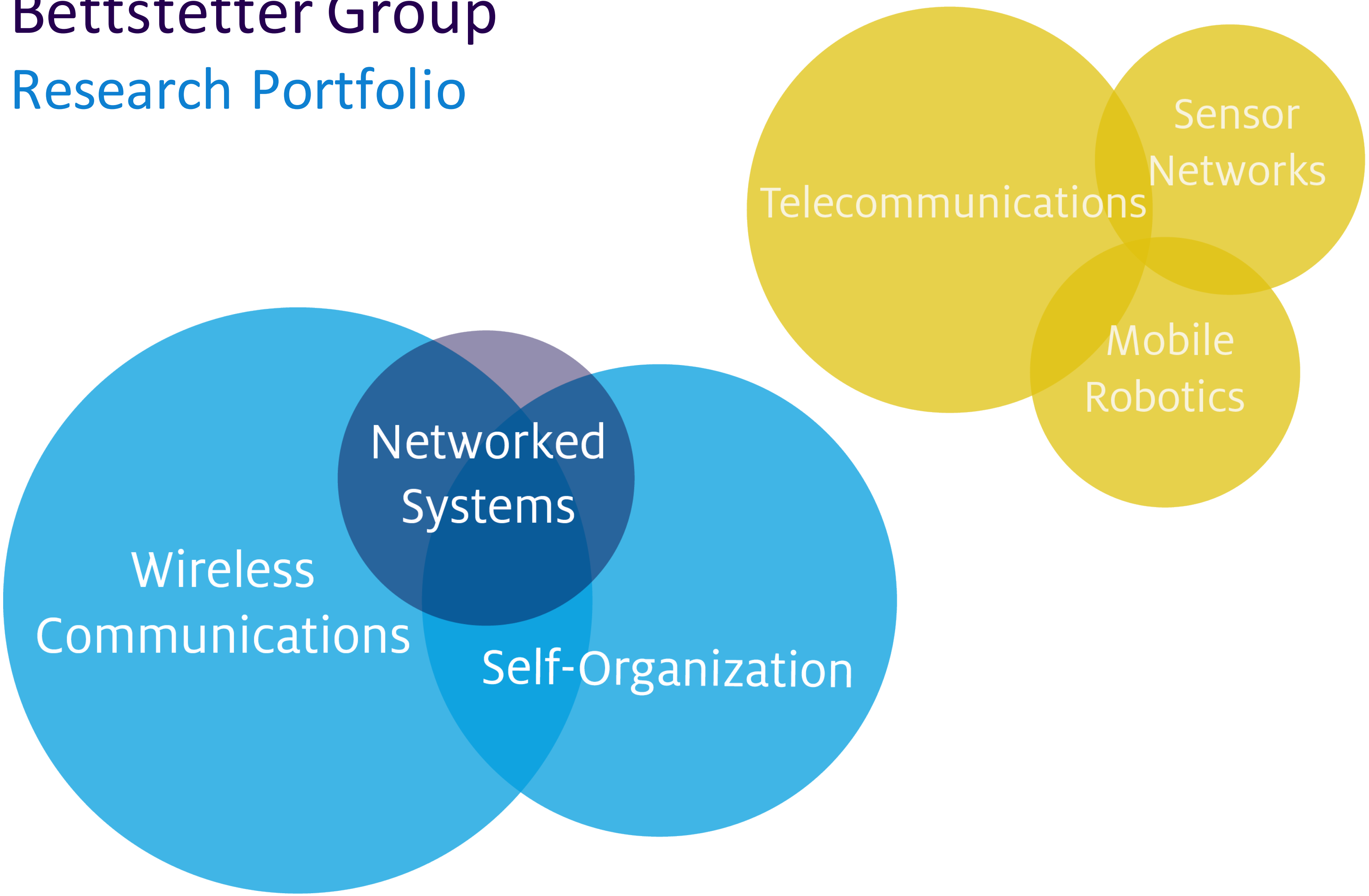
University of Klagenfurt and Lakeside Park



Founded in 1970
10,000 students; 1,500 staff
CS, ICT, Math: 21 groups

Bettstetter Group

Research Portfolio



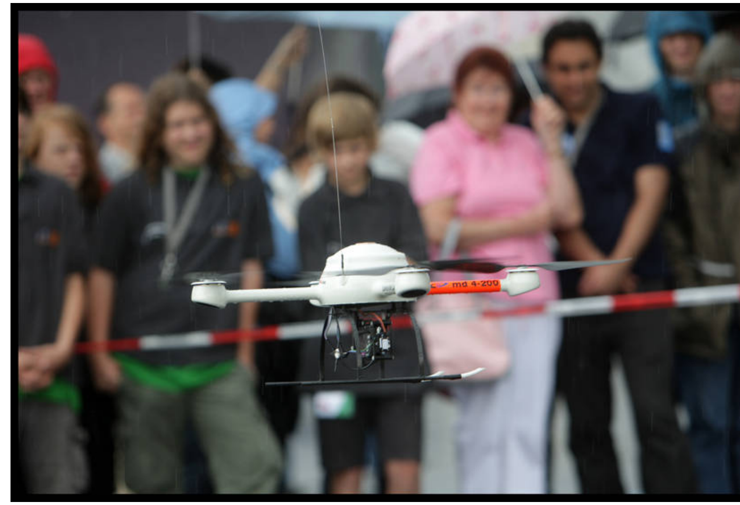
Portfolio in Aerial Robotics | Drone Systems

Research topics

- Autonomous navigation
- Coordination
- Human-drone interaction
- Image processing
- Mission and path planning
- Wireless communications

Application areas

- Aerial surveillance
- Delivery
- Digital farming
- Search and rescue



Key facts

Started 2008

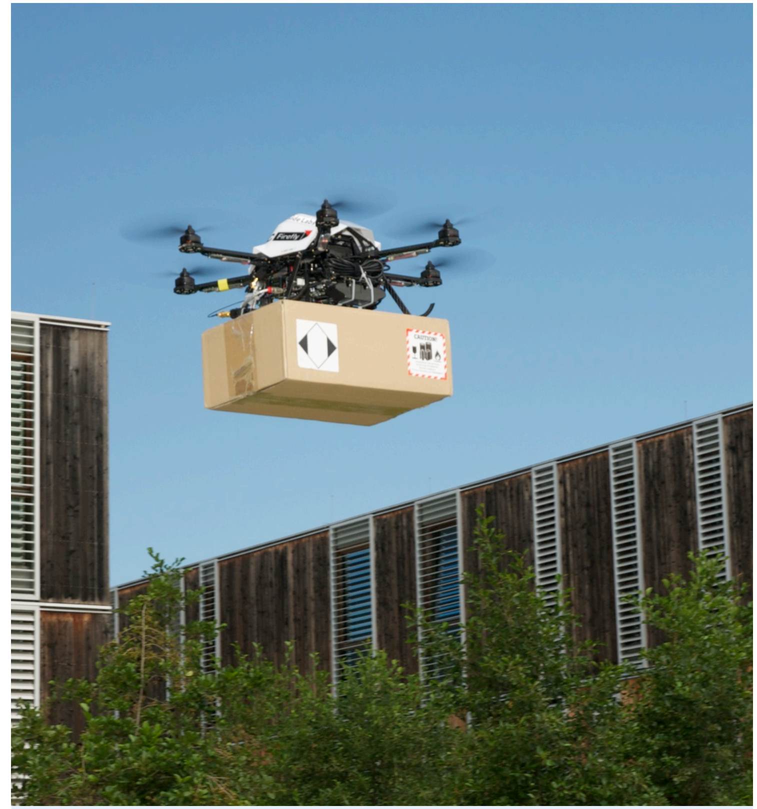
8 Profs, 15 PhDs, Postdocs

9 funded projects

~ 60 publications

Wireless communications and networking

Duration: 30 minutes



Job selection for delivery services

Duration: 15 minutes

Wireless Communications and Networking for Small Drones

1

- What are the requirements?
- What can WLAN offer?
- Are standard antennas suited?
- How to model the radio link?
- What throughput is achieved?
- What are common research issues of control, vision, and networking?

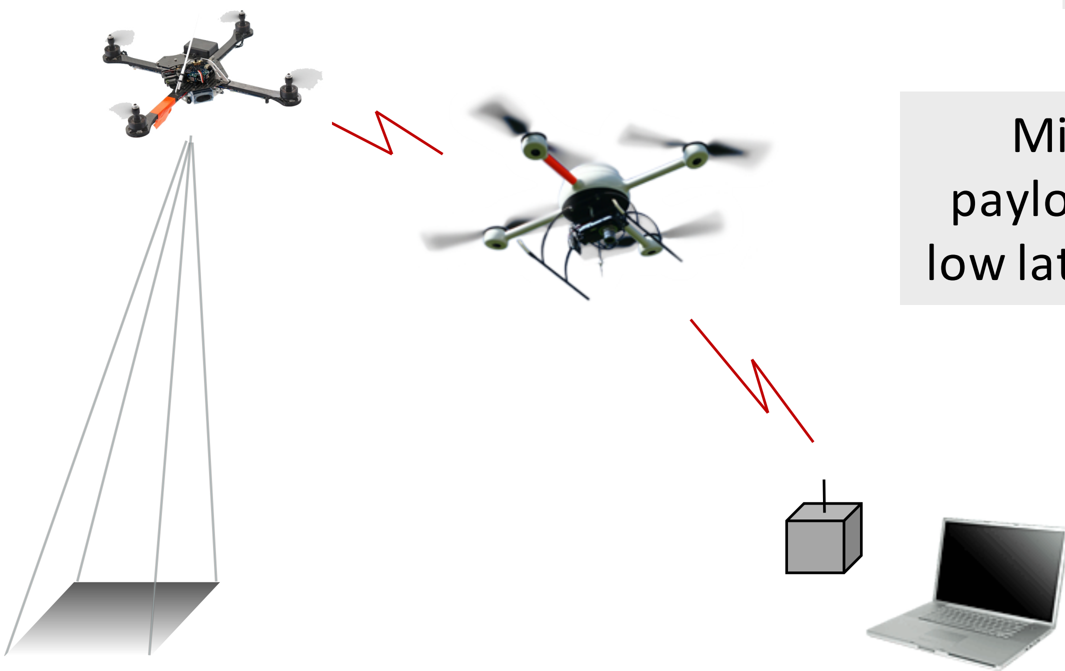
Wireless Communications for Small Drones

Scenario and requirements

3D mobility

Infrastructure and mesh networking

Reliability and robustness against interference



Mix of traffic types, payload and control, incl. low latency, high data rates

Precise time sync and localization

Wireless Communications for Small Drones

Mix of different traffic types

Traffic type	Requirement
Drone control	Low latency + high reliability
Vision-based navigation	High data rate + low latency
Multimedia applications	High data rate + QoS support

Example: VGA camera: 2.6 kbit · 30/s = 80 Mbit/s (one drone)

Wireless Communications for Small Drones

State of the art

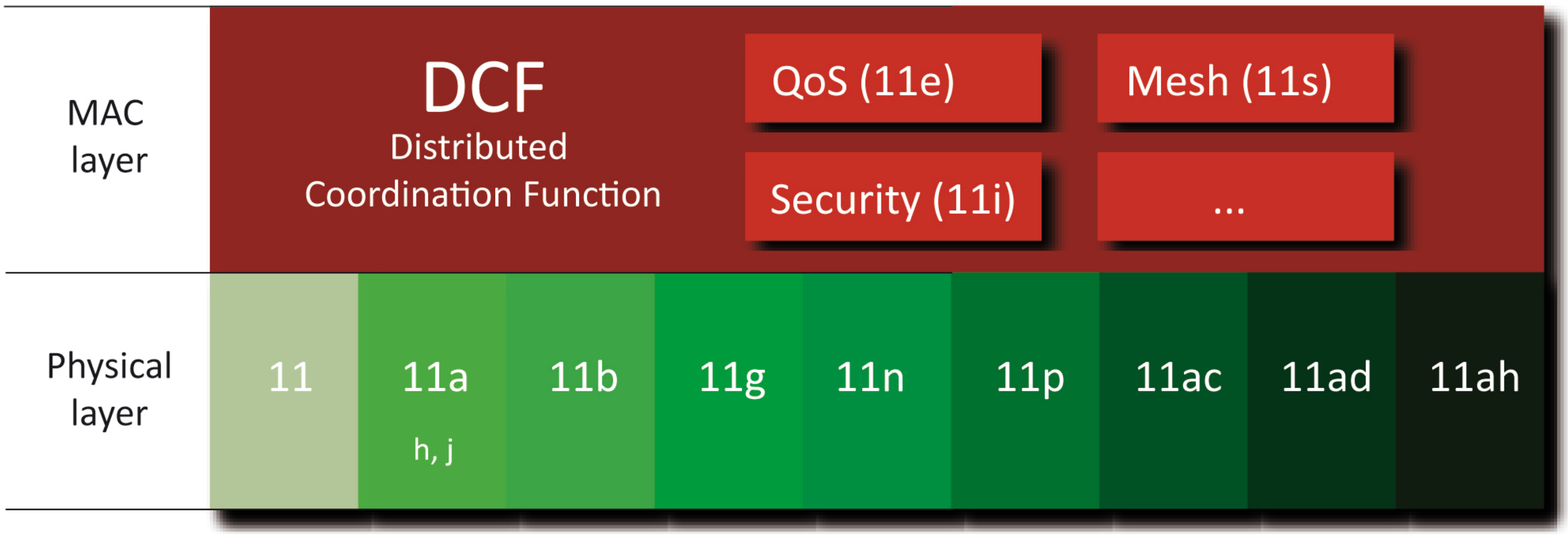
- Most of commercially available drones use WLAN IEEE 802.11
- 802.11 operates in unlicensed spectrum and chips are cheap
- 802.11 has not been designed for such purpose

Questions for experimental research

- How far do we get with off-the-shelf IEEE 802.11?
- Do we meet the requirements of certain drone applications?

WLAN Standard IEEE 802.11

Overview



WLAN Standard IEEE 802.11

Physical layers

	Year	Frequency	Max. rate	Range
11a	1999	5 GHz ISM	54 Mbit/s	< 100 m
11g	2003	2.4 GHz ISM	54 Mbit/s	< 250 m
11n	2009	2.4 + 5 GHz ISM	135 Mbit/s	< 250 m
11p	2010	5.9 GHz licensed	27 Mbit/s	< 1 km
11ac	2013	5 GHz ISM	780 Mbit/s	
11ad	2012	60 GHz (mm)	6.7 Gbit/s	< 10 m
11ah	2016	900 MHz	20 Mbit/s	1 km

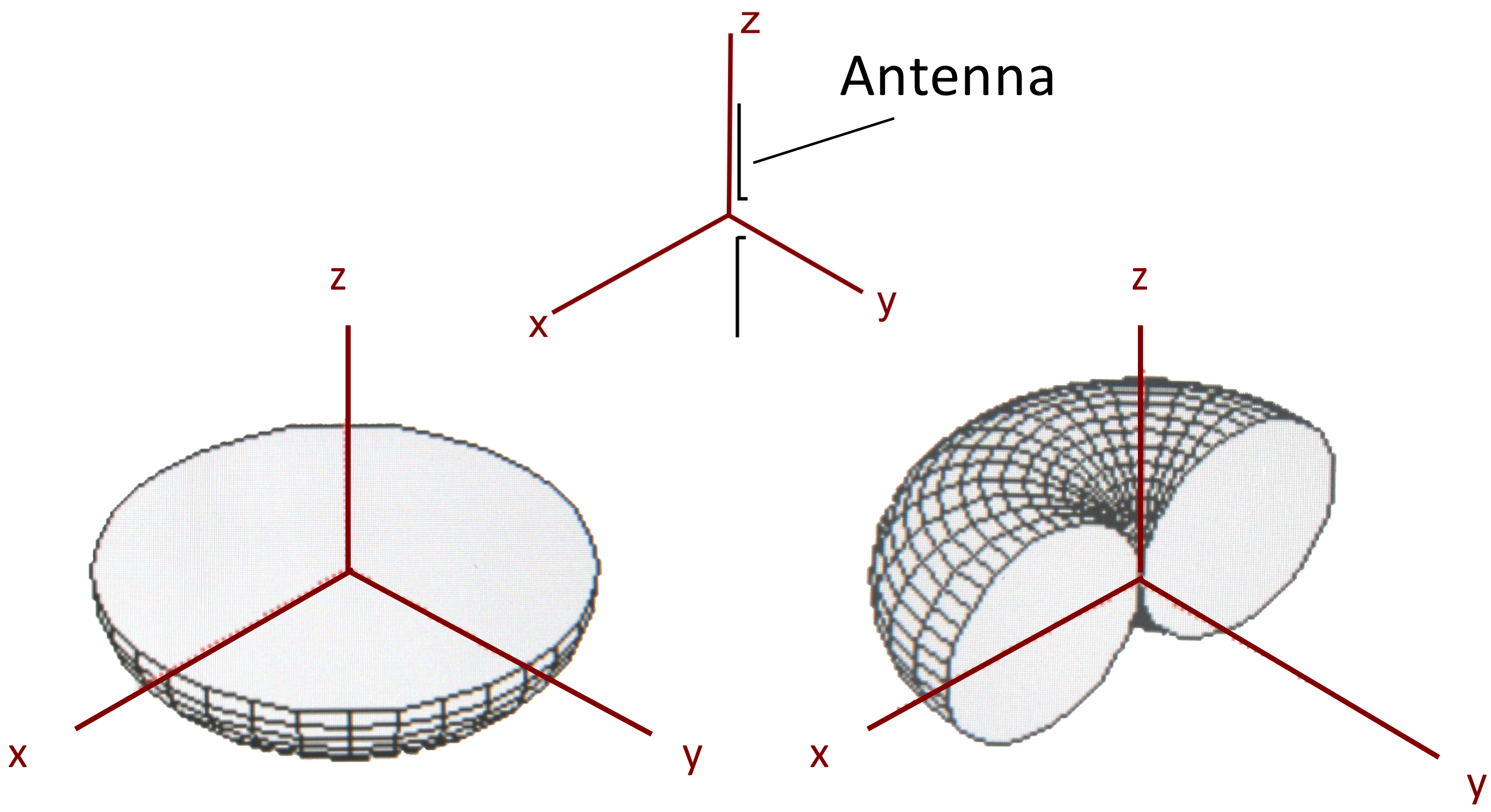
Wireless Communications for Small Drones

What influences the communication quality?

- Wireless technology (e.g., IEEE 802.11, LTE, 802.15.1)
- Antenna radiation pattern and polarization
- Shielding by drone hardware
- Radio propagation environment
  - Obstacles
  - Multipath propagation of the radio wave
- Movement pattern of drones
- And other factors

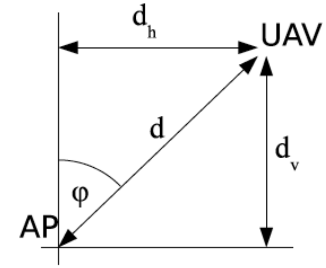
Antennas

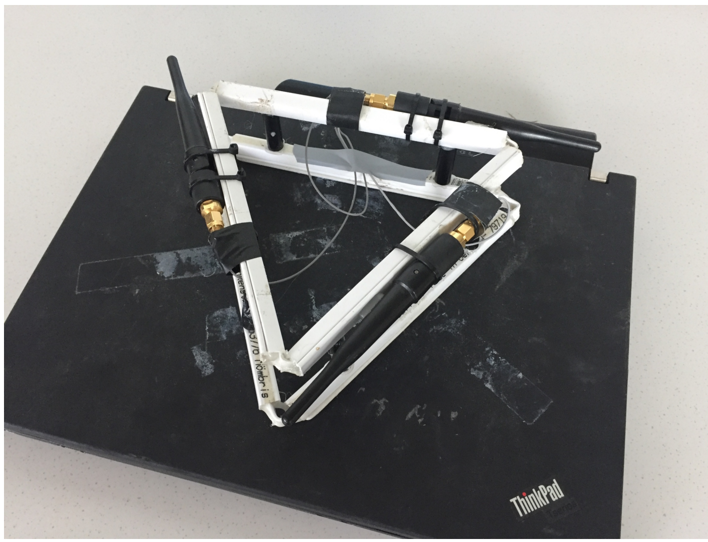
Directivity pattern of a dipole antenna



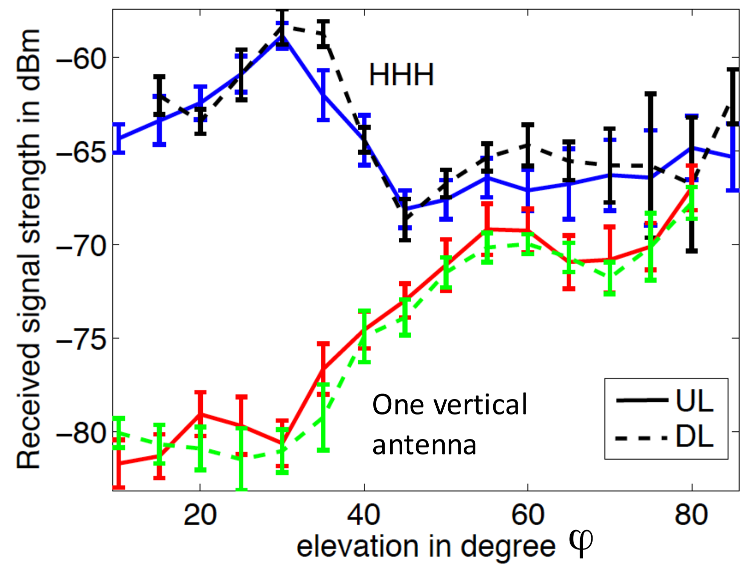
Antennas

A simple proposal to improve range





Three horizontal antennas (HHH)



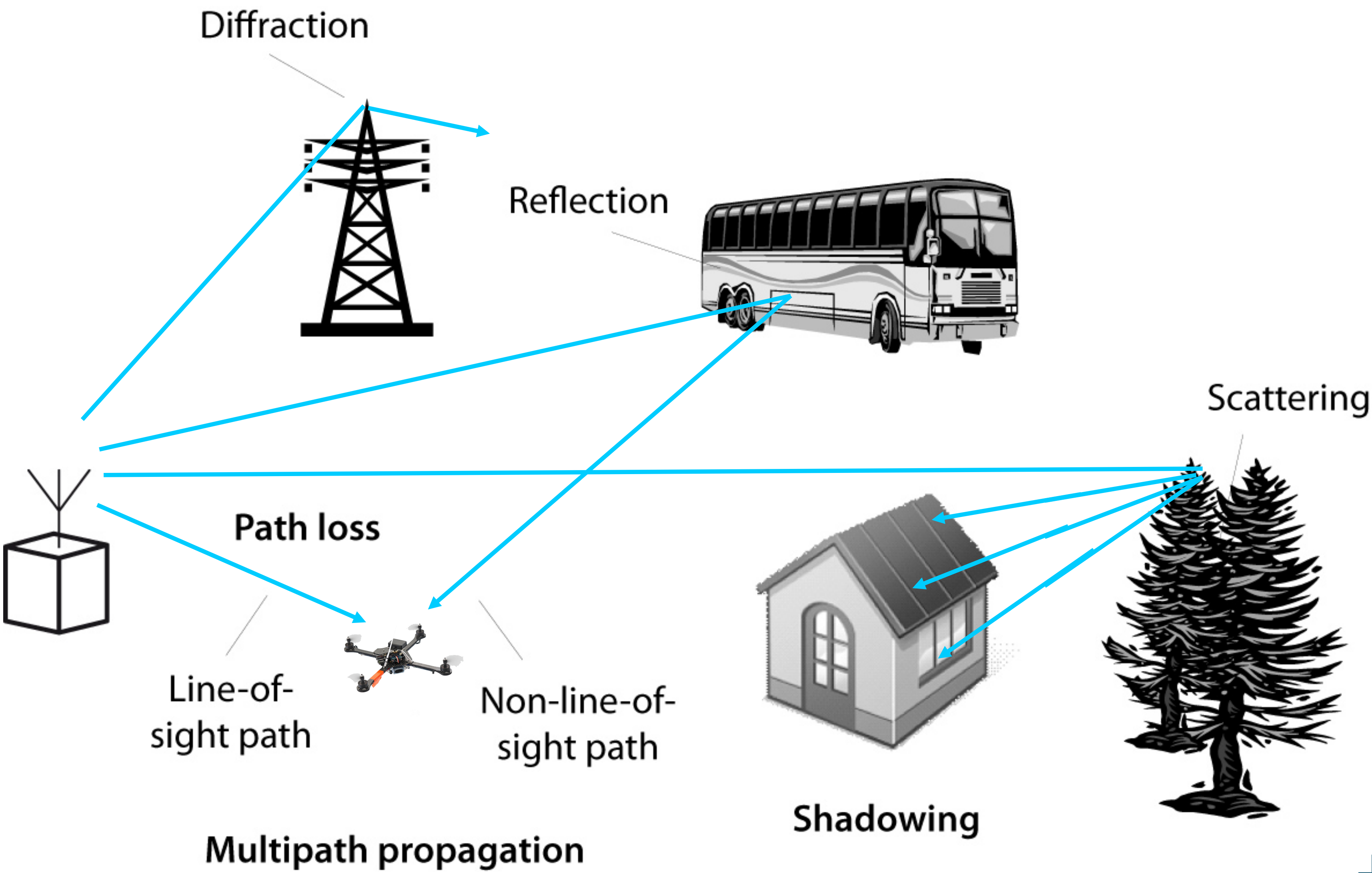
Uplink
Downlink

Measurements with IEEE 802.11a

at distance of 100 m

E. Yanmaz, R. Kuschnig, C. Bettstetter. Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility. In *Proc. IEEE Intern. Conf. on Computer Commun. (INFOCOM)*, Turin, Italy, 2013.

Radio Propagation Environment



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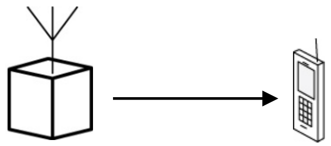
Radio Propagation Environment

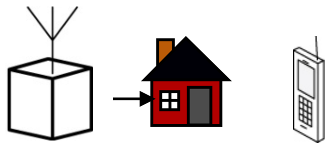
Path loss

The reception power decreases with distance *d* between sender and receiver.



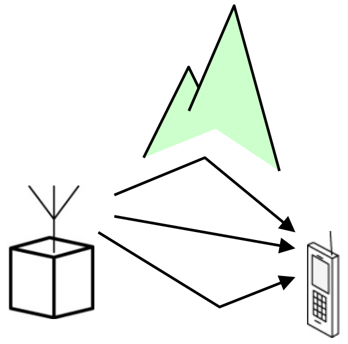
Shadowing

Radio wave is disturbed by obstacles in the transmission path.



Multipath propagation

Radio wave is reflected and scattered at objects and at the ground, leading to multiple received copies of the same transmitted wave.

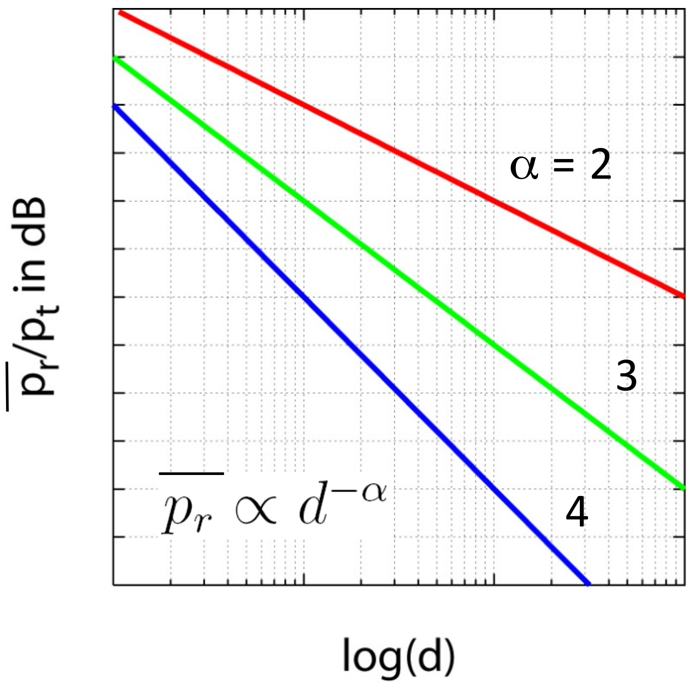


Radio Propagation Environment

Simple path loss model

$$g_\mathrm{p} \doteq \frac{\bar{p}_\mathrm{r}}{p_\mathrm{t}} = g_0 \left(\frac{d}{d_0}\right)^{-\alpha}$$

for $d > d_0$



Path loss exponent α:

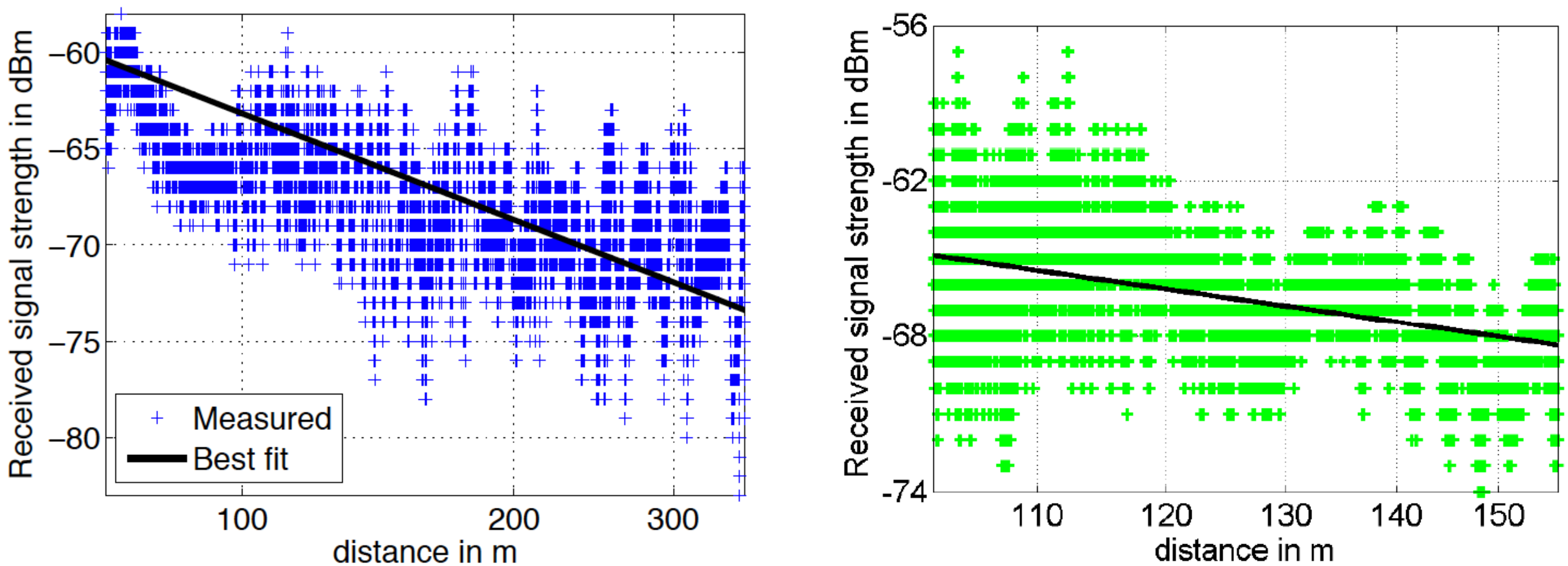
- Characterizes the environment
- Free space: $\alpha = 2$
- Urban environment: $3 \leq \alpha \leq 6$

Constants:

- Reference distance d_0
- Gain at d_0 is g_0

Radio Propagation Environment

Path loss exponent for outdoor *ground-to-drone* link



(a) Horizontal: moving away

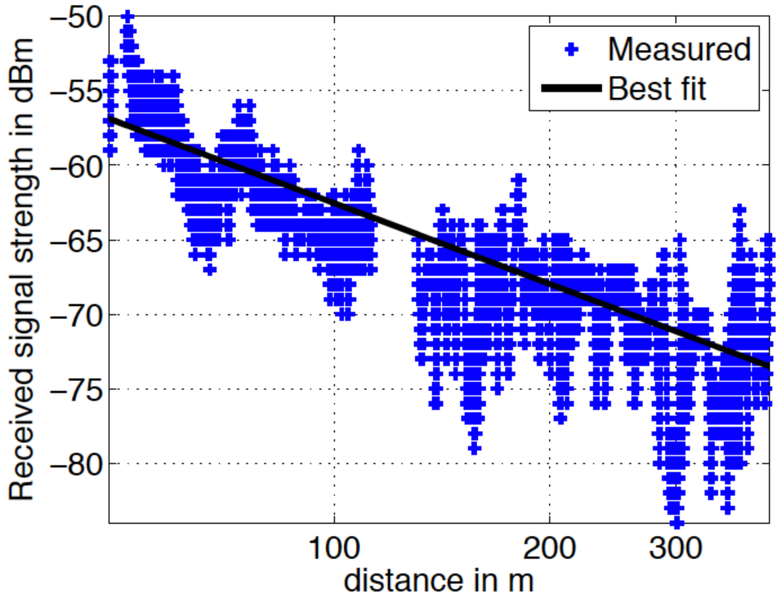
(b) Vertical: ascending

Experiments yield $\alpha = 2.01$ independent of mobility type.

E. Yanmaz, R. Kuschnig, C. Bettstetter. Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility. In *Proc. IEEE Intern. Conf. on Computer Commun. (INFOCOM)*, Turin, Italy, 2013.

Radio Propagation Environment

Path loss exponent for outdoor *drone-to-ground* link



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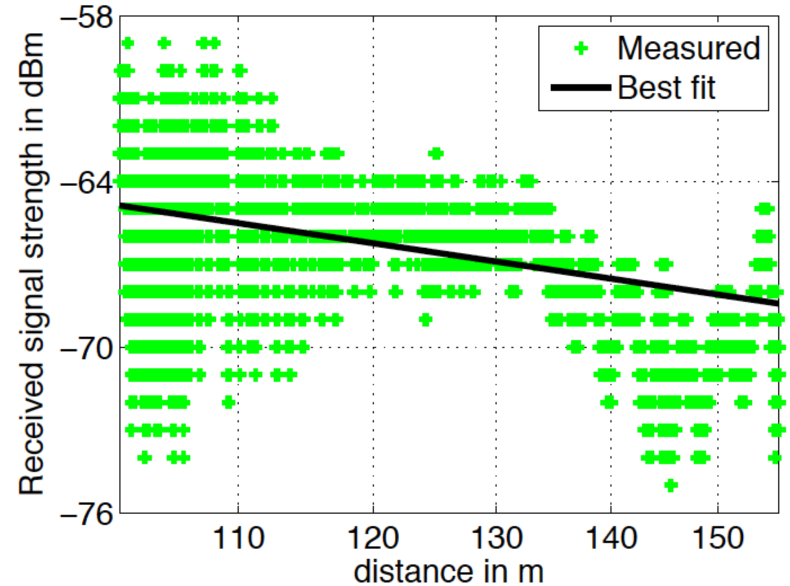

(b) Vertical: ascending

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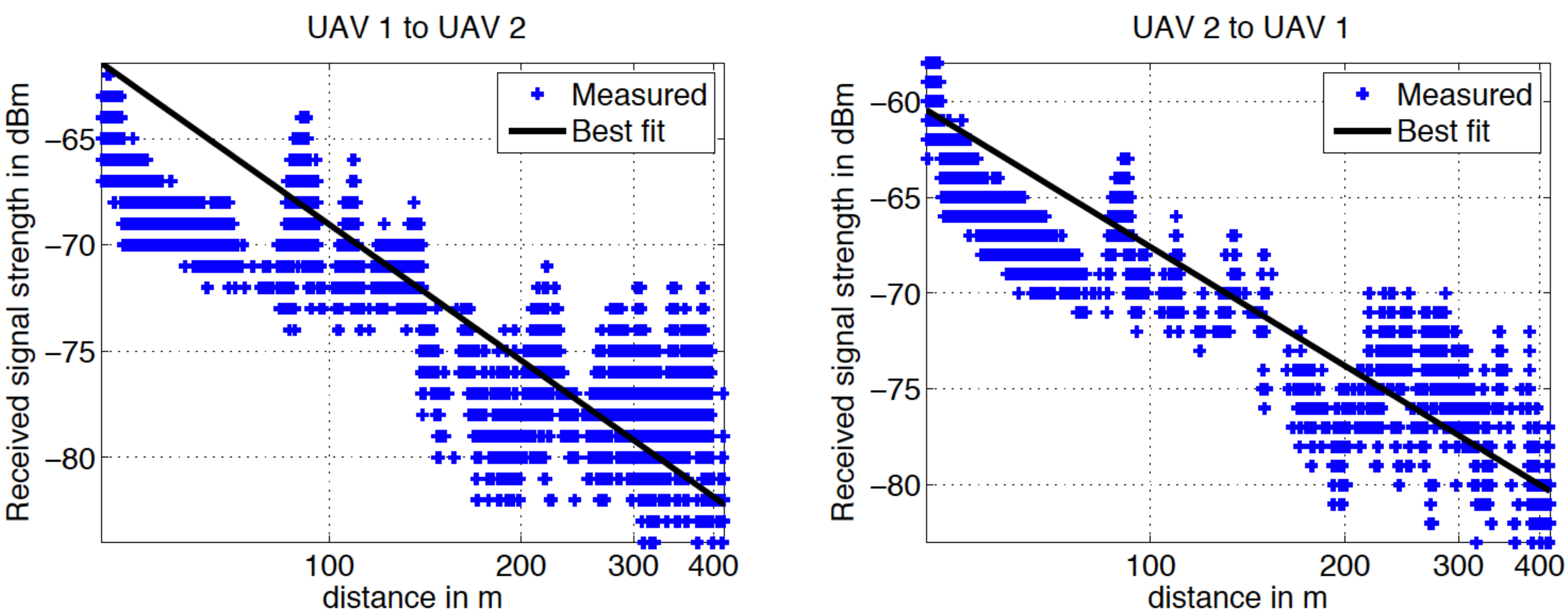
Radio Propagation Environment

Path loss exponent for outdoor *drone-to-drone* links



(a) (b)

Experiments yield $\alpha = 2.03$.

E. Yanmaz, R. Kuschnig, C. Bettstetter. Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility. In *Proc. IEEE Intern. Conf. on Computer Commun. (INFOCOM)*, Turin, Italy, 2013.

Radio Propagation Environment

Path loss

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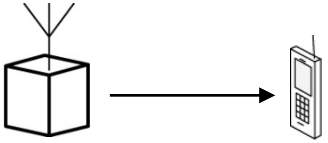

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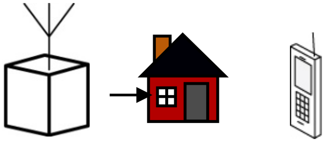

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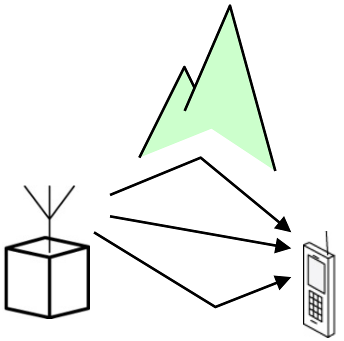
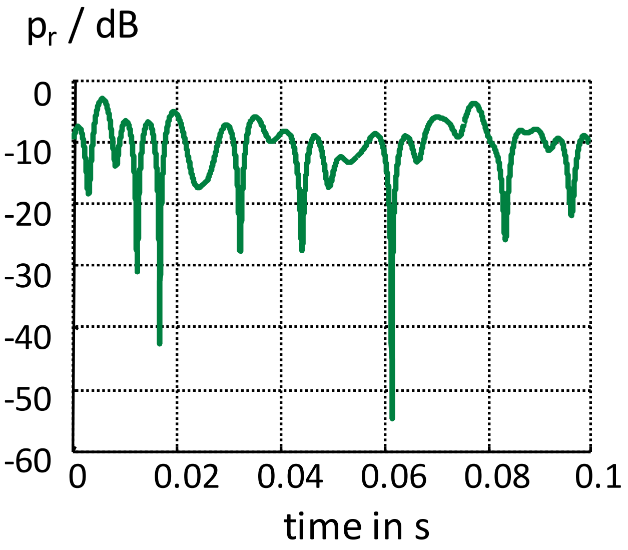


Radio Propagation Environment

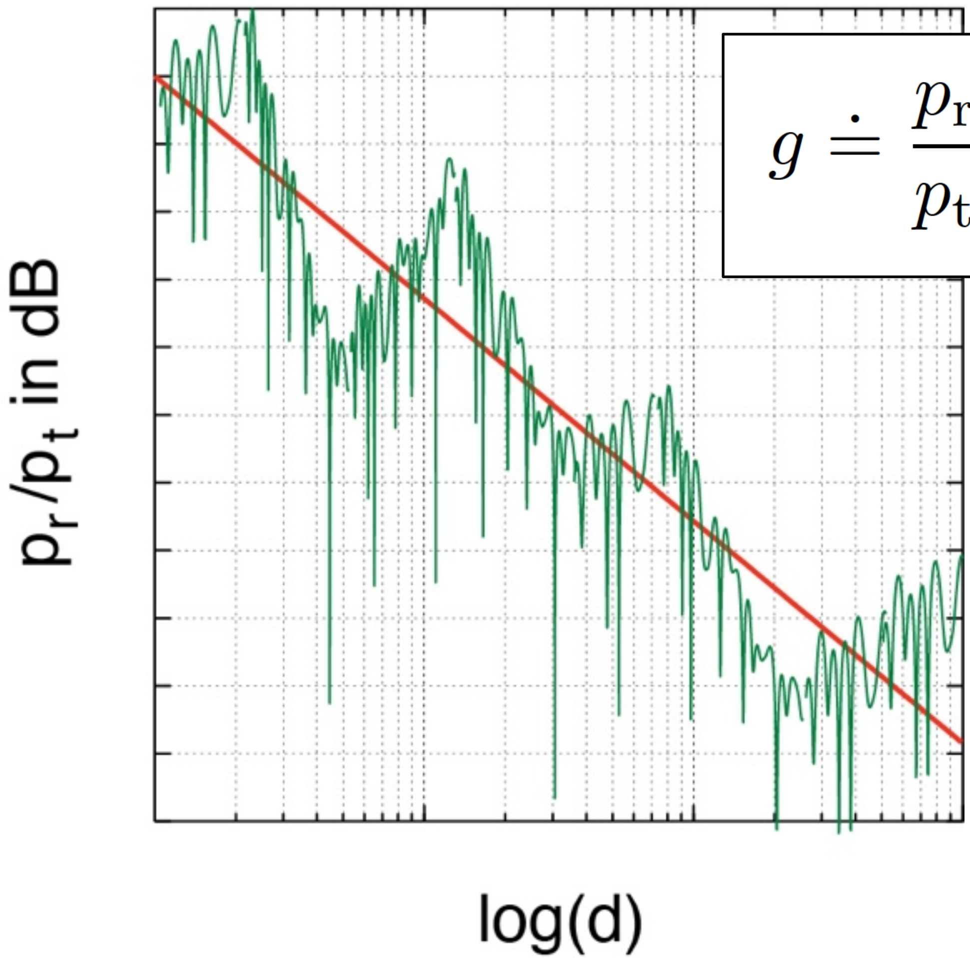
Multipath propagation leads to small-scale fading



- The multiple incoming radio waves superimpose at the receiver.
- The overall reception power shows rapid variations over time and space.
- Variations already occur over small distances in the order of one wavelength.
- Even if the receiver is not mobile, small-scale fading may occur due to the mobility of surrounding objects.

Radio Propagation Environment

Stochastic modeling of small-scale fading



$$g \doteq \frac{p_\mathrm{r}}{p_\mathrm{t}} = g_\mathrm{p} \cdot g_\mathrm{m} = \frac{\bar{p}_\mathrm{r}}{p_\mathrm{t}} \cdot g_\mathrm{m}$$

Mean value is given by *path loss model*.

Fading is modeled by a *random variable*.

Radio Propagation Environment

Nakagami model for small-scale fading

- The received power is gamma distributed with shape parameter m and scale parameter μ/m (see Appendix).
- The probability that the received power is larger than a certain threshold Θ is:

$$\mathrm{P}\left[p_{\mathrm{r}} > \Theta\right] = \frac{\Gamma\left(m, m\frac{\Theta}{\bar{p}_{\mathrm{r}}}\right)}{\Gamma(m)}$$

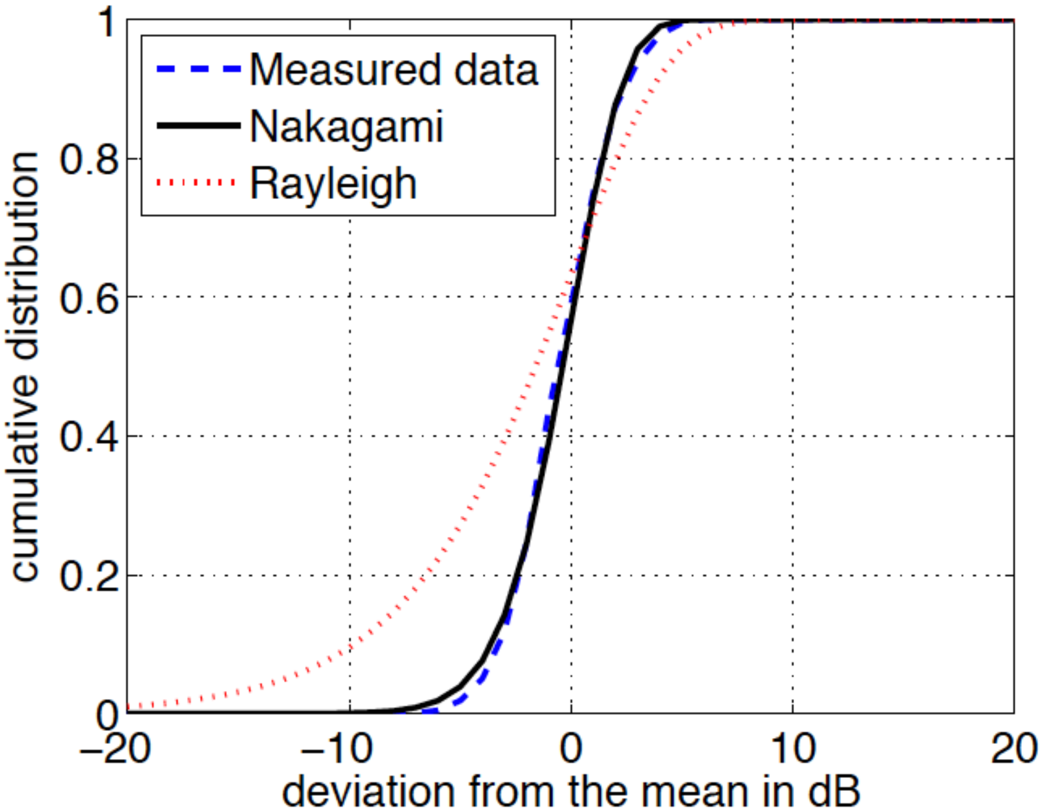
Gamma function $\Gamma(\cdot)$

Incomplete Gamma function $\Gamma(\cdot,\cdot)$

- The severeness of fading can be tuned by $m \in [0.5,\infty)$. Nakagami fading with $m = 1$ is Rayleigh fading.

Radio Propagation Environment

Small-scale fading in outdoor drone-to-ground link



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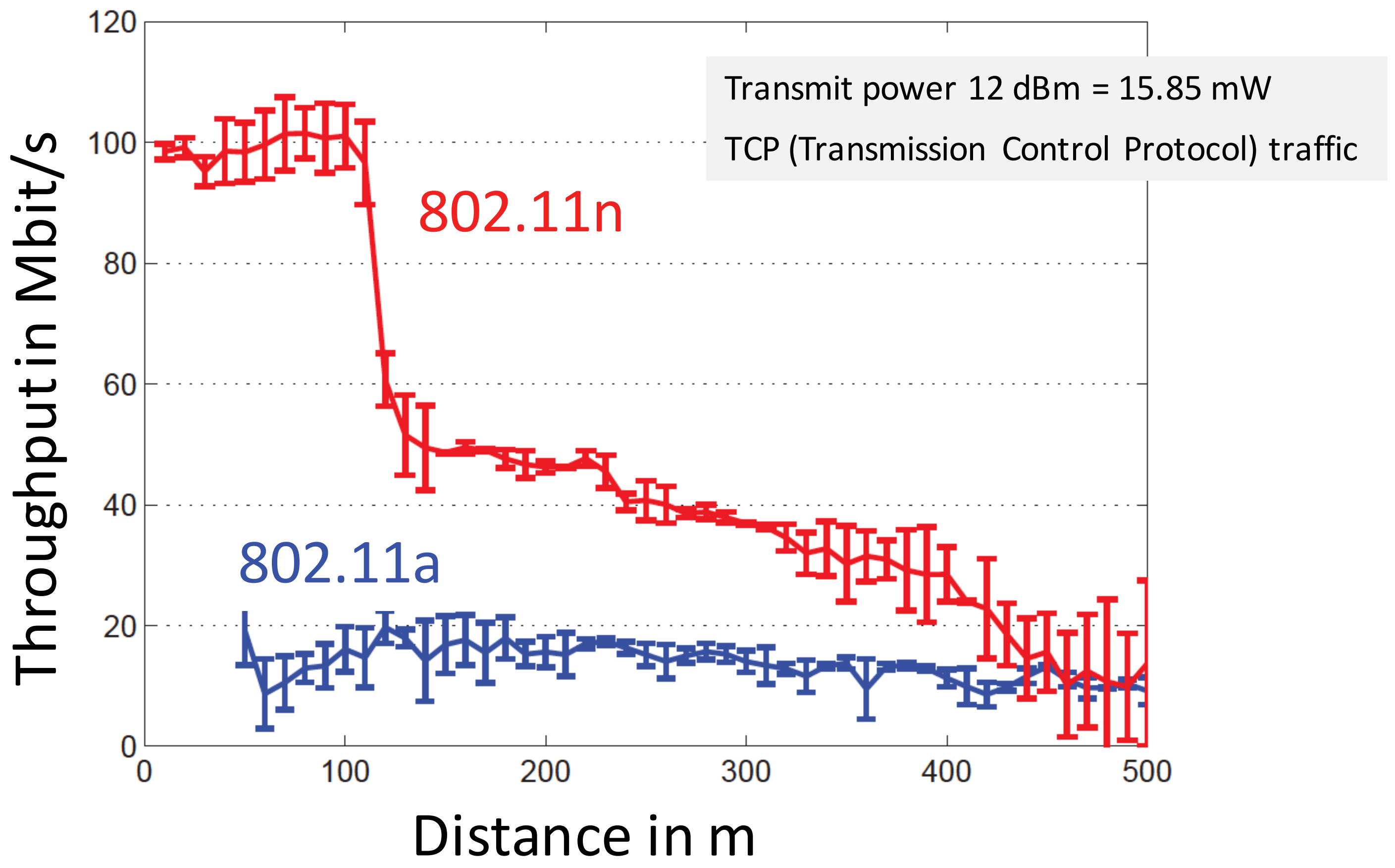
Throughput Performance

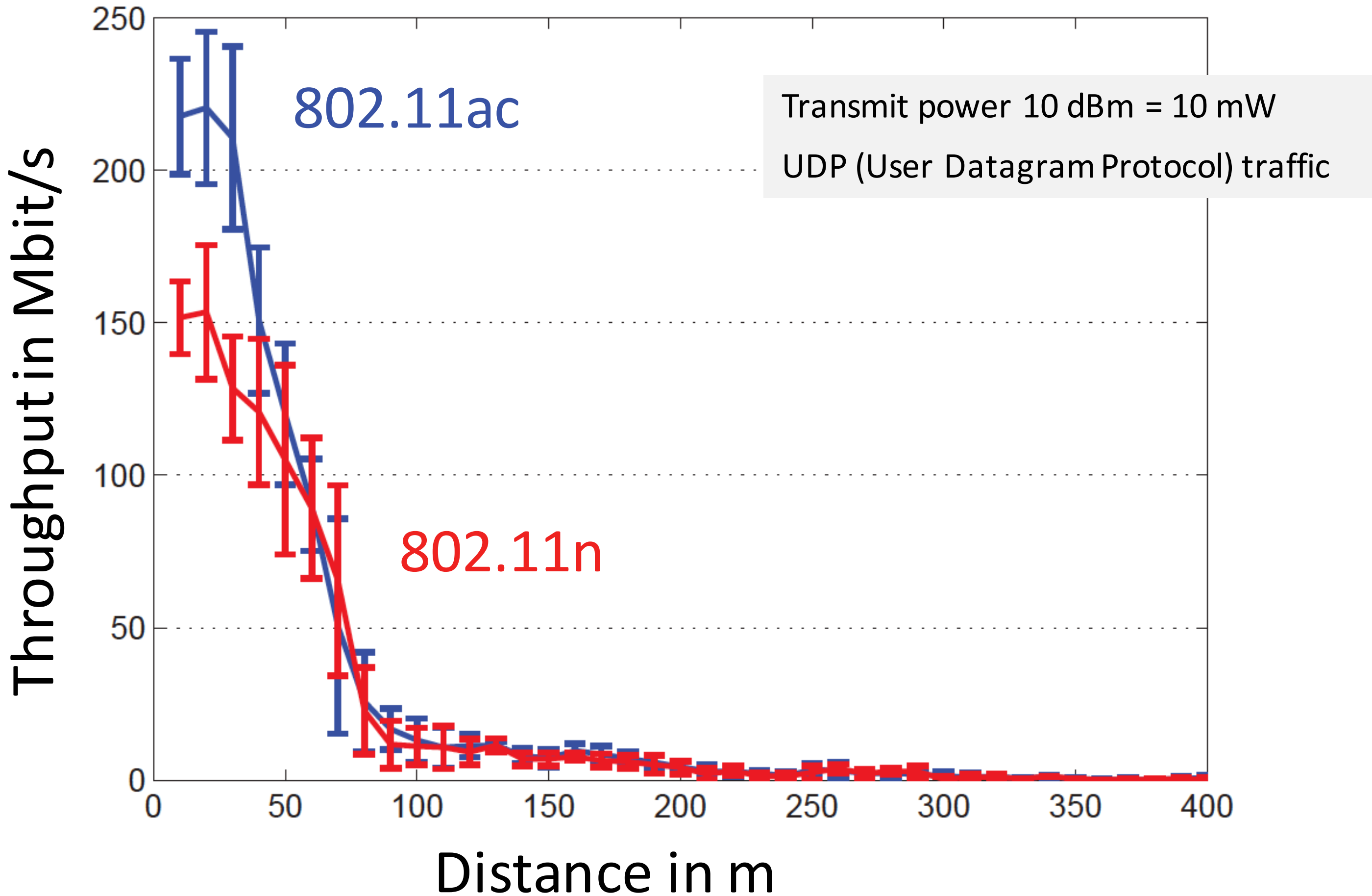
802.11a and 11n over outdoor drone-to-ground link



S. Hayat, E. Yanmaz, C. Bettstetter. Experimental analysis of multipoint-to-point UAV communications with IEEE 802.11n and 802.11ac. In *Proc. IEEE Intern. Symp. on Personal, Indoor, and Mobile Radio Commun. (PIMRC)*, Hong Kong, 2015.

Throughput Performance

802.11n and 11ac over outdoor drone-to-ground link



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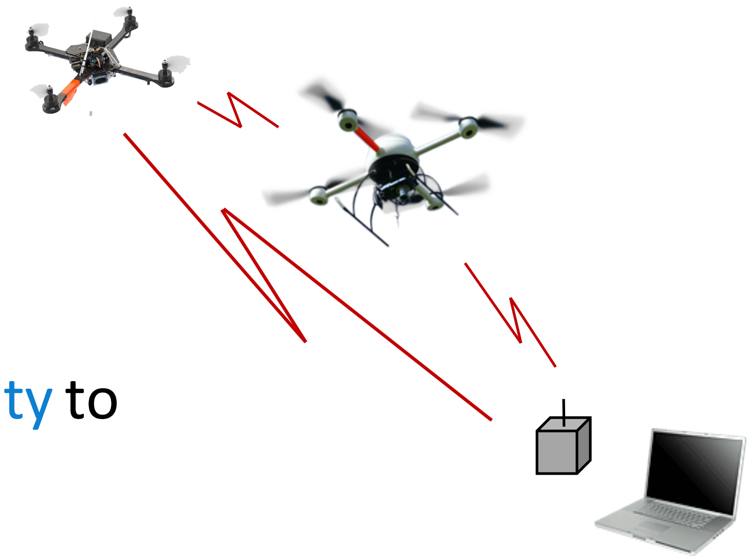
Wireless Networking for Small Drones

Protocol architecture

Application			Application
Transport			Transport
Network	Network	Network	Network
Data link	Data link	Data link	Data link
Physical	Physical	Physical	Physical

Wireless Multihop Communications



- Drones serve as relays for traffic from other drones.
- Drones form a mesh network using IEEE 802.11s.
- Drones exploit cooperative diversity to make links more robust.
- Large drone network uses ad hoc routing protocols.
- Large drone network may use concepts from delay-tolerant networking for certain applications.

Different approach for each traffic type possible.

E. Yanmaz, S. Hayat, J. Scherer, C. Bettstetter. Experimental performance analysis of two-hop aerial 802.11 networks. In *Proc. IEEE Wireless Communications and Networking Conf. (WCNC),* Istanbul, Turkey, 2014.

Wireless Communications and Path Planning

Case study in “search and rescue” scenario

Mission

Multiple drones search a target on the ground in an area.

↓

When the target is found, information about it (e.g., video) must be continuously communicated to a ground station.

↓

A wireless communication path between the target and ground station is formed for this purpose.

S. Hayat, E. Yanmaz, T. X Brown, C. Bettstetter. Multi-objective UAV path planning for search and rescue. In *Proc. IEEE Intern. Conf. on Robotics and Automation (ICRA),* Marina Bay, Singapore, 2017.

Wireless Communications and Path Planning

Case study in “search and rescue” scenario

- Proposed multi-objective optimization using a genetic approach
- Minimized mission time consisting of:
  - Time to find target (area coverage)
  - Time to setup relay chain (network connectivity)
- Evaluated different communication strategies:
  - Data mule = “inform first”
  - Relay chain = “connect first”
  - Hybrid approach = “simultaneous inform and connect”

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Wireless Communications for Small Drones

Summary and outlook

Take home messages

- Tune antenna configuration to improve radio range if needed
- Model channel by standard path loss and Nakagami fading
- Use latest IEEE 802.11 technologies with certain limitations
- Develop a *common* view on networking, path planning, and sensing in certain applications to jointly optimize them

Potential topics for collaboration with CARRE

- Joint communications and [adaptive] path planning in swarms
- Wireless communications for vision-based navigation

Wireless Communications for Small Drones

Outlook

What is needed?

- Test prototypes of new wireless technologies (5G) for low-latency, high-throughput, real-time aerial applications
- Lobby for spectrum allocation for drone communications to avoid interference and jamming
- Develop complete protocol stack for drone networks, including security/safety, time synchronization, and localization
- Develop specific networking solutions for large drone swarms

Wireless communications and networking

Duration: 30 minutes

Job selection for delivery services

Duration: 15 minutes

Job Selection for Drone-Based Delivery Services

2

- Why is this topic interesting?
- How to model the system?
- Which drone should satisfy which customer demand?
- When to make this decision?
- How to dimension such a transport system?

Drone-Based Delivery Services
Urgent goods

Photo: Fotolia (Bernd Leitner)

Drone-Based Delivery Services
Last mile problem in rural areas

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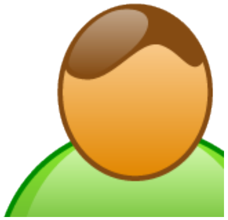
Drone-Based Delivery Services

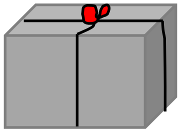
Last mile problem in crowded cities

Of importance is customer satisfaction and profit
Autonomous online decision making

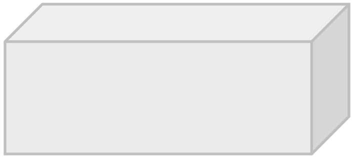
Delivery Services

Modeling the system





Customers request Goods that are



stored in Depots (L) and delivered by Vehicles (K) .

Customer demands (jobs) arrive over time on certain locations according to a space-time stochastic process.

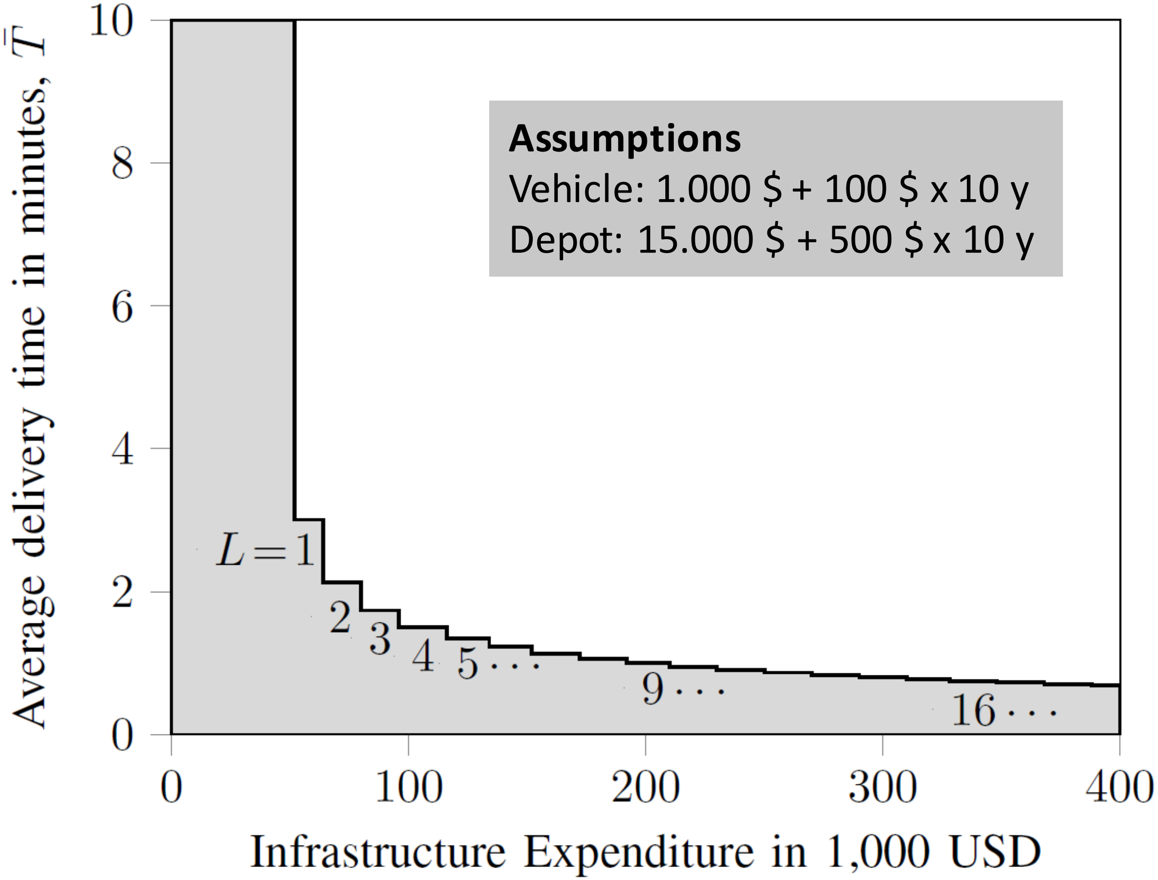
Delivery Services

Modeling the system

- Area: 16 km^2
- Jobs: λ = 0.65 per minute (Poisson)
- One good per job
- *L* depots
- *K* vehicles flying at 30 km/h
- Air-to-charging time ratio: 1/3

Delivery Services

Network planning: How much to invest?



P. Grippa, D. A. Behrens, C. Bettstetter, F. Wall. Job selection in a network of autonomous UAVs for delivery of goods. Accepted for *Robotics: Science and Systems (RSS)*, Cambridge, MA, 2017.

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Job Selection in Delivery Services
The system "intelligence"

Job selection goes beyond merely picking the next demand, it does all decisions needed to operate the transport system.

Example questions to be addressed:

- Which customer demand to serve next?
- Which vehicle to let serve the next customer demand?
- At which depot to let vehicles load up goods?
- Which paths to let vehicles follow?
- Where to let vehicles return to if no customers are waiting?

Different problem than dynamic vehicle routing

Job Selection in Delivery Services

Two classes of non-partitioning policies

First job first (FJ)

- Central entity selects next job based on the arrival times of the jobs and assigns it to a vehicle.

Nearest job first (NJ)

- Every vehicle selects a job based on its own location and the locations of waiting customers and depots.
- Selected jobs are removed form the list of waiting jobs.

P. Grippa, D. A. Behrens, C. Bettstetter, F. Wall. Job selection in a network of autonomous UAVs for delivery of goods. Accepted for *Robotics: Science and Systems (RSS)*, Cambridge, MA, 2017.

Job Selection in Delivery Services

Timing of decision

Should we delay the decision on job selection to obtain more information on new customer requests to reduce delivery time?

Two extreme cases

- Selection made as soon as possible (just after the previous job)
- Selection made as late as possible (just before loading the good)

Both cases are evaluated for both policies (NJ, FJ).

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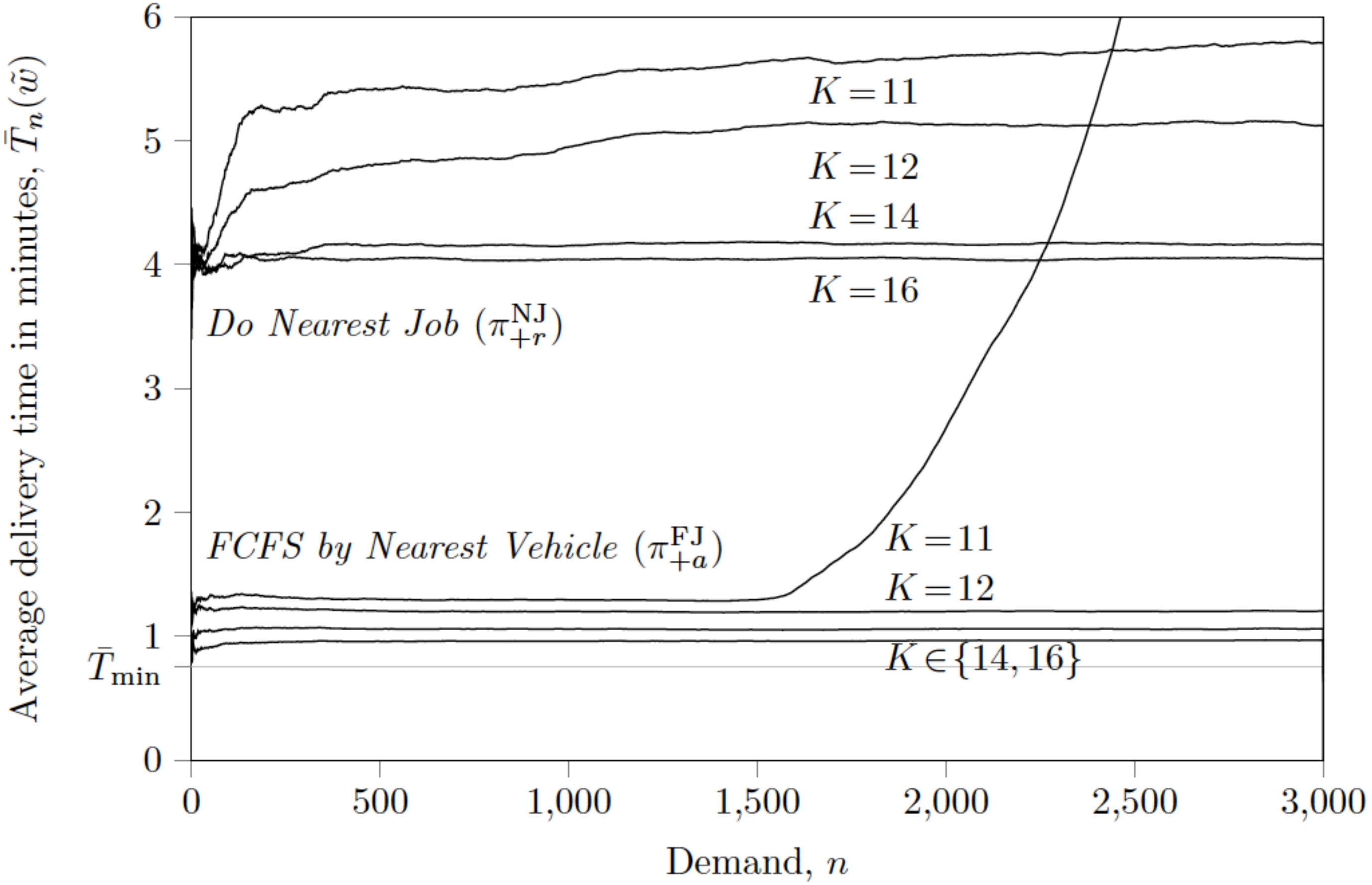
Job Selection in Delivery Services

Four policies investigated

		Do nearest job	Rush to depots	FCFS by nearest vehicle	FCFS by 1st vehicle at depot	
In which order are jobs selected?						
First come first served from shared queue				●	●	FJ
No specific selection order of jobs		●	●			NJ
Where are decisions made?						
At customer, just after completing service		●		●		early (+)
At depot, just before loading goods			●		●	late (-)
What if >1 vehicle wants to select a job?						
Random vehicles gets job		●	●			random
Nearest vehicle gets job				●	●	assortative
No jobs:	Vehicle goes to nearest depot	●	●	●	●	

Job Selection in Delivery Services

Startup phase

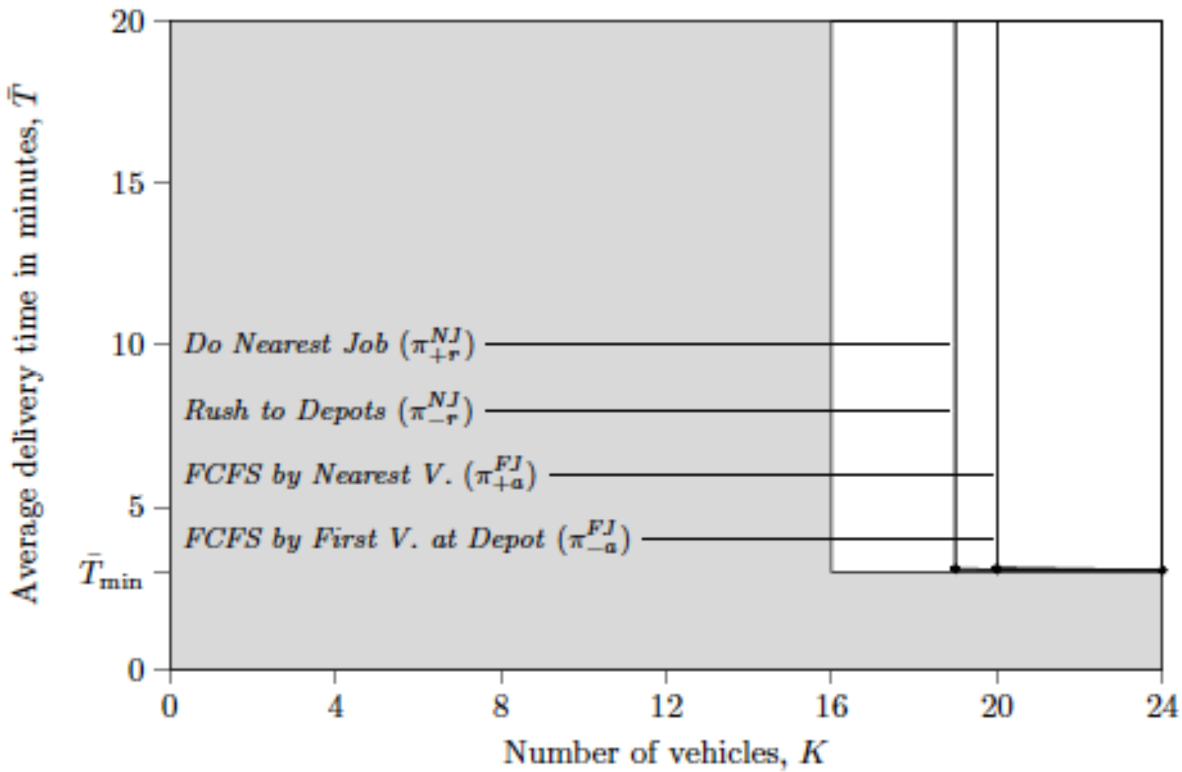


L = 16 depots
K drones

P. Grippa, D. A. Behrens, C. Bettstetter, F. Wall. Job selection in a network of autonomous UAVs for delivery of goods. Accepted for *Robotics: Science and Systems (RSS)*, Cambridge, MA, 2017.

Job Selection in Delivery Services

Comparing policies in the steady phase



Number of depots $L = 1$

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Job Selection in Delivery Services

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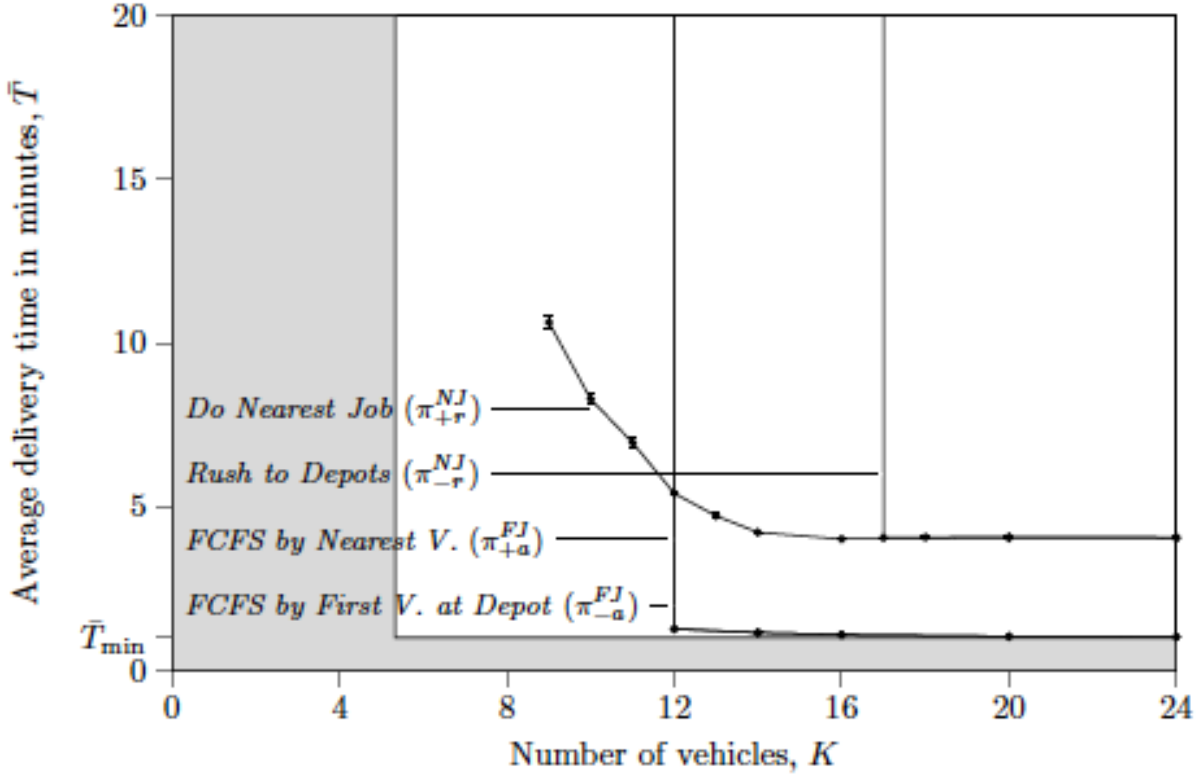

Number of depots $L = 9$

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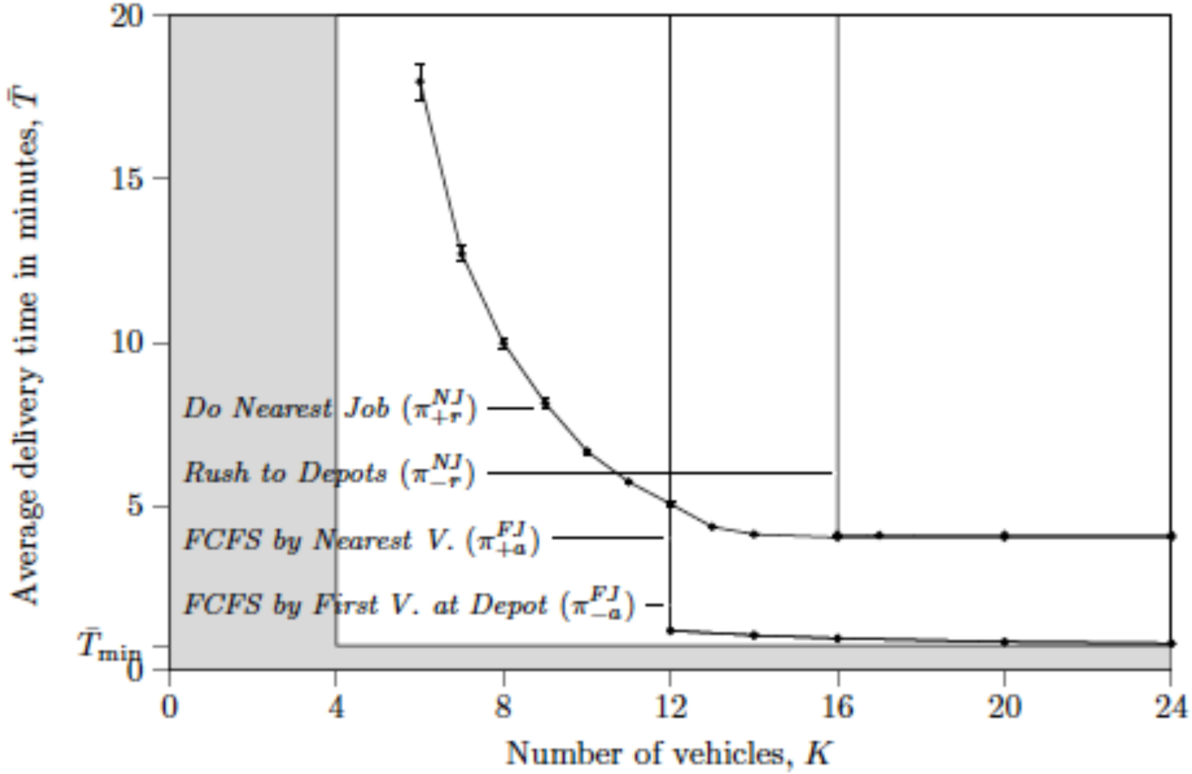
Job Selection in Delivery Services

Comparing policies in the steady phase



Number of depots $L = 16$

P. Grippa, D. A. Behrens, C. Bettstetter, F. Wall. Job selection in a network of autonomous UAVs for delivery of goods. Accepted for *Robotics: Science and Systems (RSS)*, Cambridge, MA, 2017.

Lakeside Labs

Job Selection in Delivery Services

Some insight

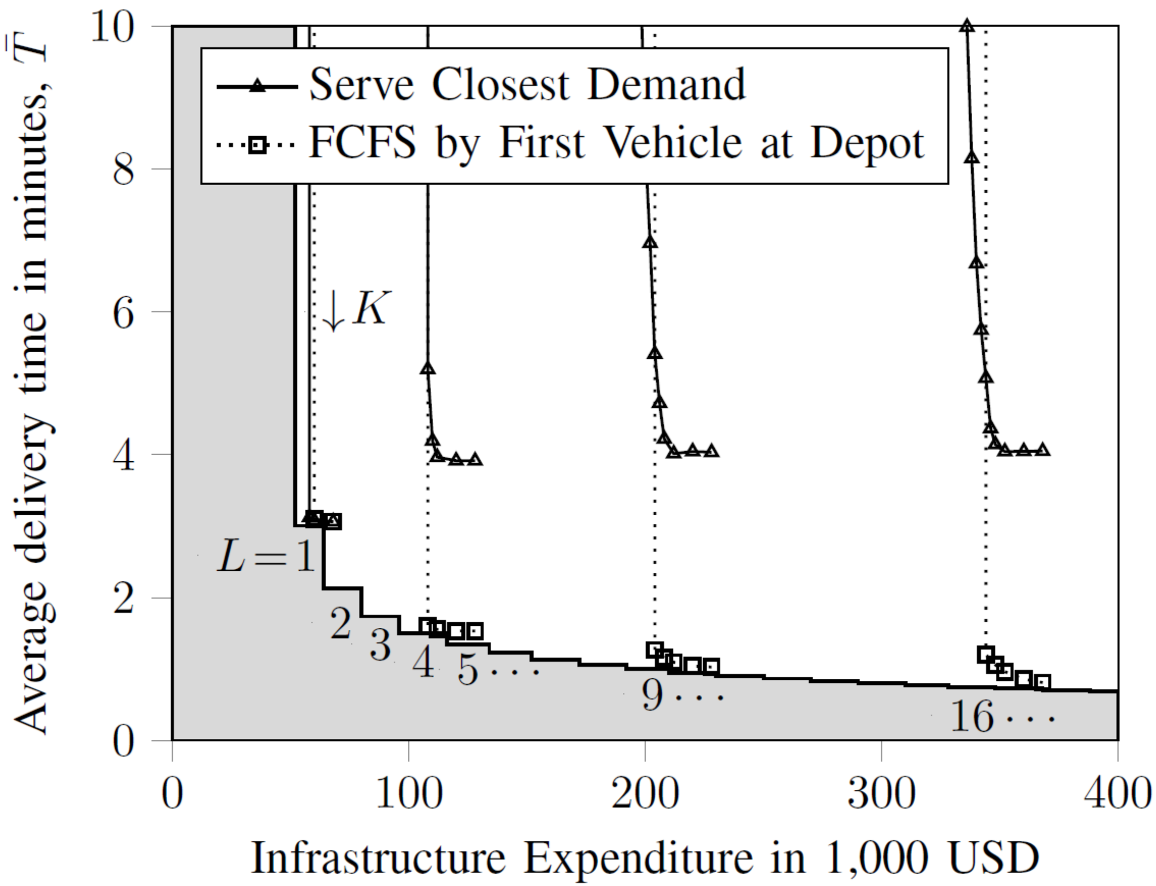
Differences in policies

- Job selection can occur as soon or as late as possible with FJ.
- Job selection should be made as soon as possible with NJ.

Delayed decisions can also have a negative effect. This relates to the fact that one of the most important decisions is where a vehicle should return to after satisfying a customer demand.

Job Selection in Delivery Services

Network planning: How much to invest in practice?



L depots
K drones

P. Grippa, D. A. Behrens, C. Bettstetter, F. Wall. Job selection in a network of autonomous UAVs for delivery of goods. Accepted for *Robotics: Science and Systems (RSS)*, Cambridge, MA, 2017.

Job Selection in Drone-Based Delivery Services

Summary and outlook

Take home messages

- System dimensioning with three time horizons
- Different job selection policies have different behavior
  - Timing of decision matters for some policies
  - Threshold behavior for some policies
- Similar methods can be used for pickup-and-delivery w/o depots

General challenges and potential for joint work

- Transfer customers' expectations in to system intelligence
- Have simple decision policies for complex systems
- Include learning in job selection

3

Project overview

Duration: 10 minutes

Collaborative Microdrones

Achievements

- Developed outdoor system for aerial sensing with small drones
- Contributed to path planning, image stitching, communications
- Performed system integration
- Tested and evaluated system with firefighers and industry

Key facts

Duration: 2008–2013

Funding: about 2 M€

Autonomous Forest Inventorying with Drones

Funded project with application partners

Research topics

- GPS-free state estimation
- Real-time local 3D motion planning
- High-detail 3D reconstruction
- Prototype forest inventory system

Partners

- U Klagenfurt (Weiss, lead)
- Lakeside Labs, Joanneum
- E.C.O., Umweltdata

Key facts

Duration: 2016–2018

Funding: 0.45 M€

FFG Lakeside Labs

CPSwarm

European Commission | Horizon 2020 European Union funding for Research & Innovation

Objectives

- Develop toolchain for swarms of cyber-physical systems
- Consider complete path from setup over test to deployment
- Develop algorithm library for swarming & evolutionary design

Partners

- Inst. Sup. Mario Boella (lead)
- Lakeside Labs, U Klagenfurt
- Fraunhofer FIT, Search Lab
- Robotnik, Softteam, TTTech

Key facts

Duration: 2017–2020

Funding: 4.9 M€

Networked Autonomous Aerial Vehicles (NAV)

Doctoral school

Common objective

- Collaborative 3D reconstruction

Research topics

- Multimodal sensor fusion
- Decentralized mission planning
- Decentralized time synchronization
- Multimedia communications

KARL POPPER KOLLEG

Key facts

Duration: 2017–2020

Funding: 0.5 M€

Core faculty

Christian Bettstetter

Hermann Hellwagner

Bernhard Rinner

Stephan Weiss

Team Members on Drones

Predoctoral researchers

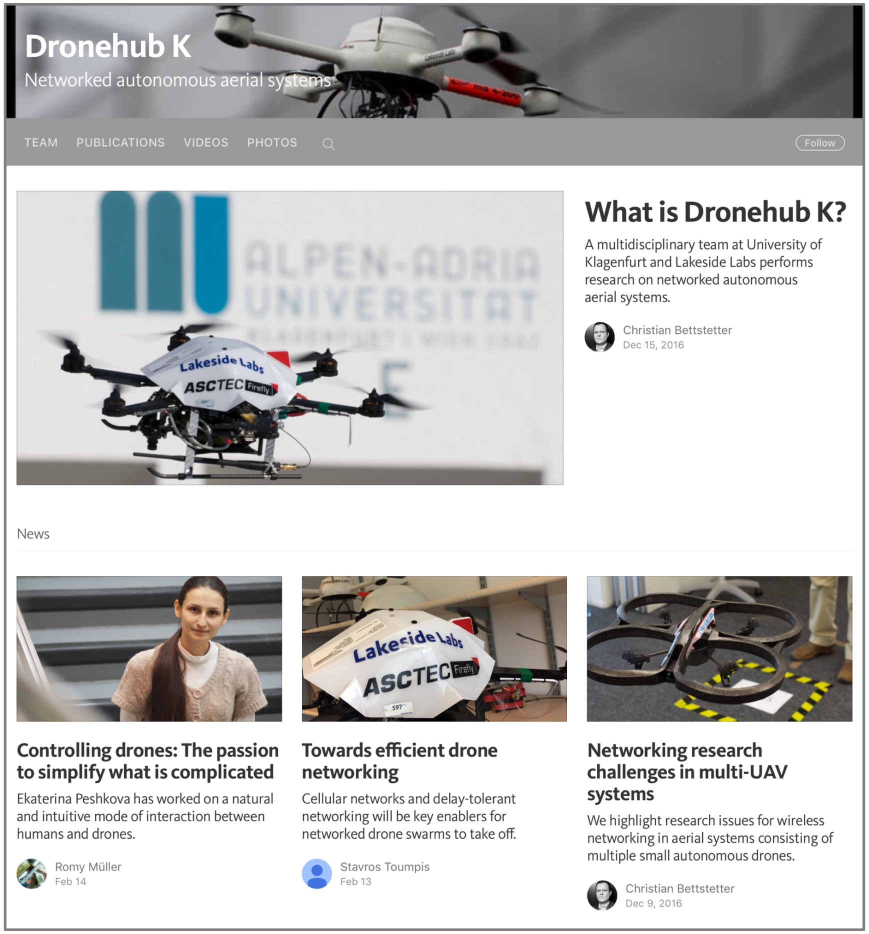
- Torsten Andre (2010-15)
- Pasquale Grippa (2012-18)
- Samira Hayat (2012-18)
- Raheeb Muzaffar (2012-16)
- Arke Vogell (2016-)

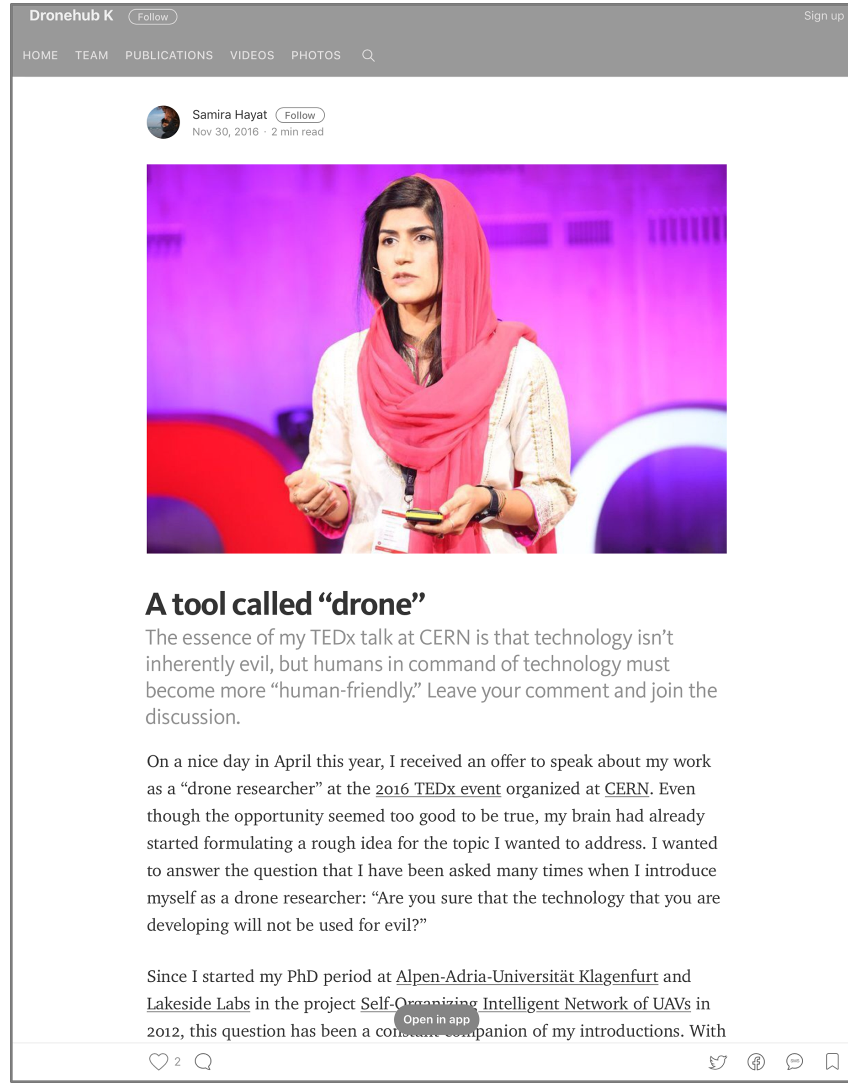
Postdoctoral researchers

- Vladimir Vukadinovic (2014-15)
- Evsen Yanmaz (2008-)

Thanks!

Dronehub K





Visit us at **uav.aau.at.**

Selected Recent Publications from Dronehub K

Hayat, Yanmaz, Brown, Bettstetter. Multi-objective UAV path planning for search and rescue. In *Proc. IEEE Intern. Conf. Robotics and Automation*, 2017.

Peshkova, Hitz, Kaufmann. Natural interaction techniques for an unmanned aerial vehicle system. *IEEE Pervasive Computing*, 2017.

Hayat, Yanmaz, Muzaffar. Survey on UAV networks for civil applications: A communications viewpoint. *IEEE Communication Surveys & Tutorials*, 2016.

Khan, Rinner, Cavallaro. Cooperative robots to observe moving targets: A review. *IEEE Transactions on Cybernetics*, 2016.

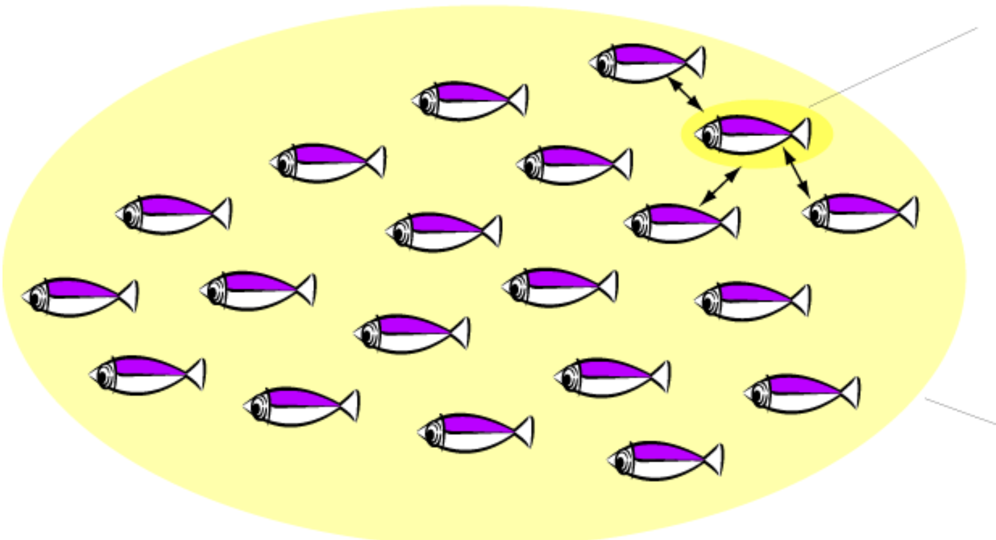
Khan, Yanmaz, Rinner. Information exchange and decision making in MAV networks for cooperative search. *IEEE Transactions on Control of Network Systems*, 2015.

Andre, Hummel, Schoellig, Yanmaz, Asadpour, Bettstetter, Grippa, Hellwagner, Sand, Zhang. Application-driven design of aerial communication networks. *IEEE Communications Magazine*, 2014.

Yanmaz, Kuschnig, Bettstetter. Achieving air-ground communications in 802.11 networks with three-dimensional aerial mobility. In *Proc. IEEE INFOCOM*, 2013.

Appendix

Self-Organization



Individual Entity (Fish)

- Has simple behavior rules
- Has local view only

⇩ Emergence

Entire System (Shoal)

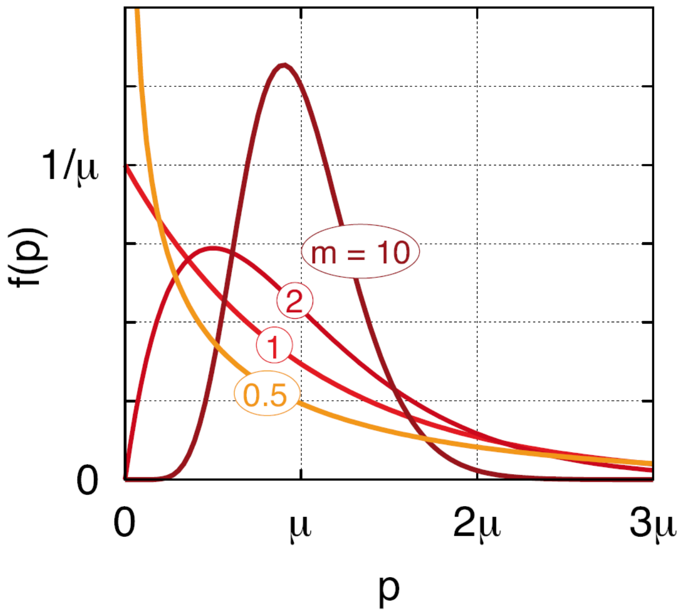
- Solves a complex task
- Is adaptive to changes
- Is scalable and robust

Camazine, Deneubourg, Franks, Sneyd, Theraulaz, Bonabeauet: Self-Organization in Biological Systems, 2001.

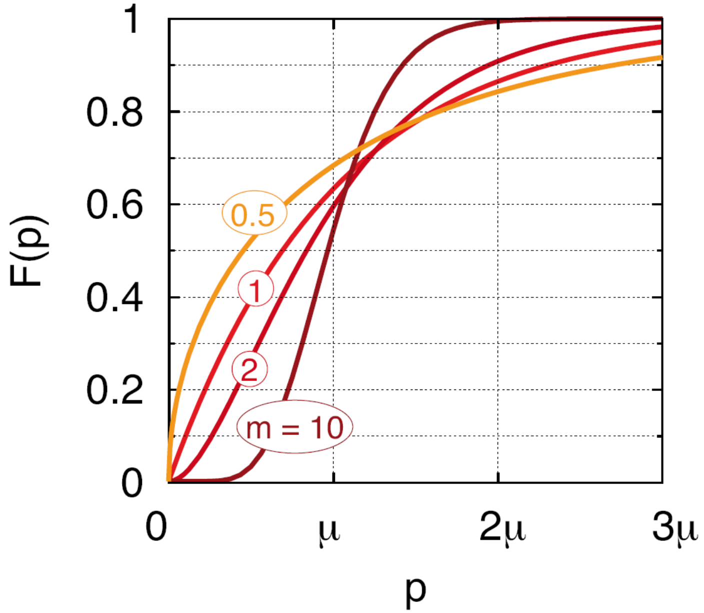
Prehofer, Bettstetter: Self-organization in communication networks: Principles and design paradigms. IEEE Communications Magazine, July 2005.

Gamma Distribution

With shape parameter *m* and scale parameter µ/*m*



(a) Probability density function



(b) Cumulative distribution function

$$f_p(p) = \left(\frac{m}{\overline{p}}\right)^m \frac{p^{m-1}}{\Gamma(m)} \exp\left(-\frac{mp}{\overline{p}}\right) \qquad F_p(p) = 1 - \frac{\Gamma\left(m, \frac{mp}{\overline{p}}\right)}{\Gamma(m)}$$

Lakeside Labs

Gamma Function

- Gamma function:

$$\Gamma(x) := \int_0^\infty t^{x-1}\, e^{-t}\, dt$$

$$\Gamma(1) = 1 \text{ and } \Gamma(0.5) = \sqrt{\pi}$$

$$\Gamma(x) = (x-1)! \quad \text{for} \quad x \in \mathbb{N}$$

- Incomplete Gamma function:

$$\Gamma(x,a) := \int_a^\infty t^{x-1}\, e^{-t}\, dt$$

- Values are listed in books and software packages:

Function	Maple	Mathematica	Matlab
$\Gamma(x)$	`GAMMA(x)`	`Gamma[x]`	`gamma(x)`
$\Gamma(x,a)$	`GAMMA(x,a)`	`Gamma[x,a]`	–
$1 - \frac{\Gamma(x,a)}{\Gamma(x)}$			`gammainc(a,x)`