Lecture 10: Commun. architectures
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Lecture 10: Communication architectures and communication issues in reactive multi-robot systems

B3M33MRS — Aerial Multi-Robot Systems

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Multi-Robot Systems group, Faculty of Electrical Engineering
Czech Technical University in Prague

Motivation

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- Communication infrastructure is the crucial component for exchanging data in Multi-Robot Systems
  - ✓ Required in centralized control architectures
  - ✓ Expected for sense-and-avoid and UAV commanding in urban mobility of near future

- Various tasks in complex systems require communication
  - ✓ UAV-control station or UAV-operator (the most common case in classical, less-autonomous systems)
  - ✓ UAV-UAV direct communication (centralized MRS and also decentralized if allowed)
  - ✓ UAV-cloud connectivity (a popular approach allowed by better terrestrial and satellites mobile networks nowadays)

Motivation

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Types of Communication Systems for UAVs

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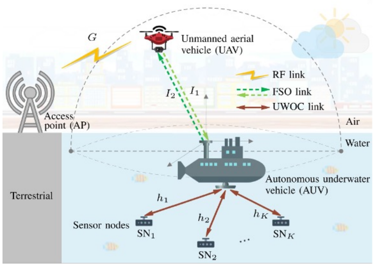
- RF Wireless Communication
  - ✓ Electromagnetic waves carry data
  - ✓ Antennas radiate modulated electromagnetic waves
  - ✓ Antennas receive electromagnetic waves
  - ✓ Mature technology (although still under active research)

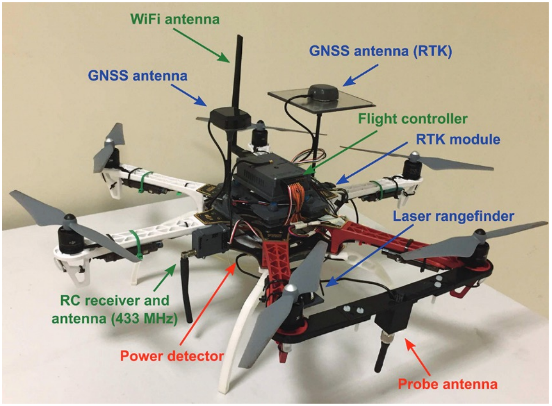
- Optical Wireless Communication
  - ✓ Optical signals carry data
  - ✓ LEDs emit modulated optical signals
  - ✓ Photosensitive devices (e.g., cameras, photodiodes, etc.) receive modulated light
  - ✓ Early stage of development for robots - no commercial technology yet for UAVs
  - ✓ Difficult to attack/jam – allows secured communication infrastructure

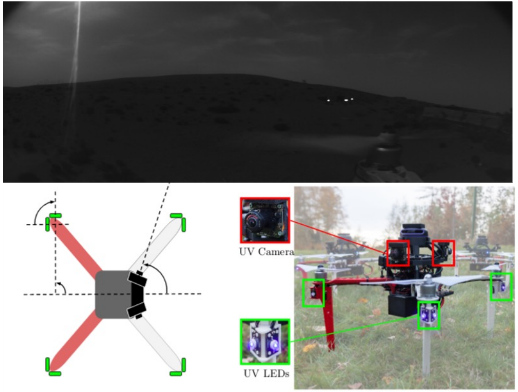
May be complementary technologies



P. Agheli, H. Beyranvand and M. J. Emadi., “UAV-Assisted Underwater Sensor Networks Using RF and Optical Wireless Links,” *Journal of Lightwave Technology, vol. 39, no. 22, 2021.*

Types of Communication Systems for UAVs

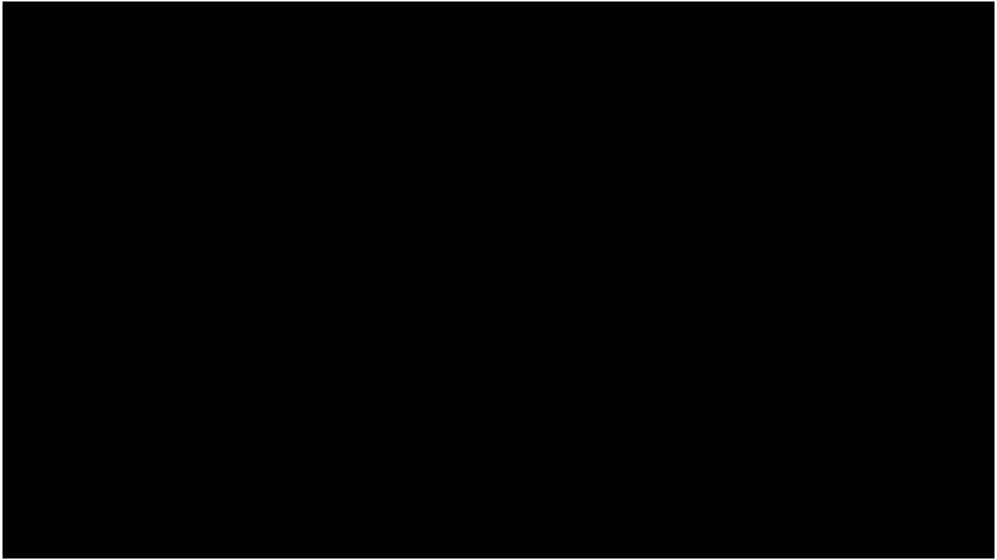




M. G. Fernandez, et al., "On the Use of Unmanned Aerial Vehicles for Antenna and Coverage Diagnostics in Mobile Networks," *IEEE Communications Magazine, vol. 56, no. 7, 2018*

D. Bonilla Licea, et al., "Optical communication-based identification and localization for multi-UAV systems: a theoretical foundation," *IEEE Transactions on Robotics (submitted).*

Types of Communication Systems for UAVs – DARPA SubT



Types of Communication Systems for UAVs – DARPA SubT

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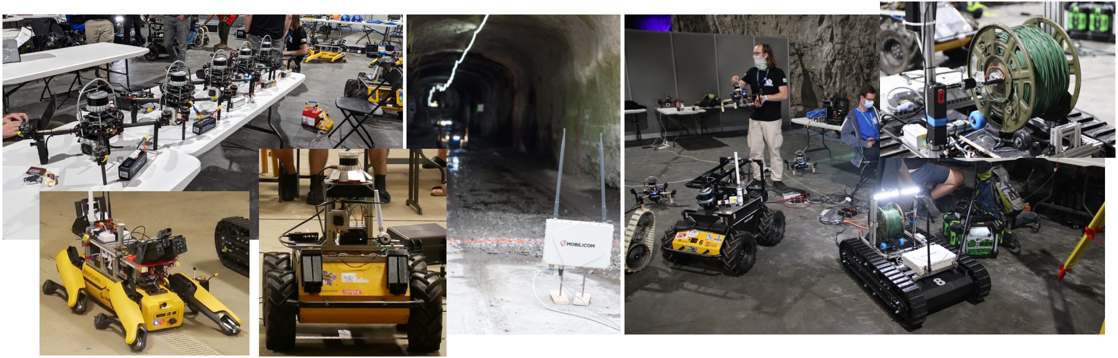
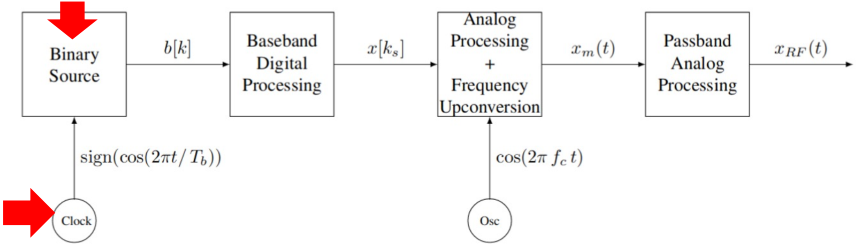
- Tunnels in under-ground environments are challenging for the communication infrastructure
- Large number of heterogenous robots working in the same environment
- Robots ↔ base station (reporting artefacts) and robot ↔ robot (MESH relay) communication

Types of Communication Systems for UAVs – DARPA SubT

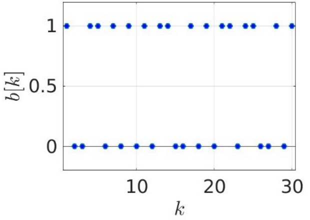
- Combination of multiple communication systems
- Cables, Wi-Fi – onsite debugging, initial setup
- Mobilicom MESH – semi-military long-range solution (high bandwidth – pictures of artifacts)
- Bread crumbs – radio modules MESH (low bandwidth – positions of robots, mission status information)
- Moving Mobilicom high-power basestation connect with the operator trough a cable (to extend the range)



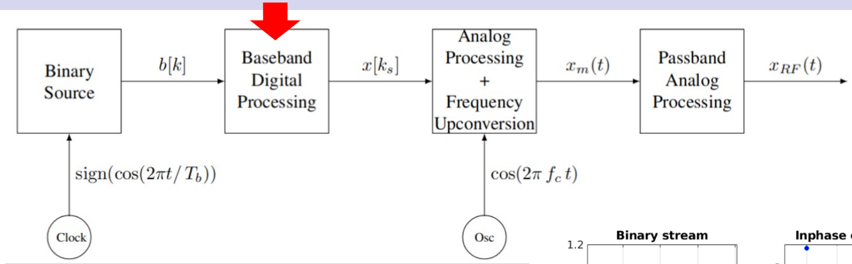
RF wireless generic transmitter architecture



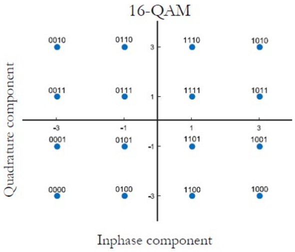
- The Binary Source: any onboard sensor or computer creating information to be transmitted
- The Clock signal: to determine the rate at which the Binary Source feeds the data to the transmitter; With a period T_b, called the 'bit duration'
- The binary stream $b[k]$ is a discrete-time binary signal

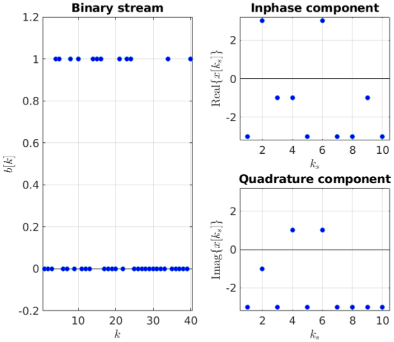


RF wireless generic transmitter architecture

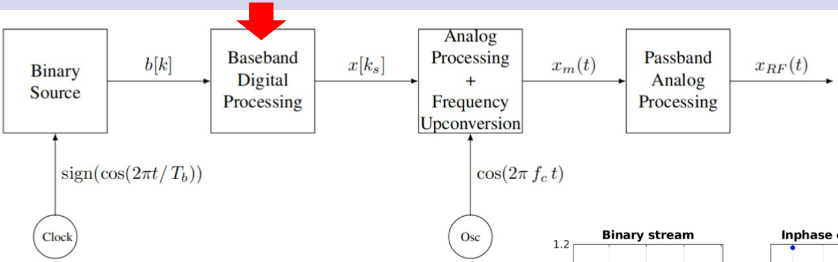


- Baseband Digital Processing: to transform the binary stream $b[k]$ into a discrete-time complex signal $x[k_s]$
- A modulation scheme used to map group of bits into complex symbols



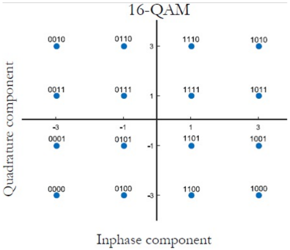


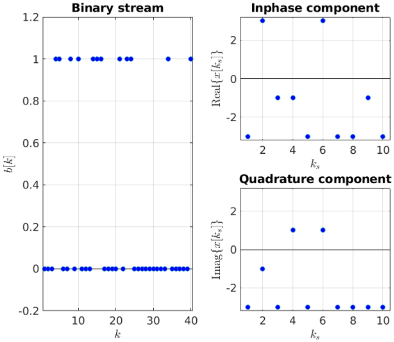
RF wireless generic transmitter architecture



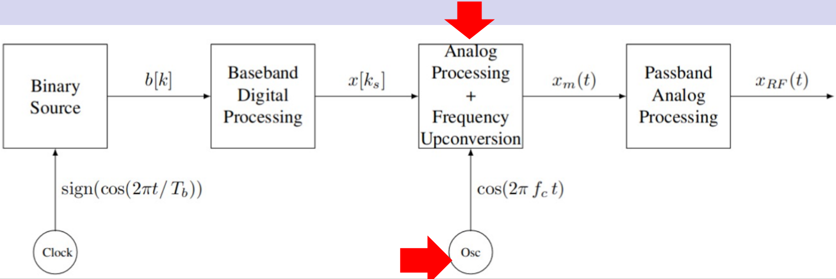
16-QAM:

- Each group of 4 bits mapped to complex symbols
- The In-phase component - the real part of the symbol
- The Quadrature component - the imaginary part of the symbol
- Each symbol represents 4 bits
- The symbol rate is 4 times slower than the bit rate

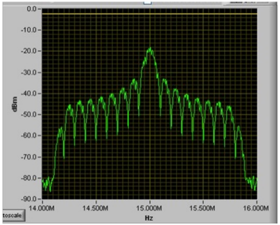


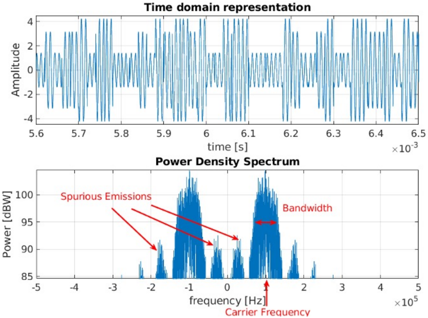


RF wireless generic transmitter architecture

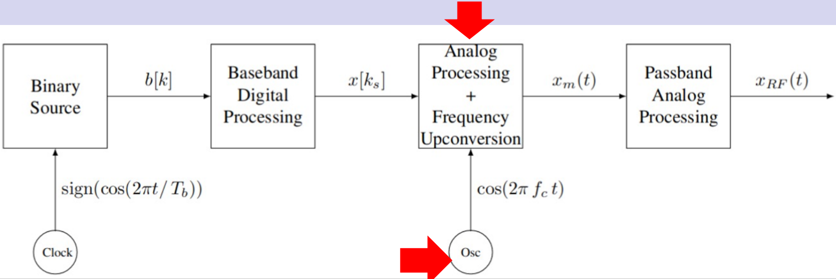


- $x[k_s]$ – a complex baseband signal with frequency spectrum centered on the DC component
- Small size antennas radiate more efficiently high frequency signals
- Radiating low frequency signals (as baseband signals) with small antennas is inefficient

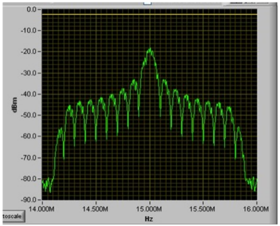


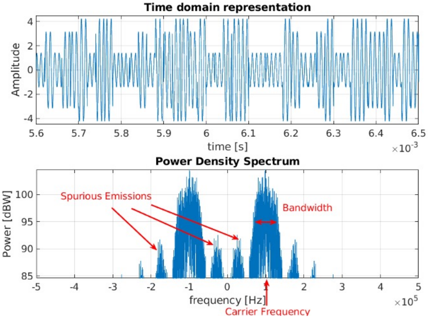


RF wireless generic transmitter architecture



- The digital baseband signal $x[k_s]$ is converted to an analog signal, filtered and its frequency spectrum is shifted using the carrier signal generated by the local oscillator
- The upconversion transforms the baseband signal into a passband signal





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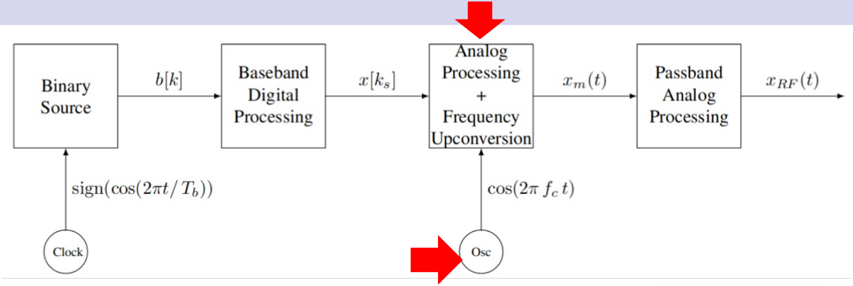
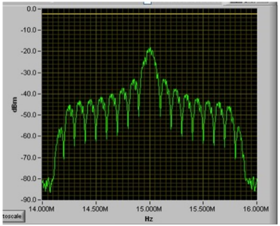
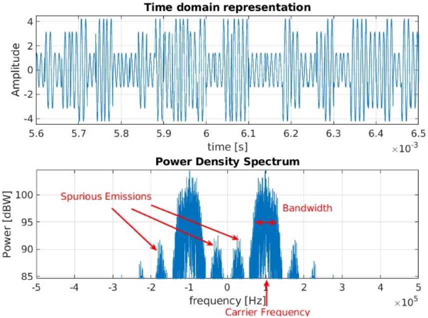


- The passband signal with frequency spectrum centered around carrier frequency f_c
- The local oscillator generates a carrier signal of frequency f_c performing the upconversion
- The carrier frequency should be high enough to allow the use of small antennas to efficiently radiate the signal





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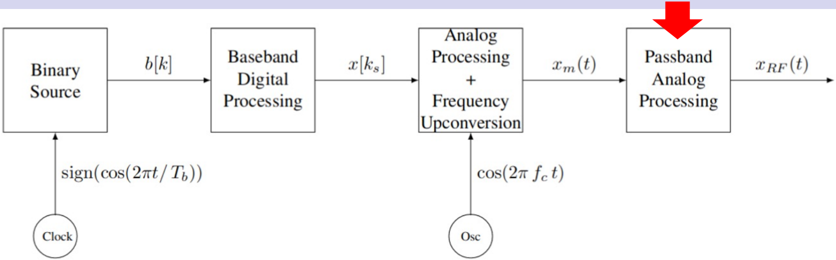
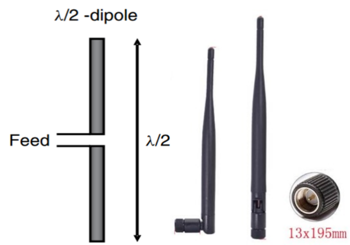
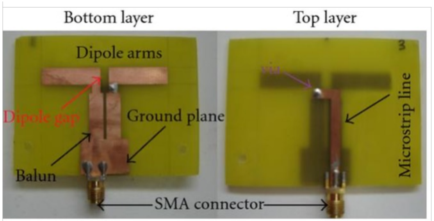
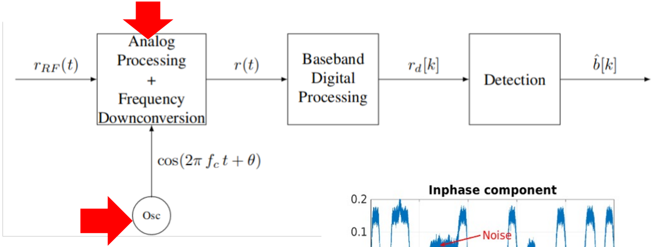


- Passband Analog Processing transforms the electric signal into an electromagnetic wave and radiates it by an antenna
- A common antenna is the half-wave dipole. It has an electrical length of $L = \lambda/2$
- $\lambda = c/f_c$
- c – speed of light

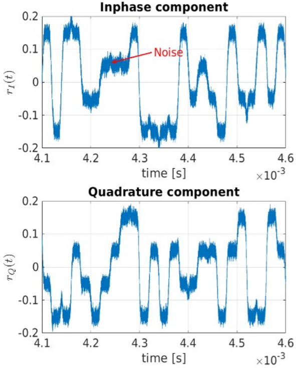


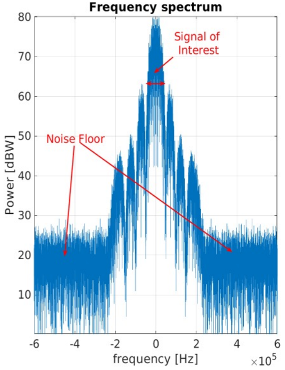


RF wireless generic receiver architecture

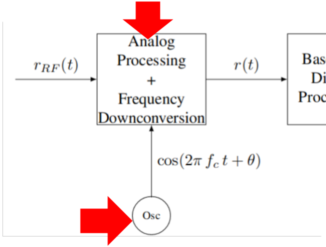


- The antenna receives the intended RF signal together with interference (unwanted signals from other transmitters – artificial or natural)
- The desired signal often with low power
- Amplification of the received signal and down converting to a baseband signal
- Baseband signals are easier to pass through A/D conversion than passband signals
- Baseband signals require lower sampling rate and simpler circuits

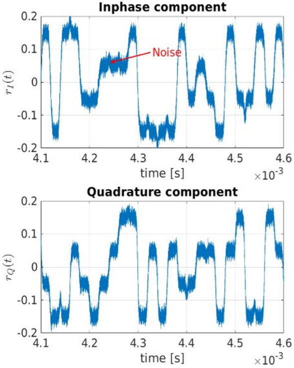


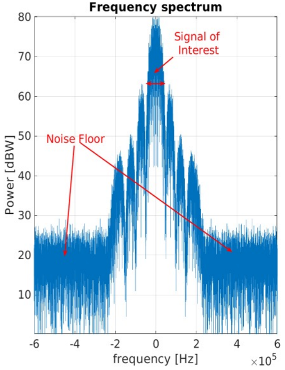


RF wireless generic receiver architecture



- Thermal noise generated by resistors in analog circuits contaminates the weak received signal
- The noise can be modelled as a zero-mean additive white Gaussian stochastic process
- Its power depends on the quality of the circuits and their temperature





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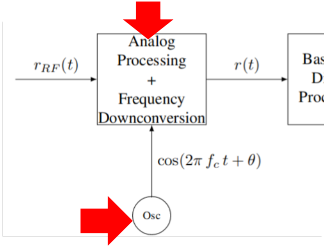
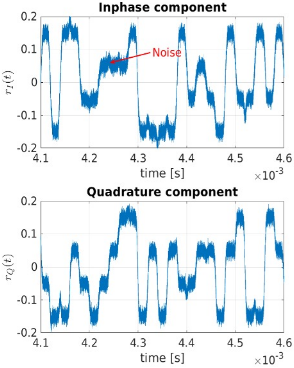
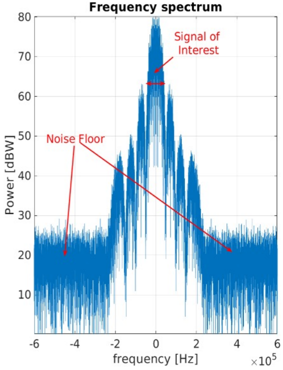


- The white noise has a constant power over all frequencies; It determines the sensitivity of the receiver
- The sensitivity: the minimum power of the desired signal that can be detected
- The sensitivity influences the range of a communication link (in addition to transmitter and environment properties)





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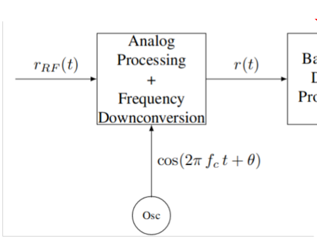
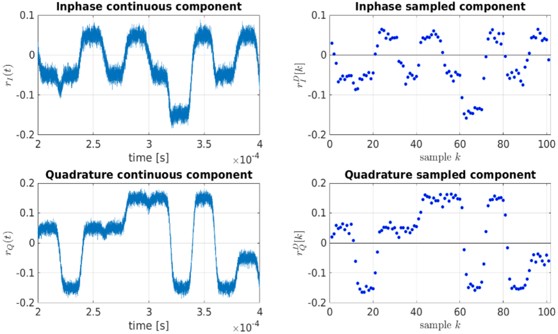


- The baseband processing performs analog/digital conversion



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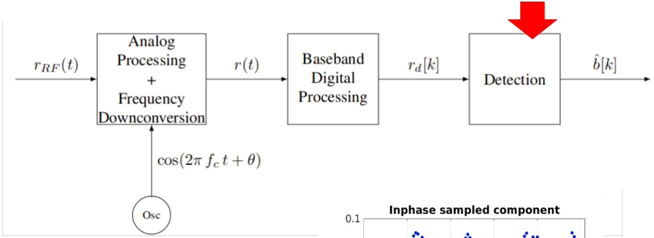
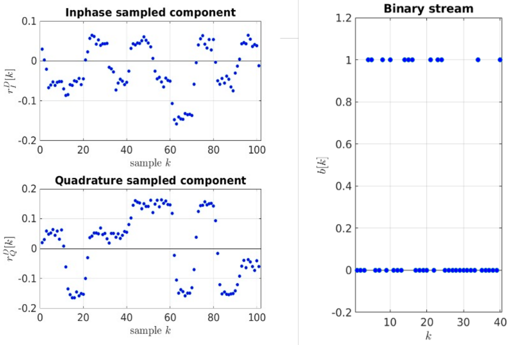


- Digitalization of the complex baseband signal (contaminated with noise)
- Determination of the sequence of bits depending on the modulation scheme used
- Errors due to the noise
- Characterized by the probability of erroneous bit, or by the bit error rate



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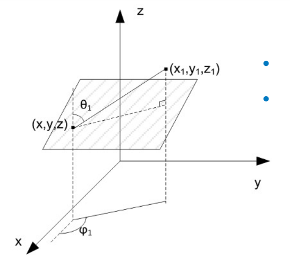
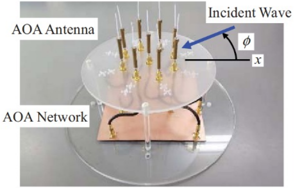
- **Angle of arrival (AoA)** - the angle to which the wave emitted by the transmitter arrives to the antenna of the receiver (measured w.r.t. receiver's antenna); Two components: the azimuth angle φ_1 and the elevation angle θ_1
- **Angle of departure (AoD)** (Reciprocal angle) - the angle of the wave that reaches the receiver (w.r.t. to the transmitter antenna); Also with azimuth and elevation components



- (x,y,z) - the receiver's location
- (x_1, y_1, z_1) - the transmitter's location

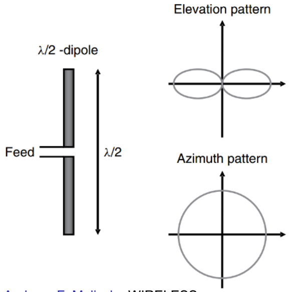
B. Li, K. Zhao and X. Shen, Dilution of Precision in Positioning Systems Using Both Angle of Arrival and Time of Arrival Measurements, *IEEE Access, vol. 8, 2020*



D. Iwamoto, et al., "Experiments on Interferometric Angle of Arrival Estimation Using a Simple Weight Network," *2018 International Symposium on Antennas and Propagation (ISAP).*

Antennas

- **Gain of the antenna:** Depends on the AoA (when it operates as a receiver), or the AoD (when it operates as a transmitter).
- **Radiation pattern:** The map of the gain according to the AoA (or AoD); Usually plotted in polar coordinates in two planes: the Elevation plane and the Azimuth plane
- Shown for the half-wave dipole in the picture
- The part of the radiation pattern that is plotted in the Azimuth plane is called the Azimuth pattern (the one shown in the figure)



Andreas F. Molisch, WIRELESS COMMUNICATIONS, *2011 John Wiley & Sons Ltd.*

Radiation patterns

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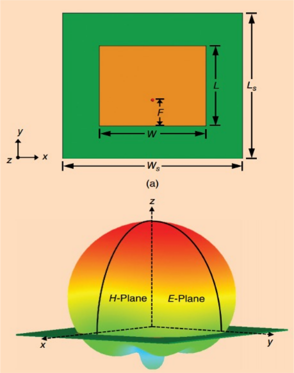
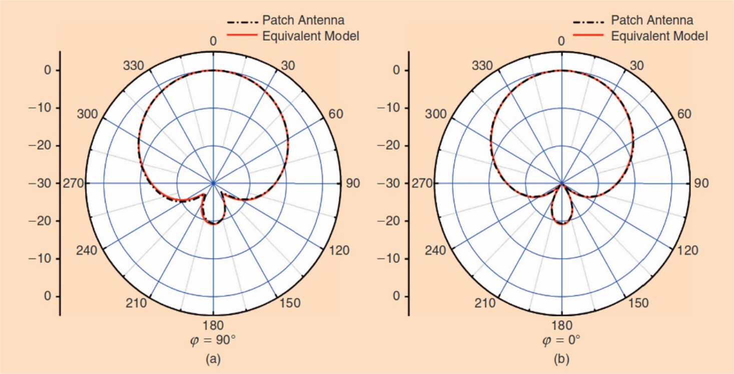
- Antennas do not radiate power equally in all directions

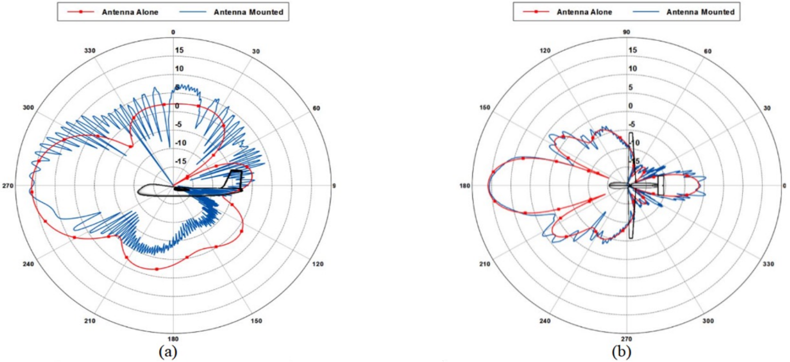




P. Gao, et al., “Installed Radiation Pattern of Patch Antennas: Prediction based on a novel equivalent model” *IEEE Antennas and Propagation Magazine, vol. 57, no. 3, 2015*

Antennas

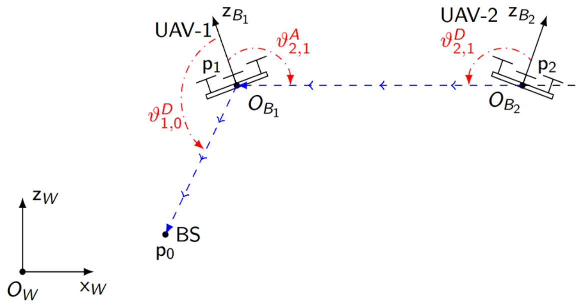
- Anechoic chambers used for the **radiation pattern of the antenna measuring** without the disturbance of any object (red pattern)
- In real conditions deployment: interaction with the environment modifies the radiation pattern
- In the image, the antenna deployed on a fixed-wing UAV; Metallic airframe modifies the radiation pattern



A. Rizwan, et al., “Impact of UAV structure on antenna radiation patterns at different frequencies,” *2017 IEEE International Conference on Antenna Innovations & Modern Technologies for Ground, Aircraft and Satellite Applications (iAIM).*

Antennas on UAVs

- AoA and AoD change with UAVs motion (tilting necessary to fly, maneuver, compensate the wind) → the power transmitted between the antennas is changed
- Communication aware planning is required



Daniel Bonilla Licea, et al., "Optimum Trajectory Planning for Multi-Rotor UAV Relays with Tilt and Antenna Orientation Variations," *EUSIPCO 2021.*

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Free-space path loss model

- **Free-space path loss model**: The simplest communications channel model of transmitted and received signals
- The transmitter and receiver are in open space
- Valid for outer space communication (e.g. satellites)
- Usable for UAV-to-UAV communication far from obstacles and in high altitudes

$$\underbrace{y[k]}_{\text{Signal Received}} = \overbrace{\left(\frac{K G_{tx}^{1/2}(\boldsymbol{\theta}_{AoD}[k])\, G_{rx}^{1/2}(\boldsymbol{\theta}_{AoA}[k])}{\|\mathbf{p}_{tx}[k] - \mathbf{p}_{rx}[k]\|^{\alpha/2}}\right)}^{\text{Channel Gain}} \underbrace{x[k]}_{\text{Signal Transmitted}} + \overbrace{n[k]}^{\text{Noise}}$$

- $x[k]$ - the complex baseband transmitted signal; can be normalized over its average transmission power
- $y[k]$ - the complex baseband received signal
- $n[k]$ - the zero-mean white Gaussian noise

Free-space path loss model

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$$\underbrace{y[k]}_{\text{Signal Received}} = \overbrace{\left(\frac{K G_{tx}^{1/2}(\boldsymbol{\theta}_{AoD}[k]) G_{rx}^{1/2}(\boldsymbol{\theta}_{AoA}[k])}{\|\mathbf{p}_{tx}[k] - \mathbf{p}_{rx}[k]\|^{\alpha/2}}\right)}^{\text{Channel Gain}} \underbrace{x[k]}_{\text{Signal Transmitted}} + \overbrace{n[k]}^{\text{Noise}}$$

- The channel gain composed of three terms:
- **The power gains** of the receiver and transmitter antennas $G_{tx}(\theta_{AoD})$ and $G_{tx}(\theta_{AoA})$ depend on the AoA and AoD
- The gain K accounts for the transmission power (if $x[k]$ was normalized), and any other gain on the circuits (apart from the antenna gain).
- The denominator - a polynomial loss depending on the distance between the transmitter and the receiver
- α - the power path-loss coefficient ($\alpha = 2$ in the free-space model)

Signal-to-noise ratio (SNR)

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- Signal-to-noise ratio - an important metric to determine the performance of the communication system
- Ratio of the power of the desired signal received over the power of the noise generated at the receiver
- Often expressed in decibels.

$$\Gamma[k] = \frac{P_{signal}}{P_{noise}} = \frac{K^2 G_{tx}(\boldsymbol{\theta}_{AoD}[k]) G_{rx}(\boldsymbol{\theta}_{AoA}[k]) P}{||\mathbf{p}_{tx}[k] - \mathbf{p}_{rx}[k]||^{\alpha} \sigma_n^2}$$

$$\Gamma_{dB}[k] = 10 \log_{10} (\Gamma[k])$$

Reflections, and two-ray model

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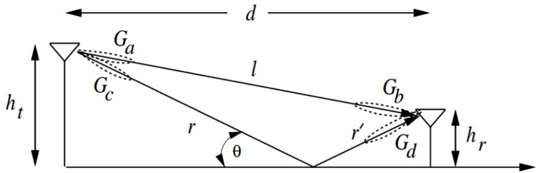
- Problem of reflections of a signal between UAVs flying above a flat ground
- Two waves received: a line of sight (LoS) wave, and a wave reflected on the floor
- The two waves with different antenna gain (they have different AoA and different AoD)
- Both waves travel different distances and thus reach the receiver's antenna with different phase - superimposed in the antenna



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Reflections, and two-ray model

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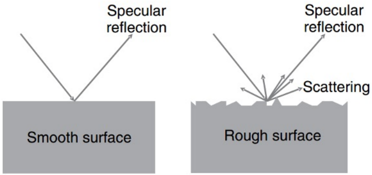
- Smooth surface - specular reflection: the wave is reflected in a single direction (determined by Snell's law of optics)
- Rough surface – scattering: weaker specular reflection because the power is disseminated within the scattering waves
- Smooth/rough surface classification - depending on the wavelength of the carrier signal



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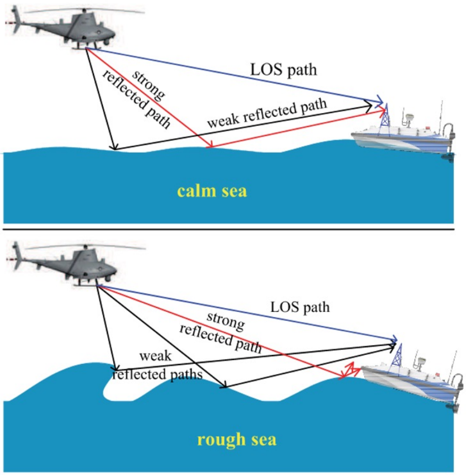
Reflections, and two-ray model

- Sea water is a great conductor: many reflections if communicating over sea water
- Varying number of reflected waves – depending on roughness of the sea
- Time-variant communications channel – due to changing of water surface shape (waves, wind)



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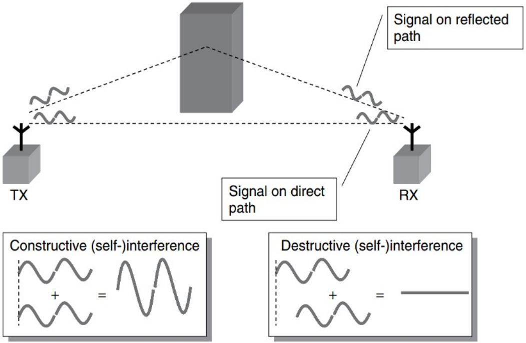
Multipath fading (small-scale fading)

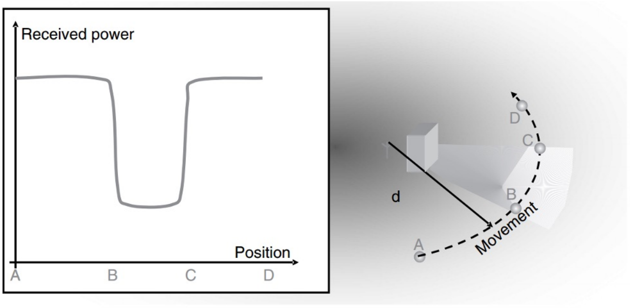
- The reflected wave and the direct wave (or LoS wave) travel different distances → arrive at the antenna with different phases → constructive or destructive interference
- Depending on the phase difference – a stochastic process
- Received power significantly changing in small distances (w.r.t. to the wavelength)
- Called multipath fading (because of the various waves combined) or small-scale fading (because the power of the received signal changed over small distances w.r.t. the wavelength).



Andreas F. Molisch, Wireless Communications *John Wiley & Sons Ltd. (2011)*

Shadowing (large-scale fading)

- Occurs due to obstructions of big objects → large-scale fading.
- The figure: an agent moving around a semi-circle while communicating with a base station; constant distance between both agents
- The LoS obstructed by a big object which causes shadowing between B and C → decrease of the received power



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Shadowing (large-scale fading) and Communications-aware path planning

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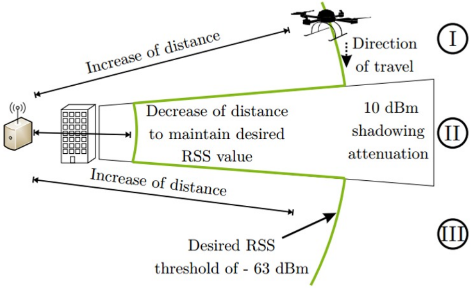
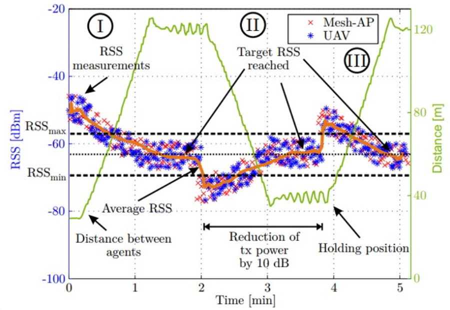
- Communications-aware path planning: communications channel behavior considered in the path planning
- For example, the shadowing considered for UAV planning below
- Left figure: the trajectory (in green); Right figure: the distance of the UAV to BS and the received power
- Part II – shadowing → UAV deviates to get closer to the BS to maintain the received power as required

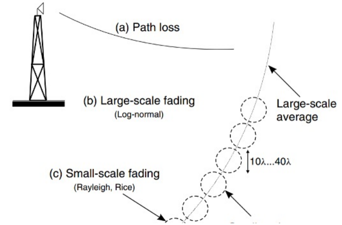




N. Goddemeier, S. Rohde and C. Wietfeld, "Experimental validation of RSS driven UAV mobility behaviors in IEEE 802.11s networks," *2012 IEEE Globecom Workshops, 2012*

Path loss, Shadowing, and multipath fading

- Dynamics of the communications channel determined at different scales by the path loss, shadowing, and multipath fading
- The path loss: large scale behavior; The shadowing: medium scale behavior (behavior on the order of 10s of wavelengths); The multipath fading: small-scale behavior (less than 1 wavelength)
- Right image: the RF map of an experiment done in a basement, real-world measurements dBm is dBs w.r.t 1mW of power; R1 - antenna location; R2, R3, and R4 - hallways



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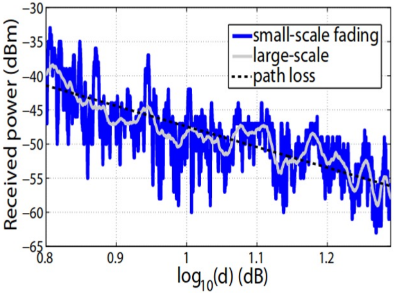
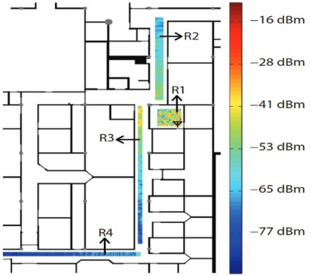
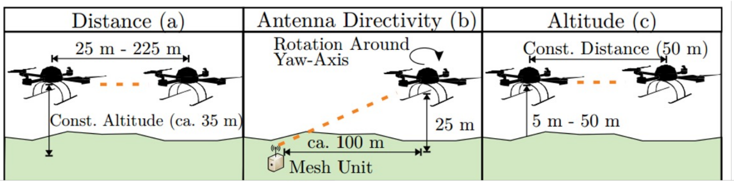


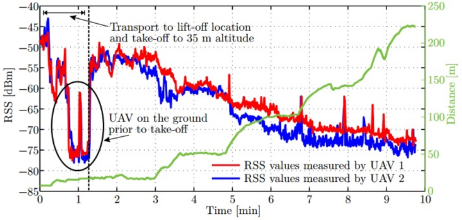


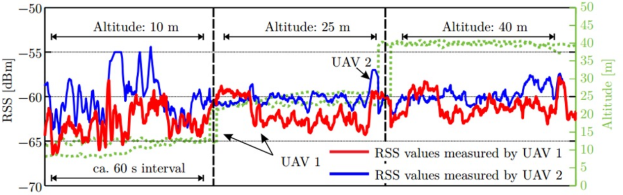
M. Malmirchegini and Y. Mostofi, "On the Spatial Predictability of Communication Channels," *IEEE Transactions on Wireless Communications, vol. 11, no. 3, 2012*

Effect of altitude

- The altitude affecting the communication channel
- Low altitudes - reflections on the ground affecting the channel gain







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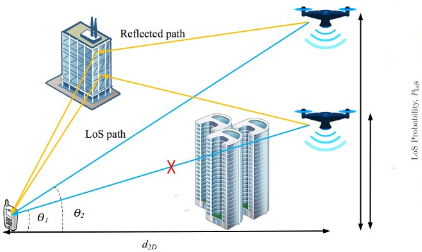
Effect of altitude

- Increasing altitude → increase of the probability of line of sight (LoS)
- Right figure: probability of LoS as a function of the distance for two different altitudes obtained by real measurements
- Higher altitude → higher probability of LoS, but also higher distance to the receiver → losses of energy



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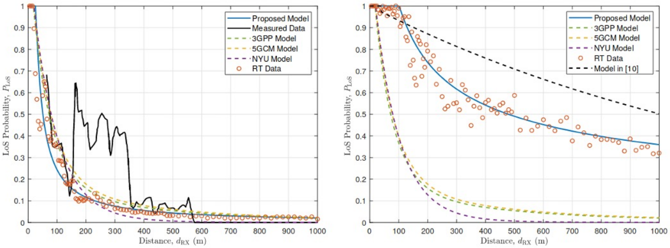
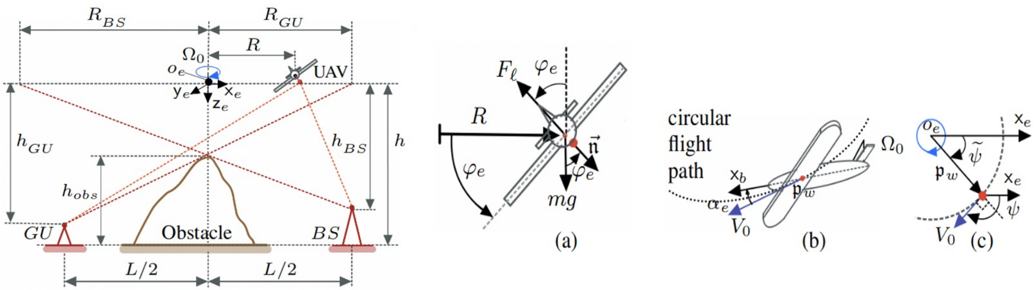


(a) Low altitude ($h_{TX} = 35$ m) (b) High altitude ($h_{TX} = 605$ m)

Q. Zhu et al. "A Data-Driven Multi-Height Empirical LoS Probability Model for Urban A2G Channels," *2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring)*

Airframe Shadowing

- The airframe of the fixed-wing UAV blocking the waves emitted to achieve a communication link



Daniel Bonilla Licea, Moises Bonilla E., Mounir Ghogho, and Martin Saska, "Energy-efficient fixed-wing UAV relay with considerations of airframe shadowing" *IEEE Communications Letters (Submited)*

Airframe Shadowing

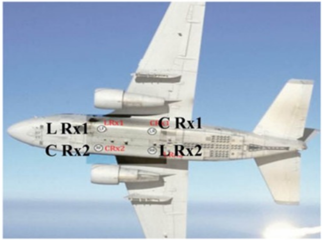
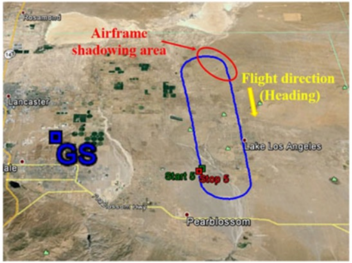
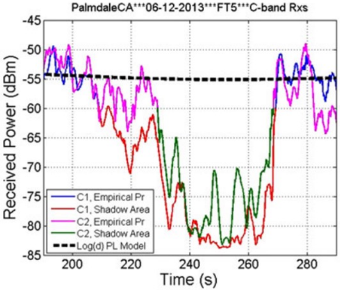


Fig. 3. Aircraft and Rx antenna locations.





- The power received for two receiver antennas CRx1 and CRx2 operating in the frequency band C (4–8 GHz)

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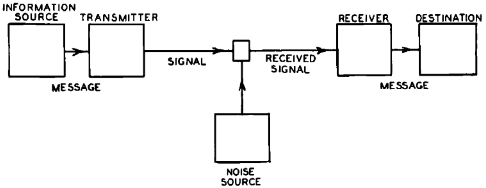
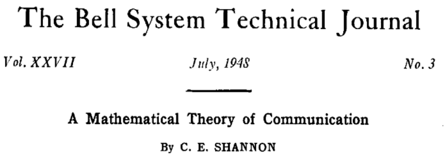
Channel capacity

C. E. Shannon, “A Mathematical Theory of Communications,” *The Bell System Technical Journal, vol. 27, no. 3, 1948.*

- One of the most important articles providing the foundation of communications and information theories
- The abstraction of communication systems used by Claude Shannon to study communications theory




The Bell System Technical Journal

Vol. XXVII July, 1948 No. 3

A Mathematical Theory of Communication

By C. E. SHANNON

Channel capacity

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- Introduced by Shannon - measured in bits/s
- Derived from information theory to determine the maximum bit rate R achievable through a communications channel while reaching an arbitrarily small error in the reception
- Transmitting at a bit rate R higher than channel capacity $C \rightarrow$ non-negligible bit error rates
- For a constant channel gain, the channel capacity: $C = B \log_2(1 + \gamma)$
- B - the bandwidth of the transmitted signal
- γ - the SNR (signal-to-noise ratio) at the receiver
- Signals with larger bandwidths can carry more information

Channel capacity influenced by atmospheric absorption

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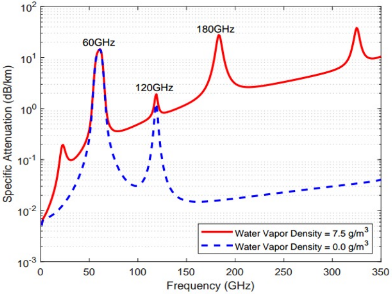
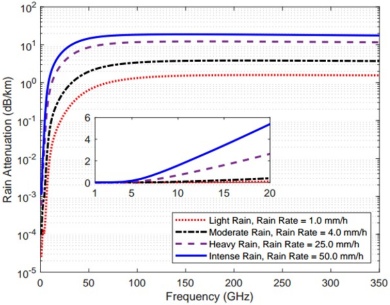
- Higher frequency → larger bandwidth, but more susceptible to power absorption from the air (mainly due to water molecules)
- Higher humidity and rain increase the absorption (and decrease communications range)
- Higher frequency → more information, but shorter communications range



The specific attenuation caused by atmospheric oxygen and water vapor at microwave and mmWave frequencies under whether there has water vapor with the density of 7.5 g/m^3 or not. Here, atmospheric pressure $P = 101.325$ kPa, temperature $T = 20°C$, and distance $d = 1$ km.



The rain attenuation at microwave and mmWave frequencies under different rainfall intensities in terms of rain rates. Here, distance $d = 1$ km.

L. Zhang et al., "A Survey on 5G Millimeter Wave Communications for UAV-Assisted Wireless Networks," *IEEE Access, vol. 7, 2019*

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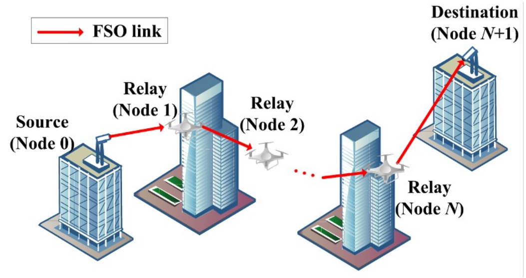
Laser (optical) communication

- Free Space Optical (FSO) communication - an experimental technique in early stages of development and research
- Lasers for transmitting and photosensitive diodes for receiving the signal
- Theoretically very large bit rates
- Resistant to jamming → secured communication systems



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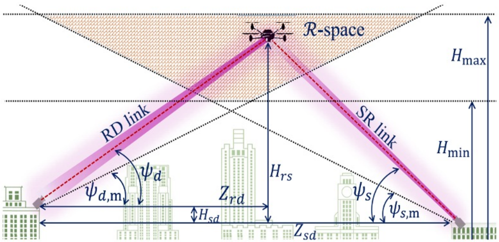

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Laser communication

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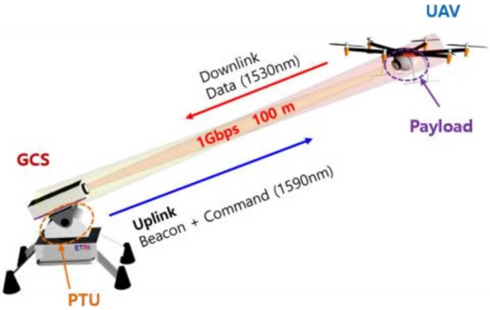
- FSO communications for UAVs - pointing and tracking system required
- UAV equipped with a gimbal to point correctly the laser back to the ground node
- FSO possible added value: transmission of energy to power the UAV together with secured communications channel to exchange information



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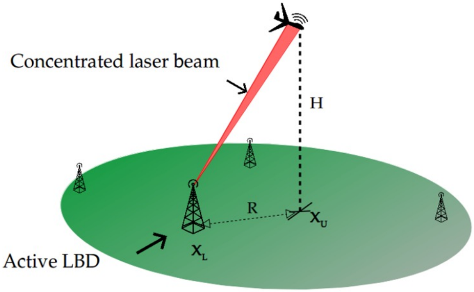
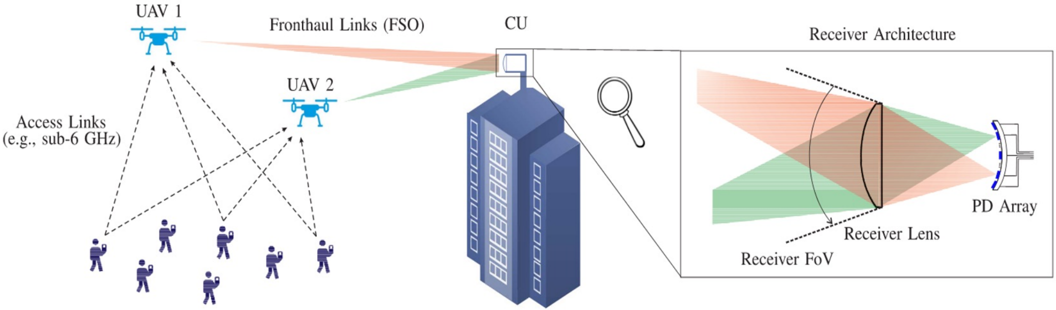


M. -A. Lahmeri, et al., "Stochastic Geometry-Based Analysis of Airborne Base Stations With Laser-Powered UAVs," *IEEE Communications Letters, vol. 24, no. 1, 2020.*

Laser communication

- Light does not interact with electromagnetic waves → possible combination of both types of communication systems simultaneously without any cross-interference
- Increasing the overall transmission rates and reliability



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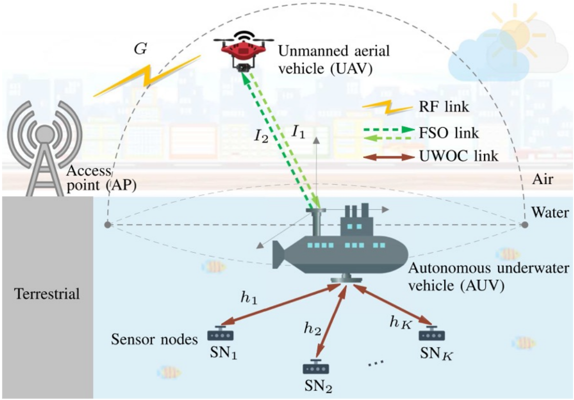
- Free space optical systems proper for direct communication between autonomous underwater vehicles (AUVs) and UAVs
- Optical communications and RF electromagnetic communications are complementary



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Laser communication for UAVs is a reality

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GA-ASI Successfully Tests Air-To-Space Laser Communication System

SAN DIEGO – 20 February 2020 – General Atomics Aeronautical Systems, Inc. (GA-ASI) has successfully ground tested its Airborne Laser Communication System (ALCoS) by establishing a link with a satellite in Geo-synchronous Earth Orbit (GEO). GA-ASI conducted the test with Tesat-Spacecom (TESAT), the leader of space-based laser communication (lasercom), using their GEO Laser Communication Terminal (LCT), the LCT 135. This was the first demonstration of an air-to-space lasercom system with Size, Weight and Power (SWAP) that is compatible with a Medium-altitude, Long-endurance (MALE) Remotely Piloted Aircraft (RPA).

GA-ASI tested the ALCoS from an optical observatory located on Tenerife in the Canary Islands and closed link with TESAT's LCT 135 terminal onboard the GEO satellite Alphasat. The test successfully demonstrated acquisition and tracking, and sufficient power to close the link with the LCT 135. GA-ASI is completing the development of the flight system for use on a GA-ASI-produced MQ-9 RPA.

"This test was a critical step towards enabling our aircraft with a high-bandwidth communication system that cannot be jammed or detected by an adversary," said Linden Blue, CEO, GA-ASI. "ALCoS allows a new generation of high-performance sensors by breaking the data bottleneck of current RF SATCOM technology."

ALCoS is the result of a five-year, GA-ASI-funded effort to deliver Low Probability of Intercept (LPI), Low Probability of Detect (LPD) communications link to the MQ-9. With 300 times the data carrying capacity of conventional RF SATCOM systems, ALCOS will be able to operate as a gateway to the Joint Aerial Network for forward-deployed forces.

The system has the capability to work in two optical wavelengths, 1064nm and 1550nm. TESAT brings more than 12 years of experience with deployed lasercom systems for space. TESAT's LCT 135 terminals are currently in use on seven satellites in orbit. These LCTs make over 60 satellite-to-satellite links over a distance of 45,000 km per day and have logged over 30,000 links total. TESAT has proven the commercial viability of laser satellite communications.

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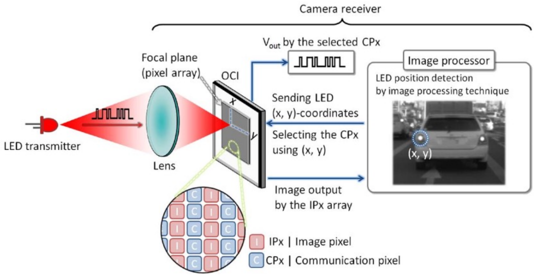
- LED - the transmitter
- Camera - the receiver
- Each optical signal on a different pixel → receiving multiple optical signals simultaneously
- No pointing problem as in FSO → much less demanding tracking of optical sources



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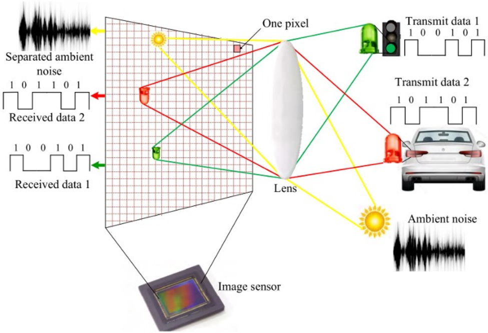

M. Z. Chowdhury, et al., "A Comparative Survey of Optical Wireless Technologies: Architectures and Applications," *IEEE Access, vol. 6, 2018*

Optical Camera Communications (OCC)

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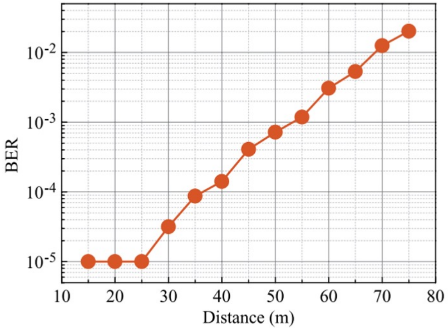
- Pixels saturated at small distances → the SNR (signal-to-noise ratio) independent to the distance between the transmitter and the receiver → also the Bit-Error Rate (BER) independent to the transmitter-receiver distance for small distances
- For example, UVDAR communication channel (the 9th presentation on "Cooperative localization of team members (nearby robots)")



P. Luo et al., "Experimental Demonstration of RGB LED-Based Optical Camera Communications," *IEEE Photonics Journal, vol. 7, no. 5, pp. 1-12, 2015*

Conclusion – key features of communications systems for UAVs

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- Reliable and secured communication is essential for most of the UAV systems
- Communication is always a bottleneck and troublemaker in case of real-world MRS deployment
- Issues of classical radio frequency communications:
  - ✓ Reflections, and two-ray model
  - ✓ Multipath fading (small-scale fading)
  - ✓ Shadowing (large-scale fading)
  - ✓ Airframe Shadowing
  - ✓ Communication infrastructure attacks: jamming, hacking – cyber attacks (failure detection, recovery, and communication infrastructure protection partially tackled in the 11th lecture on "Failure detection, recovery, and reconfiguration in aerial systems")

References

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