Communication and Navigation Systems

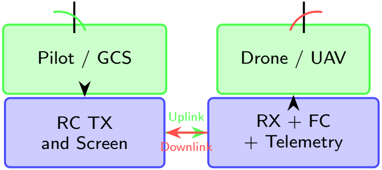
Unit 4

Course Context

- GTU Course: **Drone Technology (DI05000081)**
- Focus: **communication, telemetry, GCS, and navigation**
- Goal: explain how commands, status data, and missions move between pilot and UAV

Learning Outcome

Students should be able to choose suitable links, explain telemetry and GCS operation, and plan safe autonomous missions.



Unit Overview: Communication System Architecture

Two Main Directions

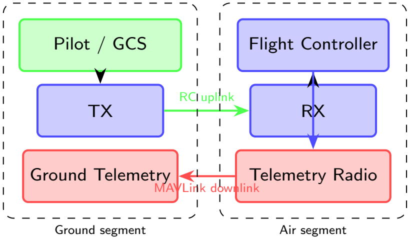
- **Uplink**: stick commands, arming, mode changes, mission edits
- **Downlink**: telemetry, health, RSSI, GPS, and optional video

Components at Each End

Ground: pilot, TX, telemetry modem, GCS, antennas
Drone: RX, FC, telemetry radio, GPS, VTX, onboard antennas

Layered View

Control is the most time-critical layer, telemetry is diagnostic, and video is the highest-bandwidth layer.



4.1 Communication Basics

Definition and Need

Communication is the **wireless exchange of information** between the ground segment and the drone using radio-frequency electromagnetic waves.

- Wireless links allow mobile flight and remote supervision.
- Commands, telemetry, video, and mission data all use RF links.

Wave Fundamentals

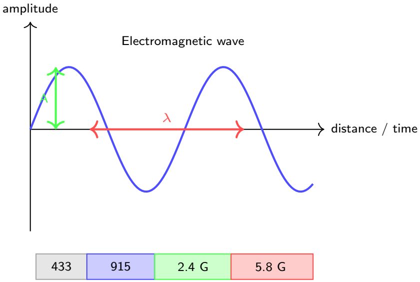
Frequency f counts cycles per second, wavelength λ is spacing between peaks, and amplitude reflects signal strength. The basic relation is

$$c = f\lambda,$$

where $c \approx 3 \times 10^8$ m/s.

RF Spectrum Overview

Common drone bands lie in **UHF and SHF**: 433 MHz, 868/915 MHz, 2.4 GHz, and 5.8 GHz.



Example drone RF bands

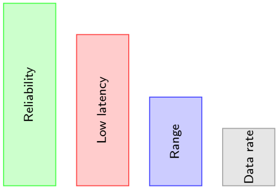
Communication Requirements for Drones

Why Requirements Matter

A drone link is useful only when it meets the mission requirement. Racing, cinematography, and surveying demand different balances of latency, bandwidth, and range.

Metric	**Control**	**Telemetry**	**Video**
Latency	$<$ 20 ms	50–500 ms	20–150 ms
Packet loss	$<$ 1% desired	small loss tolerable	some frame loss tolerable
Data rate	very low	low–medium	high
Range	safe LOS / BVLOS target	usually same or more	often shorter than RC
Compliance	ISM band rules	modem rules	EIRP / video rules

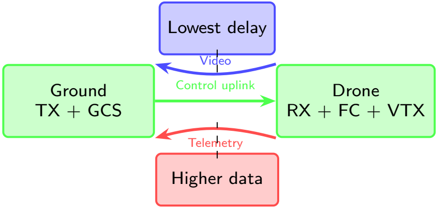
Priority order for manual control links



Control emphasises reliability and latency; video emphasises throughput.

Uplink vs Downlink

Layer	Directior	Data load	Priority
Control uplink	Ground → drone	very low	critical, lowest latency
Telemetry downlink	Drone → ground	medium	health, status, tuning
Video downlink	Drone → ground	high	view quality with acceptable delay



Control Uplink

Link Budget Basics

Core Quantities

- **Transmit power** is usually expressed in dBm.
- **Free-space path loss (FSPL)** models spreading loss with distance and frequency.
- **Receiver sensitivity** is the weakest signal that still decodes correctly.
- **Link margin** = received power − sensitivity; positive margin is required.

FSPL Formula

$$\mathrm{FSPL} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

for distance d in meters and frequency f in hertz.

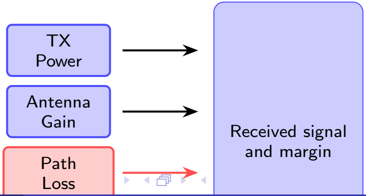
Worked Example: 2.4 GHz at 1 km

With TX power 20 dBm, TX gain 2 dBi, RX gain 2 dBi, and FSPL $\approx$ 100 dB:

$$P_R = 20 + 2 + 2 - 100 = -76\ \text{dBm}$$

If receiver sensitivity is −95 dBm, link margin is about **19 dB**, so the link is healthy.

Band	**FSPL at 1 km**	**Relative range**
433 MHz	$\approx$ 85 dB	longest
915 MHz	$\approx$ 92 dB	long
2.4 GHz	$\approx$ 100 dB	medium
5.8 GHz	$\approx$ 108 dB	shortest



4.2 Radio Transmitter

Internal Flow

Stick and switch positions are sampled, converted into digital channel values, packetized by a microcontroller, and then modulated by the RF section before transmission.

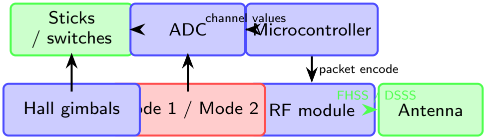
Modulation Approaches

- **DSSS**: spreads energy over wider bandwidth for resilience.
- **FHSS**: hops through many frequencies to resist interference and coexist with other users.

Transmitter Ergonomics

Mode	Stick layout
Mode 1	throttle + roll on right, pitch + yaw on left
Mode 2	throttle + yaw on left, pitch + roll on right

Hall-effect gimbals provide contactless sensing, better linearity, and lower wear than potentiometers.



Transmitter Controls in Detail

Mode 2 Stick Functions

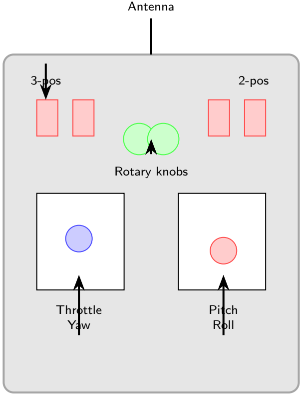
- **Left stick**: throttle on vertical axis, yaw on horizontal axis
- **Right stick**: pitch on vertical axis, roll on horizontal axis

Auxiliary Controls

- **3-position switches**: flight mode selection (Stabilize / Loiter / Auto)
- **2-position switches**: arm/disarm, return-to-home, landing gear
- **Rotary knobs or sliders**: gimbal tilt, camera zoom, gain tuning

Mechanical Feel

A spring-loaded stick returns to center automatically. A ratcheted throttle stays where the pilot leaves it, which is preferred for manual multirotor throttle control.



Radio Receiver

Receiver Role

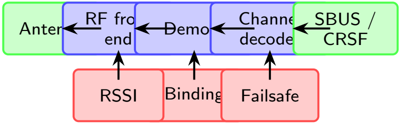
The receiver listens on the selected protocol, demodulates packets, checks validity, decodes channels, and forwards them to the flight controller.

Binding Process

Binding pairs one transmitter with one receiver by exchanging IDs, hopping pattern details, and protocol settings so that the RX ignores other transmitters.

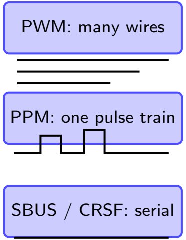
Failsafe and RSSI

- **Failsafe**: hold last values, cut throttle, or command RTL depending on aircraft type and configuration.
- **RSSI**: received signal strength indicator; used by OSD and GCS to warn the pilot before link loss.



RC Protocols

Protocol	Physical form	Latency	Resolution	Ch.	Remarks
PWM	one wire / channel	high	moderate	1 each	1000–2000 μs pulses
PPM	one shared wire	medium	moderate	8–12	sequential pulse train
SBUS	inverted UART	low	good	16	100 kbps digital bus
iBUS	UART serial	low	good	14–18	common with Fly-Sky
CRSF	fast serial	very low	very high	16+	$<$ 1 ms class, long range



Digital serial protocols reduce wiring and increase channel density

Interpretation

PWM is simple but wiring-heavy. PPM reduces wires. SBUS and iBUS carry many channels digitally. CRSF also returns link statistics and supports very low latency.

Practical Choice

Modern flight controllers usually prefer **SBUS, iBUS, or CRSF** instead of individual PWM leads.

4.3 Channels in Depth

What is a Channel?

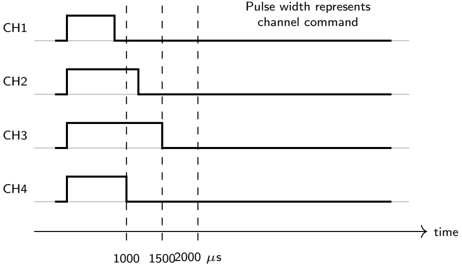
A channel is one independent control value transmitted from pilot to aircraft, usually normalized between minimum, center, and maximum.

PWM Timing and Mapping

- 1000 μs = minimum command
- 1500 μs = center / neutral
- 2000 μs = maximum command
- Common mappings: **AETR** and **TAER**

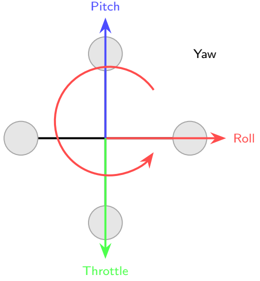
Trim, Expo, and Rates

Trim removes center offset. **Expo** softens response near center stick. **Rates** scale maximum rotational response and are common in FPV tuning.



Ch.	Name	Primary action	If missing
CH1	Roll (aileron)	bank left / right	cannot steer laterally
CH2	Pitch (elevator)	nose forward / back	cannot accelerate or brake by tilt
CH3	Throttle	total lift / altitude	aircraft cannot climb or maintain hover
CH4	Yaw (rudder)	heading rotation	cannot point nose accurately

Drone axes matched to the first four channels



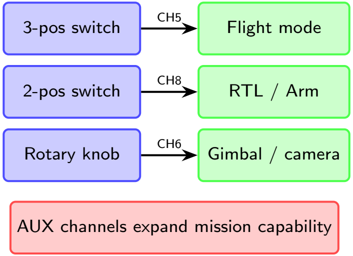
Mnemonic

AETR = Aileron, Elevator, Throttle, Rudder. This is a common order for multirotor and fixed-wing radio mapping.

Why Exactly Four?

Additional Channels (CH5+)

Channel	Typical source	Common ArduCopter use
CH5	3-position switch	flight mode selection
CH6	rotary knob	gimbal pitch or tuning gain
CH7	2-position switch	camera trigger / relay
CH8	2-position switch	return-to-home / smart action
CH9	slider / knob	landing gear / zoom
CH10+	custom AUX	autonomous-manual toggle, payload control



Why Extra Channels Matter

Modern drones do far more than basic flight. Payload control, mission mode selection, geofence override, and camera pointing all need additional independent commands.

Typical Mapping

4.4 Frequency Bands

Band	Waveleng	Typical use	Typical max EIRP*	Practical range
433 MHz	≈ 69 cm	legacy UHF RC, telemetry	region-dependent	very long
915 MHz	≈ 33 cm	long-range RC, telemetry	region-dependent	long
2.4 GHz	≈ 12.5 cm	RC control, some digital links	about 100 mW typical	medium
5.8 GHz	≈ 5.2 cm	FPV video	25–200 mW typical	short to medium

Higher frequency ⇒ more path loss

433 | 915 | 2.4 G | 5.8 G

Longer wavelength better penetration

Short wavelength more bandwidth

*Power limits vary by country and device class

Licensed vs Unlicensed

ISM bands allow low-power equipment without an individual user licence, but equipment must still respect national limits, approved channels, and emission masks.

2.4 GHz in Depth

Why 2.4 GHz Became Standard

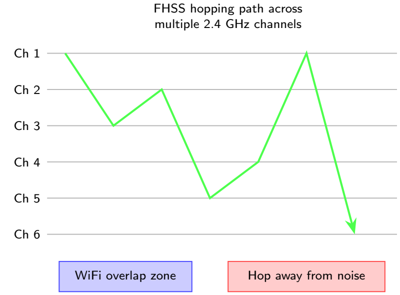
It offers a good compromise between antenna size, hardware cost, and link capacity. Many RC systems hop across about **51 channels** with about **1 ms hop periods** to avoid persistent interference.

DSSS vs FHSS

Method	Strength	Weakness
DSSS	strong noise immunity	fixed occupied band
FHSS	excellent co-existence with WiFi and other radios	more timing complexity

Operational Notes

Popular 2.4 GHz ecosystems include **FrSky**, **FlySky**, and **Spektrum**. Range falls quickly behind walls, trees, and human bodies because higher-frequency waves are blocked more easily.

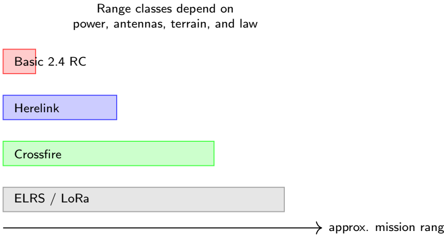


Long-Range Systems

Sub-GHz Advantage

Lower-frequency links around **433 MHz** or **868/915 MHz** suffer less path loss than 2.4 GHz and often use narrowband or LoRa-style modulation for excellent sensitivity.

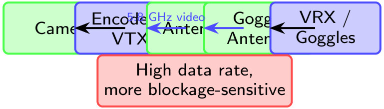
System	**Typical band**	**Range**	**Latency**	**Price / ecosystem**
Legacy UHF / SiK	433 or 915 MHz	5–20 km	medium	low, open
Crossfire	868/915 MHz	10–40 km	low	medium, mature
ExpressLRS	868/915 or 2.4 GHz	5–50 km	very low	low, fast-growing
Herelink	2.4 / 5.8	5–20 km	medium	high, in



Video Transmission

5.8 GHz FPV Video

5.8 GHz is popular for FPV because antennas are compact and enough bandwidth is available for video. The trade-off is weaker obstacle penetration than sub-GHz links.



Type	Latency	Typical range	Quality
Analogue FPV	$<$ 20 ms	about 800 m to a few km	low, noisy but graceful
DJI O3 / O4 digital	about 30 ms	up to 10 km class	HD, crisp image

Analogue vs Digital

Analogue wins on very low delay and graceful degradation. Digital wins on HD quality,

4.5 Telemetry Systems

Definition

Telemetry is the automatic transmission of aircraft state data from the drone to the ground station for monitoring, logging, and mission supervision.

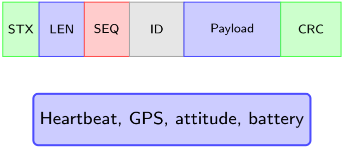
Hardware Examples

- **HolyBro SiK 100 mW**: compact, low-cost, short to medium range
- **RFD900 1 W**: high-power modem for 5–40 km class telemetry with suitable antennas

Data and Speed

MAVLink is the most common telemetry protocol. A baud rate of **57600** is a common default, though higher rates are possible on clean links.

Simplified MAVLink packet



MAVLink Protocol

Message Format

A MAVLink message typically contains a start byte, payload length, sequence number, system ID, component ID, message ID, payload, and checksum. MAVLink 2 can also add a signature.

Important Behavior

- **HEARTBEAT** proves that a system is alive.
- **COMMAND_LONG** carries commands such as arm, RTL, or speed change.
- Ground software uses sequence numbers to detect dropped packets.

Why MAVLink is Popular

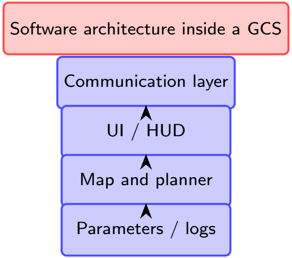
It is lightweight, open, well supported by ArduPilot and PX4, and easy to transport over serial radios, USB, WiFi, or LTE tunnels.

Message	Use
HEARTBEAT	mode, arm state, alive signal
GLOBAL POSITION INT	latitude, longitude, altitude
ATTITUDE	roll, pitch, yaw angles
BATTERY STATUS	voltage, current, remaining capacity
COMMAND	

GCS Categories

- **Laptop GCS**: large screen, deep planning, strong diagnostics
- **Tablet / mobile GCS**: field portability and touch interaction
- **Dedicated hardware GCS**: integrated radios and rugged design

Software	OS	Strengths	FC support	Maps
Mission Planner	Windows	deep setup, logs, tuning	ArduPilot-focused	strong mission maps
QGroundControl	multi-platform	clean UI, mission tools	PX4 + ArduPilot	mission + survey views



Mission Planner Overview

HUD and Flight Data

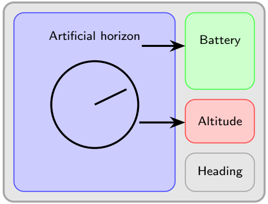
Mission Planner presents an artificial horizon, speed, altitude, heading, GPS quality, battery, and status text in the Flight Data screen.

Mission Planning Tools

- waypoint editor on map
- geofence and rally point setup
- survey grids and route editing

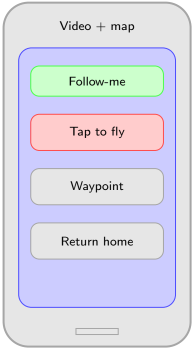
Configuration Features

Parameter lists, radio calibration, compass calibration, and PID tuning are all integrated into one software environment.



Mobile GCS Apps

App	Primary ecosystem	Typical strengths
DJI Fly	consumer DJI	easy setup, camera view, quick shots
DJI Pilot	enterprise DJI	inspection tools, enterprise workflows
Litchi	DJI-compatible	autonomous missions, orbit, waypoint scripting
Tower / DroidPlanner	ArduPilot	mobile mission planning and telemetry
DroneLink	multi-platform	cloud missions, repeatable workflows



Mobile-Specific Features

- live video preview and touch controls
- follow-me and tap-to-fly interactions
- field convenience when laptops are impractical

4.7 Waypoint Navigation Concept

Waypoint Definition

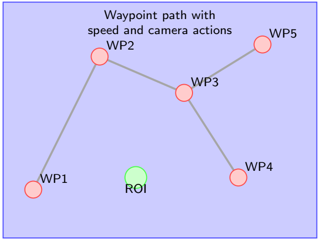
A GPS waypoint stores **latitude, longitude, altitude**, and optionally an action such as camera trigger, speed change, or region of interest.

Related Flight Modes in ArduCopter

Auto follows a mission, **Loiter** holds position, **RTL** returns home, **Land** descends, and **Guided** accepts live commands from the GCS.

Mission Commands

Mission files such as `.waypoints` contain ordered items. Commands like `DO_CHANGE_SPEED` and `DO_SET_ROI` modify behavior during the route.



Waypoint Mission Planning

Typical Workflow

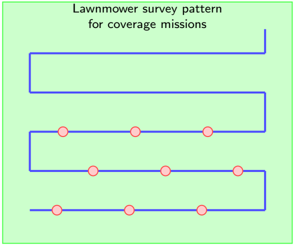
1. survey or define the area
2. place waypoints on the map
3. assign altitude and speed
4. add actions such as camera trigger
5. upload mission to the aircraft
6. arm, switch to Auto, and supervise execution

Mapping and Agriculture Use

Grid missions trigger the camera at constant spacing so that images overlap. This is the basis of crop monitoring, orthomosaic generation, and field scouting.

Pilot Responsibility

Even in Auto mode, the pilot must monitor battery, geofence, and airspace safety and must be ready to take over manually.



Return to Home (RTH)

Trigger Conditions

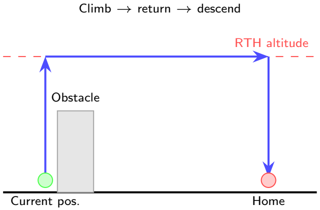
RTH may start because of pilot command, RC signal loss, low battery, mission completion, or failsafe logic.

Important Settings

- **RTH altitude**: set above the tallest obstacle in the operating area
- **Home point**: usually captured at arming location after valid GPS lock
- **Precision landing**: can use camera or beacon assistance for tighter touchdown

Behavior Options

Some autopilots climb first and then return; others may return directly if already above the configured altitude. The chosen logic must match terrain and obstacle risk.



Geofencing

Definition

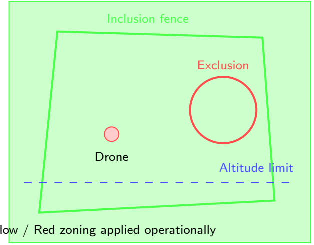
A geofence is a software boundary that constrains where the drone may fly horizontally or vertically.

Fence Types

- **Inclusion fence**: aircraft must remain inside a polygon
- **Exclusion fence**: aircraft must stay outside forbidden circles or polygons
- **Altitude fence**: aircraft must stay below or above set limits

India and ArduPilot Context

DGCA operations refer to Red, Yellow, and Green zones. In ArduPilot, fence breach actions can be warning, RTL, or Land depending on configuration.



Green / Yellow / Red zoning applied operationally

BVLOS Communication

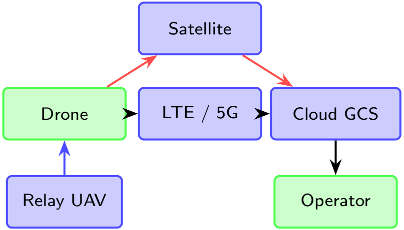
Beyond Visual Line of Sight Challenges

BVLOS operations face extended range, terrain blockage, handover, cybersecurity, latency, and stronger regulatory requirements than ordinary LOS flying.

Mode	Range	Latency	Typical use
VLOS RC	short	very low	hobby, training, close inspection
BVLOS over LTE / 5G	regional to wide	low to medium	fleet ops, cloud GCS, logistics
Satellite link	global	about 500 ms	remote areas, tracking, backup

India-Facing Requirements

BVLOS generally demands approved procedures, detect-and-avoid provisions, reliable command-and-control links, and strong documentation before routine operation.



Cellular, satellite, or relay can extend command-and-control beyond line of sight

Summary and Review Questions

Unit Summary

- Control uplink needs the lowest latency and highest reliability.
- Telemetry uses MAVLink to report aircraft state to a GCS.
- Lower frequencies generally give better range; higher frequencies support more data.
- GCS software turns radio data into maps, HUDs, waypoints, and safety actions.
- Waypoints, geofences, and RTH are core autonomous navigation tools.

Review Questions

1. Define uplink and downlink in a drone system.
2. Why must control latency usually stay below 20 ms?
3. State the relation between frequency and wavelength.
4. What is link margin and why is it important?
5. Compare PWM, SBUS, and CRSF.
6. Why are at least four RC channels required?
7. How do telemetry and video links differ?
8. Explain RTH and geofencing in safe operations.

Protocol / Band	Best for	Main trade-off
CRSF / ELRS	fast RC control	setup and regulatory care
MAVLink telemetry	status + mission data	not suitable for video
5.8 GHz FPV	live video	higher path loss