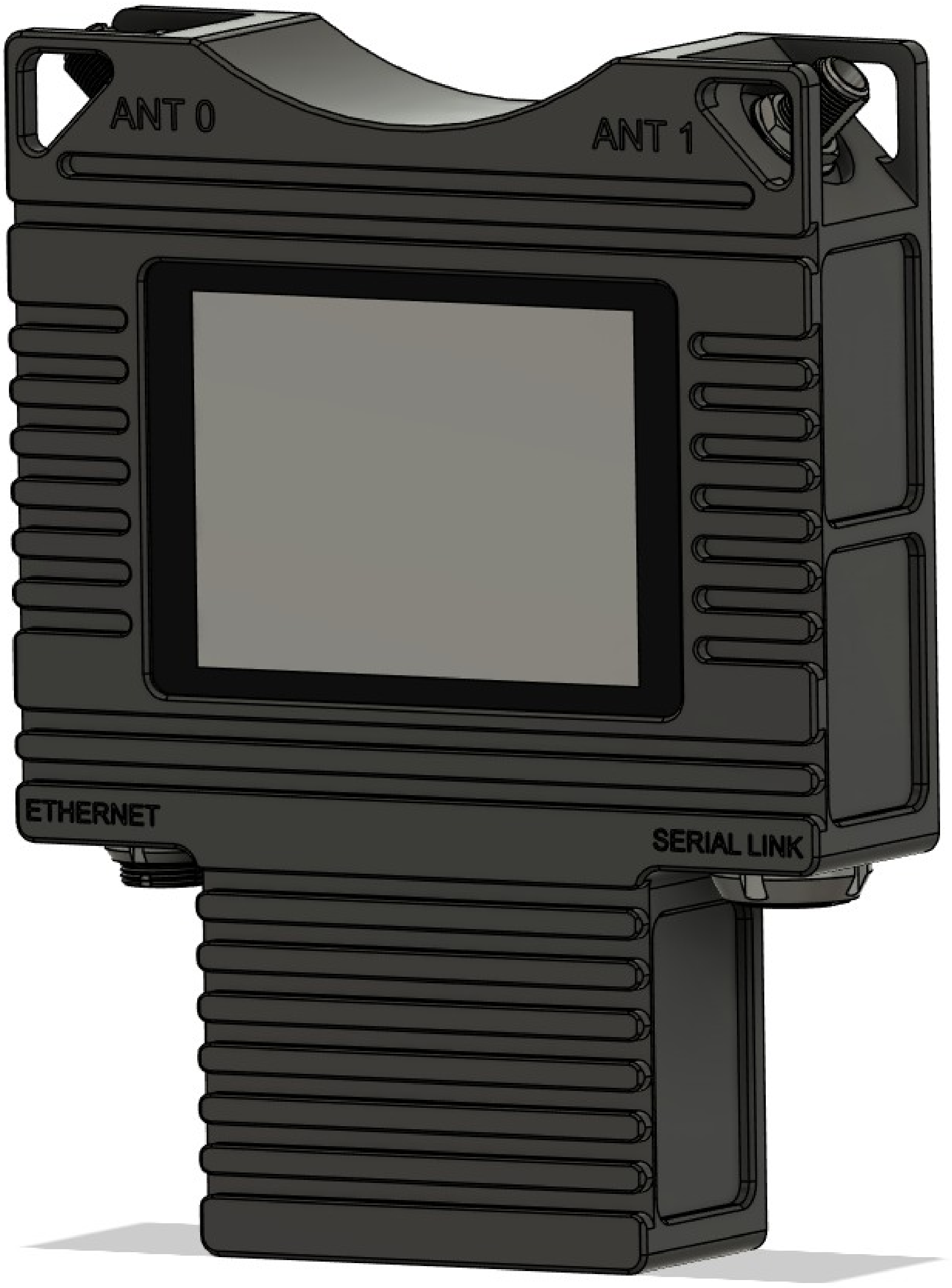
S-RADIO MIMO user manual Rev. 1.0.0

High-performance 2x2 MIMO radio modem system



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1. General Description of the S-Radio MIMO Device

S-Radio MIMO is an industrial radio modem supporting MIMO 2×2 technology, designed for digital communication links of the types "point-to-point", "point-to-multipoint", and "mesh network" in the 2.4 GHz band. The device provides simultaneous data transmission via wired Ethernet and RS485 serial port interfaces, making it a universal solution both for modern IP systems and for equipment with a serial interface.

The modem is housed in an aluminum enclosure with an anodized coating, ensuring efficient heat dissipation from the built-in radio frequency amplifiers. The enclosure measures 120×90×28 mm and is equipped with a standard UNC 3/8″-16 mounting thread as well as a V-Lock quick-release fastening system, allowing rapid installation of the device on tripods, brackets, telescopic cranes, stabilized heads, and cameras. Additionally, a PushPlate is provided for securing the radio modem to joystick control panels.

The device features a color touchscreen display with a graphical user interface, enabling configuration without connecting an external computer. The screen automatically locks after 1 minute of inactivity, which is especially important during video and photo shooting in dark environments.

Full boot time after power-up is 30–40 seconds. Power is supplied by a wide-range DC source of 11–72 V (nominal power consumption – up to 8.5 W in receive mode, up to 13 W in transmit mode at maximum power). The input circuits are protected against reverse polarity, preventing device damage in case of incorrect power connection.

1.1 Purpose and Applications

S-Radio MIMO is intended for operation in harsh environments, in particular:

- **Unmanned Aerial Systems (UAS)** – transmission of telemetry and control commands for cinematographic equipment.
- **Ground moving objects** – "vehicle-to-vehicle" and "vehicle-to-fixed-station" communication for controlling cinematographic equipment, telemetry transmission, and other types of control.
- **Industrial Automation (SCADA)** – establishing communication links with remote sensors, controllers, and actuators via RS485 interfaces.
- **Temporary Networks** – rapid deployment of radio links at sites without a developed cable infrastructure.

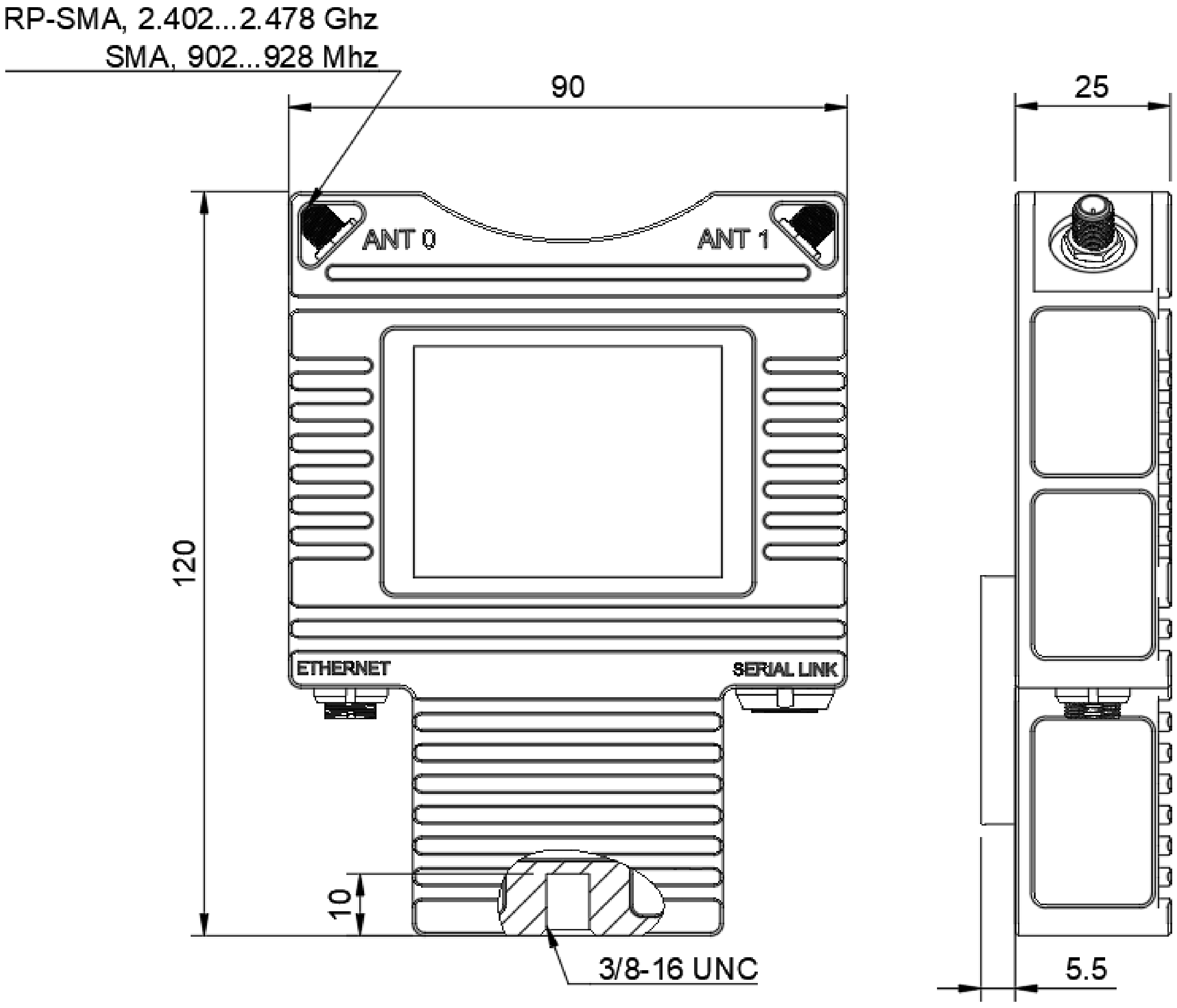
1.2 Main Technical Specifications

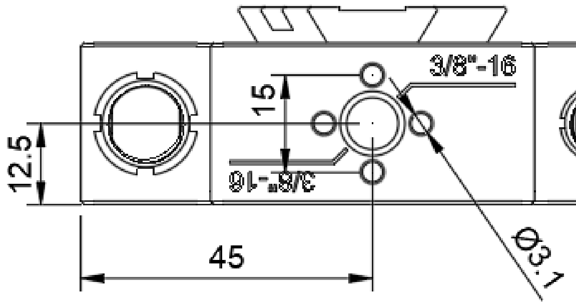
Parameter	**Value / Range**
Radio frequency range	2.402 – 2.478 GHz
MIMO modes	2×2 (two transmit / two receive chains)
Channel bandwidth	4 / 8 MHz (software switchable)
Modulation and coding schemes	BPSK 1/2, QPSK 1/2, QPSK 3/4, 16QAM 1/2, 16QAM 3/4, 64QAM 2/3, 64QAM 3/4, 64QAM 5/6 (manual or automatic selection)
Maximum output power (total MIMO)	+30 dBm (1 W) – adjustable in 1 dB steps
System gain (typ.)	up to 143 dB (depends on modulation, bandwidth, antenna gain)
Receiver sensitivity (MIMO ON, 4 MHz)	from -102.5 dBm (BPSK 1/2) to -83.5 dBm (64QAM 5/6)
Useful throughput (iPerf)	up to 27.8 Mbps (8 MHz, 64QAM 5/6)
Wired interfaces	1× 10/100BaseT Ethernet LAN, Isolated RS485
Supported encapsulation protocols	TCP, UDP, TCP/IP, ARP, ICMP, DHCP, HTTP/HTTPS, SSH, SNMP, FTP, DNS
Operating modes	Master, Slave (Remote), Repeater, Mesh
Network topologies	point-to-point, point-to-multipoint, Mesh (self-organising, self-healing)

1.3 Operational and Mechanical Characteristics

Parameter	**Value**
Input supply voltage	11 – 72 V DC
Reverse polarity protection	Yes (built-in)
Power consumption (receive, 2×2 MIMO)	≤ 8.5 W
Power consumption (transmit, 30 dBm)	≤ 13 W
Operating temperature range	-20°C … +85°C
Dimensions (L×W×H)	120 mm × 90 mm × 28 mm
Weight	____________ (left blank)
Housing material	Aluminium alloy, anodized coating
Mounting types	UNC 3/8″-16 thread, V-Lock system, PushPlate (secures to joystick panel)

1.3.1 Dimensional Drawing





1.4 User Interface

Control and configuration of S-Radio MIMO are performed via:

Color touchscreen display with graphical interface. Available functions: radio channel settings (frequency, power, modulation, bandwidth), RS485 serial port baud rate configuration, connection status monitoring (SNR, RSSI).

Automatic screen lock function: after 60 seconds of inactivity the display turns off. Lock is released by a short tap on the screen. This function is specifically implemented to prevent stray illumination during video or photo shooting in low-light conditions, where any light source may affect frame quality.

1.5 Design Features

1.5.1 Thermal Management. The aluminium enclosure acts as a heat sink: the built-in radio module (which generates up to 6–8 W of heat at maximum transmit power) is in direct thermal contact with the housing via a thermal interface material. Thanks to the large surface area and anodized coating (which increases emissivity), heat dissipation occurs by natural convection without fans. This ensures silent operation and increased reliability in dusty or aggressive environments.

1.5.2 PushPlate Mounting Bracket. A special plate on top of the enclosure allows S-Radio MIMO to be securely fastened to joystick control panels of cinematographic equipment. Fastening is accomplished by a clamp-type mechanism, preventing unintended displacement of the device under vibration or sudden movements.

1.5.3 V-Lock System and UNC 3/8”-16 Thread. The standard thread allows the use of any tripod heads, adapters, and brackets that conform to the standard widely adopted in cinema, photography, and measurement equipment. The V-Lock system provides a quick-release dovetail-type fastening with a locking lever, which is especially convenient when frequently changing the device’s mounting location (e.g., moving from a tripod to a vehicle bracket).

1.6 Scope of Delivery (typical)

- S-Radio MIMO units assembled (housing with integrated display, electronics and radio module)
- Ethernet cables with RJ-45 and barrel connectors
- Omnidirectional antennas 3 dBi, 4 pcs.
- PushPlate, 2 pcs.
- Metric locking screws

2. Ports and Interfaces

2.1 Ethernet Port

The S-Radio MIMO device is equipped with an **Ethernet** port, which is a telecommunications industry standard. This significantly expands the possible applications of this radio link, even for consumer purposes.

2.1.1 Types of Devices for Connection

In addition to cinematographic equipment and professional cameras, the following common device types can be connected to the S-Radio MIMO via the Ethernet port:

- **Computers and laptops** (data transmission, remote control, telemetry)
- **IP cameras** (video surveillance, streaming)
- **Network Attached Storage (NAS)** (file access)
- **PLCs (Programmable Logic Controllers)** (industrial automation, telemetry)
- **IoT gateways and sensors** (smart grids, monitoring)
- **IP phones** (voice communication)
- **Switches and routers** (network expansion)
- **Video servers and encoders** (video streaming)
- **Drone ground stations** (telemetry and control)
- **Professional cameras for cinema and TV** (configuration of parameters, remote control)

2.1.2 LAN Port Technical Specifications

Parameter	Value
Interface type	Ethernet 10/100/1000 BASE-T
Connector	RJ45
Data rate	10/100/1000 Mbps (auto-negotiation)
Duplex mode	Full duplex, Half duplex (auto-negotiation)
Supported protocols	TCP/IP, UDP, ARP, ICMP (provided by the device OS)
Cable type	UTP/FTP, category not lower than Cat5e (Cat6 for Gigabit)
Maximum cable length	100 m (between device and switch/client)
Protection	Transformer isolation, overvoltage (ESD) protection
Functional purpose	Data transfer, device configuration, video/audio streaming, telemetry, channel redundancy

> **Note:** The Ethernet port operates in transparent mode (Ethernet bridge) or can be configured as a management interface depending on the radio channel configuration.

2.2 Serial Link Connector

The hardware **Serial Link** port is designed for connecting external devices (e.g., controllers, sensors, terminals, PLCs, cinematographic equipment) via a serial interface. Device power is also supplied through the serial port connector, which simplifies connection and cable routing on the target device during installation.

The port supports four physical communication interfaces:

1. **RS485 (half duplex)** – primary type, available by default.
2. **RS422** – optional, upon request.
3. **RS232** – optional, upon request.
4. **UART TTL** – optional, upon request.

> **Note:** The device version with the required physical layer is determined at the time of ordering. Standard delivery includes **RS485**.

2.2.1 Supported Interfaces (RS485, RS422, RS232, UART TTL)

(As specified above – the device supports RS485 by default, with RS422, RS232, and UART TTL available as options.)

2.2.2 Data Transmission Rate (Baud Rate)

The serial port baud rate is configured via the user interface (UI). The following standard rates are supported:

- 19200 bps
- 38400 bps
- 57600 bps
- 115200 bps
- 230400 bps
- 460800 bps
- 921600 bps

2.2.3 SERIAL BAUD RATE Configuration in UI

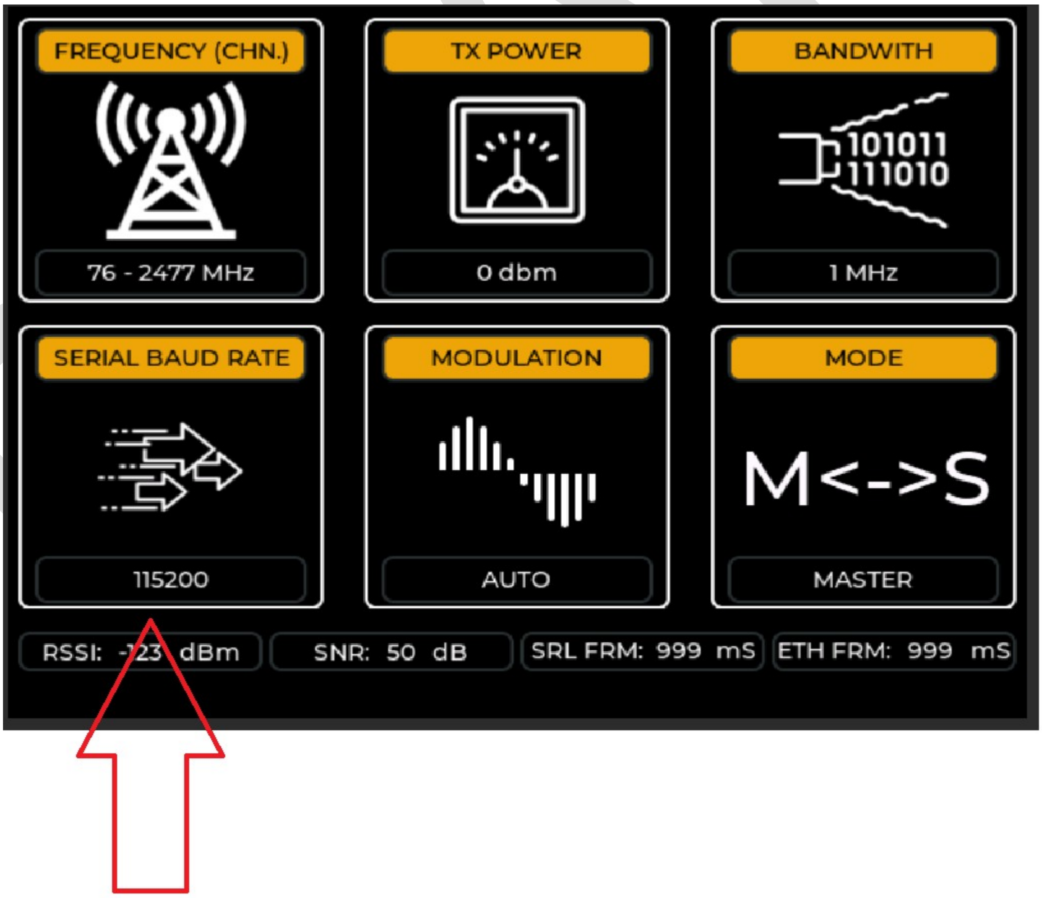
To change the Serial Link speed:

1.Activate the device screen.
2.Navigate to the **«SERIAL BAUD RATE»** menu.
3.Select the desired speed from the list.
4.Press:

•**«SAVE»** – to save and apply the parameter.
•**«CANCEL»** – to return to the main page without changes.

After pressing **«SAVE»**, the save and update procedure will begin, lasting several seconds. Upon completion, the interface will automatically return to the main screen, where the updated parameters will be read and displayed.

> **Important:** Ensure that the external connected device is configured to the same baud rate that you set on the S-Radio MIMO.



FREQUENCY (CHN.): 76 - 2477 MHz
TX POWER: 0 dbm
BANDWITH: 1 MHz
SERIAL BAUD RATE: 115200
MODULATION: AUTO
MODE: MASTER

RSSI: -123 dBm
SNR: 50 dB
SRL FRM: 999 mS
ETH FRM: 999 mS

3. Operating Modes

The S-Radio MIMO supports four main operating modes, which define the device's role within the radio network and the method of data exchange between nodes. The choice of appropriate mode depends on the system architecture, required range, topology, and channel redundancy requirements.

3.1 MASTER

MASTER mode is the central node of the network. A device in this mode:

•Initiates and synchronizes the operation of the entire radio network.
•Generates clock and frame synchronization for slave devices.
•Manages access to the transmission medium.
•Can exchange data with one or multiple slave devices (SLAVE) depending on the configuration.
•In typical scenarios, it is used on the base station side, control point, or main data processing post.

Number of connected SLAVEs – determined by the system configuration (up to several tens depending on the software version).

3.2 SLAVE

SLAVE mode is intended for peripheral network nodes. A device in this mode:

•Synchronizes with the master device (MASTER).
•Cannot initiate a communication session on its own – only responds to MASTER requests or transmits data in allocated time slots.
•Supports two-way data exchange with the MASTER (or via REPEATER).
•Can operate in low-power mode (depending on configuration).
•Used on remote objects – cameras, sensors, terminals, drones, mobile devices.

Quantity – there can be one or many SLAVEs in the network.

3.3 REPEATER

REPEATER mode is used to extend the network's radio range. A device in this mode:

- Receives a signal from the MASTER (or another REPEATER) and retransmits it further.
- Does not change the content of data packets, only amplifies and forwards them.
- Operates in half-duplex mode – reception and transmission are separated in time.
- Allows overcoming obstacles, buildings, and terrain relief.
- Can be connected in series (a chain of REPEATERs) to increase range.
- Increases overall transmission delay proportionally to the number of repeaters.

Limitation: the maximum number of serial REPEATERs depends on timeouts and channel quality (usually no more than 3–5).

3.4 MESH (Self-Organizing Network)

MESH mode provides a decentralized topology where each node can communicate directly with any other within radio line-of-sight. A device in this mode:

- Automatically discovers neighboring nodes.
- Packet routing dynamically selects the best path (based on signal level, load, number of hops).
- Supports self-healing of routes when topology changes (nodes turning on/off, obstacles).
- Each node can be both a source and a data relay for others.
- Does not require a dedicated MASTER – synchronization functions are distributed among nodes.
- Provides high network survivability through redundant paths.
- Slightly increases overhead due to routing service traffic.

Typical scenarios: dynamic groups (drones, robots, rescue teams), distributed sensor networks, wireless systems in warehouses or large areas.

3.5 Mode Comparison Table

Mode	Synchronization	Centralization	Routing	Range	Latency
MASTER	Yes	Full	None (point-to-point/multipoint)	Baseline	Minimal
SLAVE	Yes (from MASTER)	Full	None	Limited by MASTER	Minimal
REPEATER	Yes (from MASTER)	Partial	Fixed (retransmission)	Extended	Proportional to number of repeaters
MESH	Distributed	None	Dynamic (self-organizing)	Network (multi-hop)	Variable (depends on route)

3.6 How to Choose a Mode

•**MASTER + SLAVE** – for simple point-to-multipoint systems with centralized control (video surveillance, telemetry).
•**REPEATER** – added when the distance between MASTER and SLAVE exceeds direct radio line-of-sight.
•**MESH** – for complex, dynamic, or distributed systems where resilience to individual node failure is required.

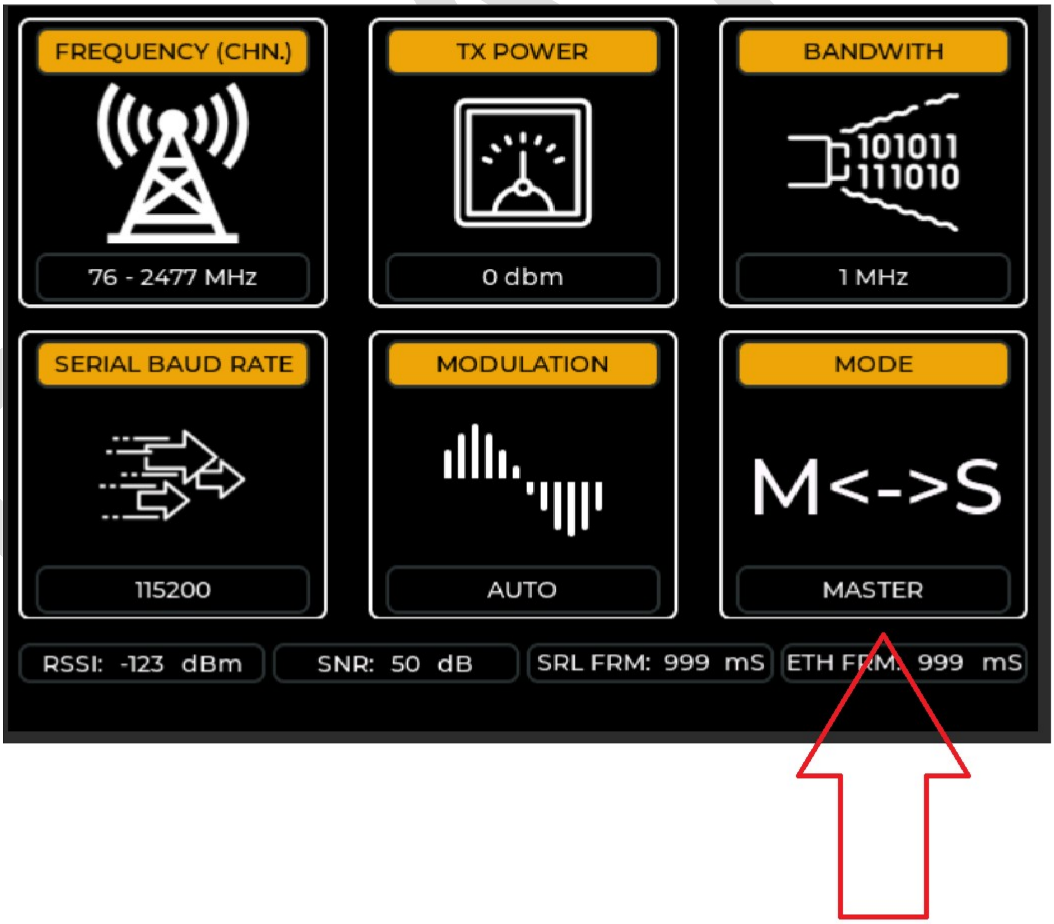
3.7 MODE Configuration in UI

To change the node operating mode:

1.Activate the device screen.
2.Navigate to the **«MODE»** menu.
3.Select the desired node operating mode from the list.
4.Press:

•**«SAVE»** – to save and apply the parameter.
•**«CANCEL»** – to return to the main page without changes.

After pressing **«SAVE»**, the save and update procedure will begin, lasting several seconds. Upon completion, the interface will automatically return to the main screen, where the updated parameters will be read and displayed.



FREQUENCY (CHN.) 76 - 2477 MHz
TX POWER 0 dbm
BANDWITH 1 MHz
SERIAL BAUD RATE 115200
MODULATION AUTO
MODE MASTER

RSSI: -123 dBm
SNR: 50 dB
SRL FRM: 999 mS
ETH FRM: 999 mS

4. Radio Channel Configuration

4.1 Frequency and Channel Selection

The S-Radio MIMO operates in the 2400–2480 MHz band, which corresponds to the standard ISM band. Proper selection of frequency and communication channel is critical for ensuring stable operation of the radio system, especially in the presence of radio interference.

4.1.1 Available Channels and Frequencies for 4 MHz

Channel	Frequency	Channel	Frequency	Channel	Frequency
4	2405 MHz	29	2430 MHz	54	2455 MHz
5	2406 MHz	30	2431 MHz	55	2456 MHz
6	2407 MHz	31	2432 MHz	56	2457 MHz
7	2408 MHz	32	2433 MHz	57	2458 MHz
8	2409 MHz	33	2434 MHz	58	2459 MHz
9	2410 MHz	34	2435 MHz	59	2460 MHz
10	2411 MHz	35	2436 MHz	60	2461 MHz
11	2412 MHz	36	2437 MHz	61	2462 MHz
12	2413 MHz	37	2438 MHz	62	2463 MHz
13	2414 MHz	38	2439 MHz	63	2464 MHz
14	2415 MHz	39	2440 MHz	64	2465 MHz
15	2416 MHz	40	2441 MHz	65	2466 MHz
16	2417 MHz	41	2442 MHz	66	2467 MHz
17	2418 MHz	42	2443 MHz	67	2468 MHz
18	2419 MHz	43	2444 MHz	68	2469 MHz
19	2420 MHz	44	2445 MHz	69	2470 MHz
20	2421 MHz	45	2446 MHz	70	2471 MHz
21	2422 MHz	46	2447 MHz	71	2472 MHz
22	2423 MHz	47	2448 MHz	72	2473 MHz
23	2424 MHz	48	2449 MHz	73	2474 MHz
24	2425 MHz	49	2450 MHz	74	2475 MHz
25	2426 MHz	50	2451 MHz	75	2476 MHz
26	2427 MHz	51	2452 MHz	76	2477 MHz
27	2428 MHz	52	2453 MHz	77	2478 MHz
28	2429 MHz	53	2454 MHz	78	2479 MHz

4.1.2 Available Channels and Frequencies for 8 MHz

Channel	Frequency	Channel	Frequency	Channel	Frequency
6	2407 MHz	30	2431 MHz	54	2455 MHz
7	2408 MHz	31	2432 MHz	55	2456 MHz
8	2409 MHz	32	2433 MHz	56	2457 MHz
9	2410 MHz	33	2434 MHz	57	2458 MHz
10	2411 MHz	34	2435 MHz	58	2459 MHz
11	2412 MHz	35	2436 MHz	59	2460 MHz
12	2413 MHz	36	2437 MHz	60	2461 MHz
13	2414 MHz	37	2438 MHz	61	2462 MHz
14	2415 MHz	38	2439 MHz	62	2463 MHz
15	2416 MHz	39	2440 MHz	63	2464 MHz
16	2417 MHz	40	2441 MHz	64	2465 MHz
17	2418 MHz	41	2442 MHz	65	2466 MHz
18	2419 MHz	42	2443 MHz	66	2467 MHz
19	2420 MHz	43	2444 MHz	67	2468 MHz
20	2421 MHz	44	2445 MHz	68	2469 MHz
21	2422 MHz	45	2446 MHz	69	2470 MHz
22	2423 MHz	46	2447 MHz	70	2471 MHz
23	2424 MHz	47	2448 MHz	71	2472 MHz
24	2425 MHz	48	2449 MHz	72	2473 MHz
25	2426 MHz	49	2450 MHz	73	2474 MHz
26	2427 MHz	50	2451 MHz	74	2475 MHz
27	2428 MHz	51	2452 MHz	75	2476 MHz
28	2429 MHz	52	2453 MHz	76	2477 MHz
29	2430 MHz	53	2454 MHz	–	–

4.1.3 Channel Selection Recommendations

•**In a clean radio environment** – any available channel can be used. It is recommended to choose mid-range values (channels 35–55) for optimal antenna performance.
•**In the presence of interference (WiFi, Bluetooth)** – use the spectrum scanning function to detect free channels. Avoid channels occupied by other devices.
•**When operating several independent radio systems in close proximity** – space their channels by at least 2–3 numbers for 4 MHz bandwidth or 4–5 numbers for 8 MHz bandwidth.

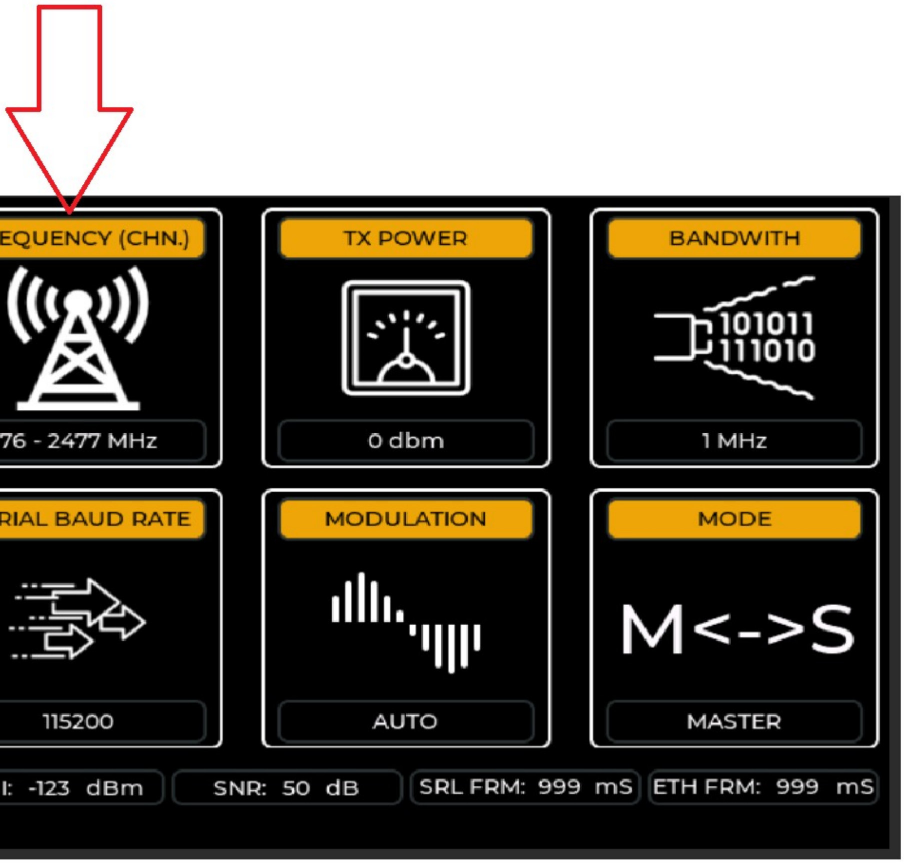
4.1.4 Channel Configuration in UI

To change the communication channel:

1.Activate the device screen.
2.Navigate to the **«FREQUENCY (CHN.)»** menu.
3.Select the desired frequency and channel number.
4.Press:

•**«SAVE»** – to save and apply the parameter.
•**«CANCEL»** – to return to the main page without changes.

After pressing **«SAVE»**, the save and update procedure will begin, lasting several seconds. Upon completion, the interface will automatically return to the main screen, where the updated parameters will be read and displayed.



FREQUENCY (CHN.): 76 - 2477 MHz
TX POWER: 0 dbm
BANDWITH: 1 MHz
SERIAL BAUD RATE: 115200
MODULATION: AUTO
MODE: MASTER
RSSI: -123 dBm
SNR: 50 dB
SRL FRM: 999 mS
ETH FRM: 999 mS

> **Important:** All devices in the same radio network (MASTER and SLAVE) must operate with the same bandwidth and on the same channel number. For MESH mode, this requirement is also mandatory.

4.2 Bandwidth Selection

The channel bandwidth is one of the fundamental parameters of the radio modem, which directly determines the trade-off between data rate and receiver sensitivity. This trade-off is an inevitable consequence of physical laws, not a design flaw.

4.2.1 Physical Relationship Between Bandwidth, Data Rate, and Noise

Theoretical basis (Shannon–Hartley theorem). The maximum achievable capacity of a communication channel in the presence of noise is described by the formula:

$C = B \cdot \log_2(1 + SNR)$

where:

- C – channel capacity (bit/s)
- B – channel bandwidth (Hz)
- SNR – signal-to-noise ratio (linear scale)

The formula shows that channel capacity scales linearly with bandwidth. For a fixed SNR, doubling B gives more than a doubling of C (due to the logarithmic component). However, the downside is that the wider the channel, the more thermal noise power the receiver collects.

Thermal noise power spectral density. The thermal noise power at the receiver input is proportional to the channel bandwidth:

$P_{noise} = k \cdot T \cdot B$

where k is Boltzmann's constant, T is the absolute temperature in Kelvin (290 K under standard conditions), and B is the channel bandwidth.

Consequence: When the channel bandwidth is doubled, the noise power at the receiver input doubles (+3 dB). To maintain the same SNR, the desired signal level must also be increased by +3 dB. If the transmitter power is fixed, this means that a twice-wider channel has 3 dB worse receiver sensitivity, and therefore shorter range.

4.2.2 Practical Comparison of 4 MHz and 8 MHz

In real radio modems, the relationship between bandwidth, data rate, and sensitivity is quantifiable. Based on the technical specifications, when switching from 8 MHz to 4 MHz (narrowing the channel by half), the following patterns are observed:

Data throughput:

•Speed roughly halves for the same modulation type
•Example for BPSK 1/2 modulation: 3 Mbps (8 MHz) → 1.51 Mbps (4 MHz)
•For 64QAM 5/6: 27.8 Mbps (8 MHz) → 14.0 Mbps (4 MHz)

Receiver sensitivity:

•Improves by 2–3 dB for all modulation types
•Example for BPSK 1/2: -99.5 dBm (8 MHz) → -102.5 dBm (4 MHz)
•For 64QAM 5/6: -81.0 dBm (8 MHz) → -83.5 dBm (4 MHz)

Explanation of the difference:

•The theoretical sensitivity gain when narrowing the channel by half should be 3 dB
•In practice, 2–3 dB is achieved due to the impossibility of completely avoiding quantization noise, synthesizer phase noise, and other internal receiver noises
•Nevertheless, even 2 dB of gain is significant: it allows either increasing range or operating under worse conditions

4.2.3 Quantitative Relationship Between Sensitivity and Range

The relationship between receiver sensitivity and maximum range is determined by the radio link equation. Sensitivity improvement of ΔR dB allows range increase (with other parameters fixed) of approximately:

$\Delta R\ (\%) \approx (10\verb|^|(\Delta P / (10 \cdot n)) - 1) \cdot 100\%$

where n is the loss exponent, which equals 2 for free space and ranges from 2.5 to 4 for typical terrestrial paths.

Approximate figures:

•2 dB sensitivity gain at n=3 (urban environment) gives a range increase of ≈15%
•3 dB sensitivity gain (theoretical maximum) at n=3 gives a range increase of ≈25%

> **Practical example:** If with an 8 MHz channel the maximum range was 5 km, then after switching to 4 MHz (without changing modulation, power, or antennas), the range will increase to approximately 5.75–6.0 km. At the same time, the speed will be halved, which is acceptable for many applications (telemetry, control commands, audio) but critical for high-definition video.

4.2.4 Other Dependencies (interference immunity, multipath)

Resistance to narrowband interference. In practice, a wider channel has a certain advantage: a narrowband interferer (e.g., from another radio device) will only affect part of the channel, and the OFDM (Orthogonal Frequency Division Multiplexing) system can cope with it through error-correcting coding. In a narrow channel, the same interferer occupies a proportionally larger portion of the bandwidth and may block communication entirely.

Sensitivity to multipath. Wideband signals (larger B) inherently have better delay resolution, allowing the receiver to distinguish paths. For typical delays in urban conditions (up to a few microseconds), 4 MHz and 8 MHz channels in practice have similar multipath resistance.

Doppler tolerance. Narrowband channels (4 MHz) have a relatively larger Doppler shift relative to the channel width, so for moving objects, a narrow channel is theoretically more critical to the Doppler effect. However, in practice, at speeds up to 150 km/h, both channels perform similarly (the main limitation is channel coherence time).

4.2.5 Bandwidth Selection Recommendations by Scenario

Scenario	Recommended Bandwidth	Justification
Fixed point-to-point, maximum range	4 MHz	Priority is range, speed is secondary
Fixed point-to-point, HD/4K video transmission	8 MHz	Priority is throughput, range is sufficient
Moving object (vehicle) – fixed station, at coverage edge	4 MHz	Higher sensitivity partially compensates for fading
Moving object – moving object (vehicle-vehicle), urban	8 MHz	Fast obstacles (buildings) require signal level margin, but better path resolution; the real range gain from 4 MHz is negated by multipath
Moving object – moving object (vehicle-vehicle), highway (LOS)	4 MHz	Line-of-sight, little interference; range gain becomes decisive
UAV (drone) – ground station, long distance	4 MHz	Higher sensitivity is more important than speed; telemetry requires low throughput
UAV (drone) – ground station, video transmission from drone	8 MHz	Video requires high speed, and the drone is usually within line-of-sight, so range is already sufficient

> **General rule:** First determine the main criterion. If you need to ensure maximum range (communication at the edge of the coverage area) – choose the smaller bandwidth (4 MHz). If the main requirement is throughput (video, large files) and range is already sufficient – choose the larger bandwidth (8 MHz).

4.2.6 Special Note on MIMO

In all the above patterns, it is assumed that MIMO (2×2) mode remains enabled. If MIMO is disabled, receiver sensitivity improves by an additional 1–3 dB (since all transmitter power is directed to one antenna rather than split between two). However, this loses interference immunity in multipath conditions. For moving objects in urban environments, MIMO remains recommended, even if bandwidth has to be slightly reduced to compensate for the worse sensitivity.

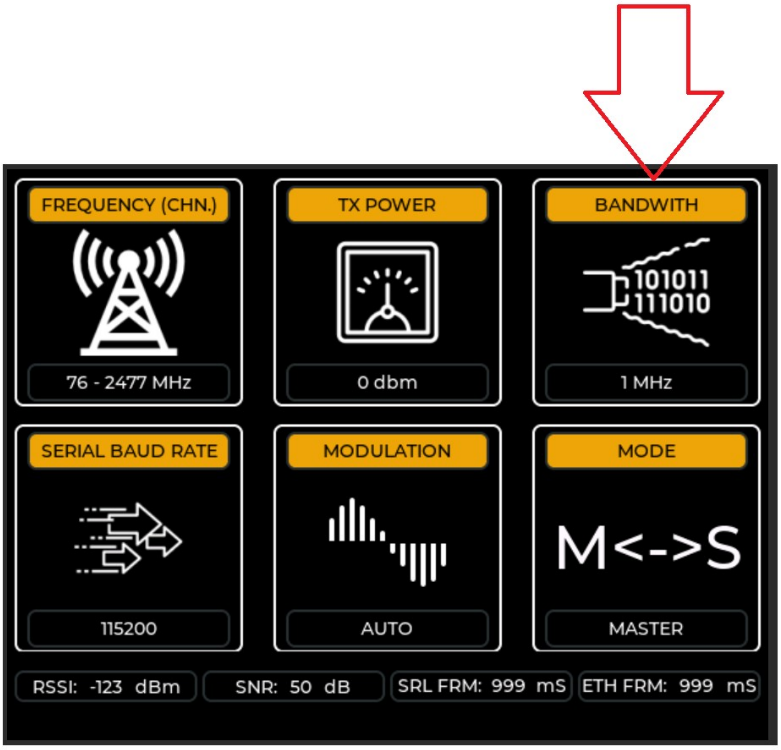
4.2.7 BANDWIDTH Configuration in UI

To change the Bandwidth:

1.Activate the device screen.
2.Navigate to the **«BANDWIDTH»** menu.
3.Select the desired channel bandwidth from the list.
4.Press:

•**«SAVE»** – to save and apply the parameter.
•**«CANCEL»** – to return to the main page without changes.

After pressing **«SAVE»**, the save and update procedure will begin, lasting several seconds. Upon completion, the interface will automatically return to the main screen, where the updated parameters will be read and displayed.



FREQUENCY (CHN.): 76 - 2477 MHz
TX POWER: 0 dbm
BANDWITH: 1 MHz
SERIAL BAUD RATE: 115200
MODULATION: AUTO
MODE: MASTER
RSSI: -123 dBm
SNR: 50 dB
SRL FRM: 999 mS
ETH FRM: 999 mS

4.2.8 Important: Bandwidth Must Be Identical on All Devices

> **Important:** The **Bandwidth** parameter must be **identical on all devices** of the same radio network (MASTER, SLAVE, REPEATER, MESH). Mismatch of this parameter will make it impossible to establish a connection between devices.

4.3 Modulation Type Selection

The choice of modulation scheme directly determines three key communication parameters:

•**Throughput (useful data rate)**
•**Receiver sensitivity** (minimum signal level for stable operation)
•**Interference immunity and maximum range**

In **2×2 MIMO** mode (two antennas for reception and transmission), MRC, ML-decoding, and LDPC error correction technologies are used. This provides better interference immunity compared to single-channel mode.

Below are the technical parameters for two typical channel bandwidths: 8 MHz (higher speed) and 4 MHz (better sensitivity). The ordering is by increasing modulation complexity.

4.3.1 Parameter Table for 8 MHz (MIMO 2×2)

Modulation and Coding	Useful Throughput (iPerf), Mbps	Sensitivity (MRC), dBm	Relative Range
BPSK 1/2	3.0	-99.5	Maximum
QPSK 1/2	5.9	-98.0	Very high
QPSK 3/4	8.8	-96.0	High
16QAM 1/2	11.6	-92.0	Moderate
16QAM 3/4	17.1	-90.0	Limited
64QAM 2/3	22.8	-85.0	Low
64QAM 3/4	25.5	-83.5	Very low
64QAM 5/6	27.8	-81.0	Minimal

> **Note:** Transmitter power in all modes – up to +30 dBm (1 W) total across two antenna ports (each port receives ~27 dBm).

4.3.2 Parameter Table for 4 MHz (MIMO 2×2)

Modulation and Coding	Useful Throughput (iPerf), Mbps	Sensitivity (MRC), dBm	Relative Range
BPSK 1/2	1.51	-102.5	Maximum (+3 dB vs 8 MHz)
QPSK 1/2	2.98	-101.0	Very high
QPSK 3/4	4.4	-99.0	High
16QAM 1/2	5.8	-95.5	Moderate
16QAM 3/4	8.6	-93.0	Limited
64QAM 2/3	11.4	-88.0	Low
64QAM 3/4	12.8	-86.0	Very low
64QAM 5/6	14.0	-83.5	Minimal

Conclusion: Narrowing the channel from 8 MHz to 4 MHz roughly halves the maximum speed but improves sensitivity by 2–3 dB, allowing operation over longer distances or under weaker signal conditions.

4.3.3 Automatic Modulation Detection Mode (Auto Rate)

The device's hardware implementation supports automatic rate selection based on measured SNR (Signal-to-Noise Ratio). The recommended threshold for reliable communication is an SNR of at least 20 dB. If SNR falls below this, the auto-rate mechanism lowers the modulation (e.g., from 64QAM to QPSK), maintaining the connection at the cost of speed.

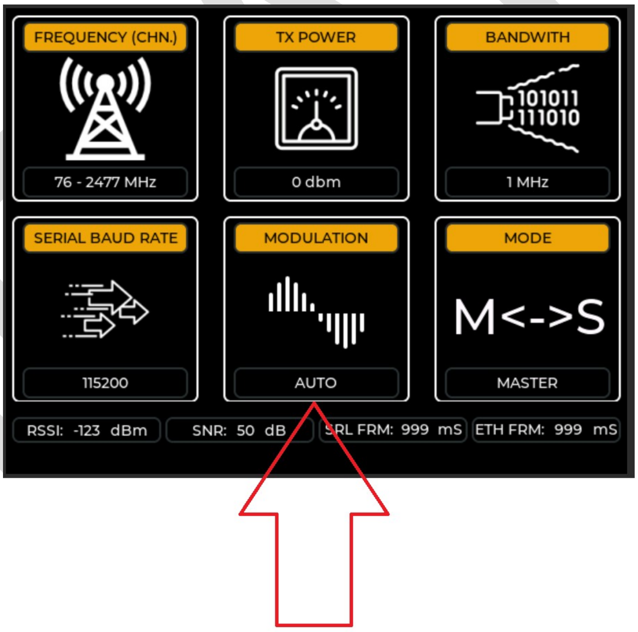
4.3.4 MODULATION Configuration in UI

To change the modulation mode:

1.Activate the device screen.
2.Navigate to the **«MODULATION»** menu.
3.Select the desired modulation from the list.
4.Press:

•**«SAVE»** – to save and apply the parameter.
•**«CANCEL»** – to return to the main page without changes.

After pressing **«SAVE»**, the save and update procedure will begin, lasting several seconds. Upon completion, the interface will automatically return to the main screen, where the updated parameters will be read and displayed.



FREQUENCY (CHN.) 76 - 2477 MHz
TX POWER 0 dbm
BANDWITH 1 MHz
SERIAL BAUD RATE 115200
MODULATION AUTO
MODE MASTER
RSSI: -123 dBm
SNR: 50 dB
SRL FRM: 999 mS
ETH FRM: 999 mS

4.3.5 Important: MODULATION Must Be Identical on All Devices (or AUTO)

> **Important:** The **MODULATION** parameter must be **identical on all devices** of the same radio network, or set to **«AUTO»** mode. Mismatch of this parameter will make it impossible to establish a connection between devices.

4.4 Transmitter Power Selection (TX Power)

Intuitively, it may seem that the higher the transmitter power, the better the communication. However, at short distances (from a few meters to a few hundred meters), excessive power not only fails to improve but actually significantly degrades the performance of the radio system. This phenomenon is often ignored by beginners but is critically important for professional applications.

4.4.1 Physical Mechanisms of Negative Effects of Excessive Power

Receiver input stage saturation (receiver saturation). Each receiver has a maximum input signal level that it can process without distortion (typically -20 to -10 dBm for most industrial radio modems). When this level is exceeded, the input amplifiers (LNA) enter saturation mode, where they cease to operate linearly. Consequences:

•Sharp increase in non-linear distortion coefficient (intermodulation distortion, harmonics)
•Reduction in the actual receiver gain (signal compression)
•Demodulation errors even with an "excellent" signal level

Practical example. With a transmitter power of +30 dBm, a distance of 10 meters, antenna gain of 5 dBi (both sides), and typical free-space loss of about 52 dB, the signal level at the receiver input will be:

P_rx = P_tx + G_tx – L_free + G_rx = 30 + 5 – 52 + 5 = –12 dBm

This value exceeds the saturation threshold of many receivers (typically -20 dBm). As a result, SNR may be excellent (e.g., 50 dB), but due to non-linear distortion, data packets are lost or have a high error percentage.

Receiver desensitization by strong signal. Even if the signal is not strong enough to cause saturation, it can shift the operating point of the receiver's active elements, reducing its sensitivity to weak signals. This is especially relevant for systems with Automatic Gain Control (AGC) – a strong signal forces the AGC to reduce the receiver gain, which impairs sensitivity to other, possibly important, signals.

Intermodulation distortion in active elements of the path. When two or more signals pass through a non-linear element (amplifier, mixer), intermodulation products of the form f_im = m·f1 ± n·f2 arise. Some of these may fall into the receiver's operating band, creating non-existent "phantom" signals or raising the noise floor.

Excessive electromagnetic stress on analog components (blocking effect). In the case of a very strong signal (around 0 dBm and above), the receiver's input RF components can enter a mode where they are completely "overwhelmed" and do not respond to changes in the input signal. After such a signal ceases, the receiver may not immediately resume normal operation (a memory effect associated with charge on capacitors).

4.4.2 Practical Symptoms of Excessive Power

When testing radio modems at close range with maximum power, the following characteristic symptoms are observed:

Symptom	Typical Cause	How to Differentiate from Other Problems
Connection is established, but speed is very low (auto-rate selects lowest modulation)	Receiver saturation → high BER → system lowers modulation to maintain link	If at the same distance, after reducing power, speed increases – the problem is precisely excessive power
Sporadic packet loss ("jerks") with excellent SNR (>30 dB)	Non-linear effects causing burst errors	SNR reading is high (above 30 dB), but RSSI is suspiciously high (>-30 dBm)
When moving away from the transmitter, communication does not fade gradually but suddenly "drops"	Receiver was in saturation; after exiting saturation, the signal level is already insufficient to maintain the link	Measure RSSI at different distances; if at close range it is above -25 dBm – this is a symptom
Signal level indicators (RSSI) show all or almost all bars, but link quality (BER) is poor	Excessive power distorting the signal	Compare RSSI and SNR; if RSSI > -20 dBm with SNR > 40 dB, but the link is unstable – this is it

> **Sound analogy:** imagine you are talking to a person standing 1 meter away from you. If you shout as loud as you can, your voice will be distorted (non-linear effects in the microphone and amplifier), and the listener will hear not words but "wheezing and crackling." A quieter conversation will be much more intelligible. The same happens with a radio signal.

4.4.3 Method for Selecting Minimum Sufficient Power

The correct approach is to set the power not to the maximum possible, but to the minimum sufficient level to ensure the required reliability (with a fade margin of 15–20 dB). This avoids saturation problems, reduces power consumption, and lowers mutual interference with neighboring systems.

Step 1. Calculate Expected Path Loss

Use the free-space model (for LOS) or a model for terrestrial paths (e.g., Lee, Okumura-Hata). For free-space conditions:

L_free (dB) = 20·log10(d) + 20·log10(f) + 32.44

where d [km], f [MHz]

Example: d = 0.01 km (10 m), f = 2450 MHz
L_free = 20·log10(0.01) + 20·log10(2450) + 32.44 = (-40) + (20·3.389) + 32.44 = (-40) + 67.78 + 32.44 = 60.22 dB

Step 2. Calculate Expected Signal Level at Receiver Input

P_rx (dBm) = P_tx (dBm) + G_tx (dBi) – L_free (dB) – L_cable_tx (dB) + G_rx (dBi) – L_cable_rx (dB)

where:

- P_tx – transmitter power (sought or given)
- G_tx, G_rx – antenna gains (e.g., 5 dBi each)
- L_cable – losses in cables and connectors (typically 1–3 dB per side)

Step 3. Set the Minimum Acceptable Signal Level

The basis is the receiver sensitivity S_rx for the selected modulation from the technical specifications, to which the required Fade Margin (FM) is added to compensate for fading, component aging, weather effects, etc.

P_rx_min (dBm) = S_rx (dBm) + FM (dB)

Recommended FM values:

- Fixed systems with LOS, open area: 10–15 dB
- Urban conditions, moderate obstacles: 15–20 dB
- Moving objects, complex terrain: 20–25 dB

Step 4. Determine Required Transmitter Power

Express P_tx from the Step 2 formula, substituting P_rx_min for P_rx:

P_tx_needed = P_rx_min – G_tx + L_free + L_cable_tx – G_rx + L_cable_rx

Step 5. Rounding and Adjustment

Convert the obtained value (in dBm) to milliwatts (if necessary) and round to the nearest available adjustment step (typically 1 dB). Important:

- If the calculated P_tx_needed is lower than the minimum available power (e.g., 7 dBm), set the minimum possible.
- If the calculated P_tx_needed is higher than the maximum (30 dBm) – the selected modulation is unrealistic for the given distance; you need to reduce speed requirements (choose a more sensitive modulation).

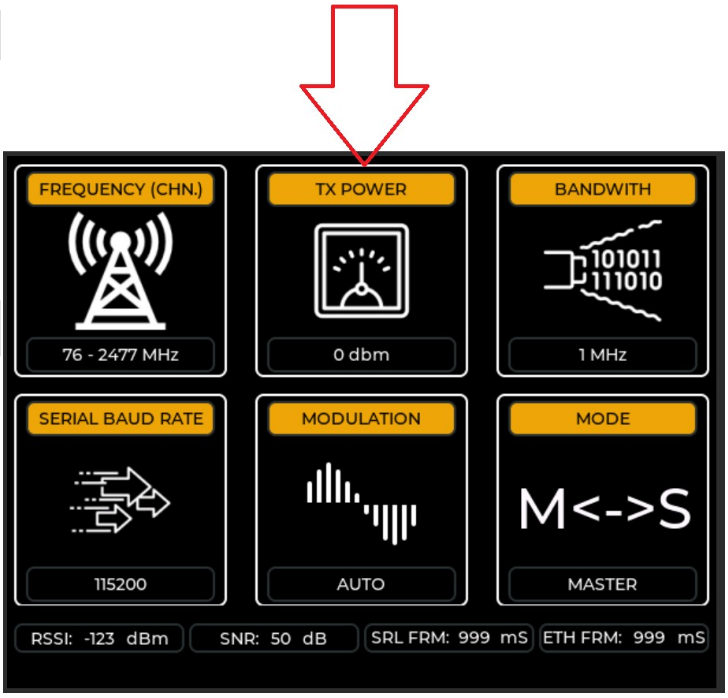
4.4.4 TX POWER Configuration in UI

To change the transmitter power:

1. Activate the device screen.
2. Navigate to the **«TX POWER»** menu.
3. Select the desired transmitter power from the list.
4. Press:

- **«SAVE»** – to save and apply the parameter.
- **«CANCEL»** – to return to the main page without changes.

After pressing **«SAVE»**, the save and update procedure will begin, lasting several seconds. Upon completion, the interface will automatically return to the main screen, where the updated parameters will be read and displayed.



FREQUENCY (CHN.): 76 - 2477 MHz
TX POWER: 0 dbm
BANDWITH: 1 MHz
SERIAL BAUD RATE: 115200
MODULATION: AUTO
MODE: MASTER

RSSI: -123 dBm | SNR: 50 dB | SRL FRM: 999 mS | ETH FRM: 999 mS

4.4.5 Additional recommendations:

•**Mutual interference with neighboring systems.** Excessive power creates interference for other radio systems operating in the same or adjacent bands. This is especially relevant in dense urban radio environments or when operating multiple independent systems at the same site (e.g., several radio modems on the same tower).

•**Power consumption.** The relationship between transmitter power and current consumption is nearly linear. Switching from 20 dBm (100 mW) to 30 dBm (1 W) increases transmitter current consumption several times. For battery-powered systems (UAVs, field radio stations), this is critical.

•**Recommended procedure when configuring a new link:**

1.Set the minimum possible transmitter power
2.Slowly increase power while observing SNR and throughput
3.Find the point after which further power increase does not improve SNR and speed (or degrades them due to saturation)
4.Add a small margin (e.g., +3 dB) to compensate for component degradation over time
5.Fix this value as the operating power

This approach guarantees an optimal balance between reliability, energy efficiency, and electromagnetic compatibility.

5. Antennas and Their Impact on Radio Communication

Antenna selection is one of the most critical decisions when building a radio link, especially for moving objects. The antenna converts an electrical signal into an electromagnetic wave and determines the direction and efficiency with which this energy is radiated.

5.1 Antenna Gain (dBi) and Radiation Pattern

Absolute gain (dBi). Antenna gain is measured in **dBi** – decibels relative to an isotropic radiator (a point source that radiates uniformly in all directions). The higher the dBi value, the more energy is concentrated in a specific direction by narrowing the radiation pattern.

> **Fundamental trade-off:** Gain is achieved not by "amplifying" the signal in a physical sense, but by redistributing power. The energy that would be radiated in all directions by an isotropic antenna is directed into the desired sector. This is like a reflector in a flashlight – the total luminous flux does not change, but the illumination within the spot increases.

Directivity. Characterizes how many times the power flux density in the direction of maximum radiation exceeds the average density at the same distance from an isotropic radiator (with the same input power).

5.2 Omnidirectional Antennas

Operating principle. Omnidirectional antennas are typically vertical whips (radiators) of various lengths: quarter-wave, half-wave, or stacked designs (e.g., collinear). Their radiation pattern in the horizontal plane is a circle (uniform 360° radiation), while in the vertical plane it resembles a "donut" or flattened sphere.

Typical gain:

•**Quarter-wave whip (λ/4):** ≈ 0–2 dBi
•**Half-wave dipole (λ/2):** ≈ 2–3 dBi
•**Collinear antennas (2–5 elements):** 3–6 dBi
•**High-gain collinear (up to 10 sections):** 8–10 dBi (trade-off – flattening of the vertical pattern)

Radiation pattern:

•Horizontal plane: nearly uniform (deviation ±1–2 dB)
•Vertical plane: the main lobe is perpendicular to the antenna axis, at a small angle to the horizon. As gain increases, this lobe narrows, becoming "closer to the plane"

Advantages:

1.No need to aim at the correspondent – ideal for moving objects and stations operating with multiple directions
2.Simple installation and maintenance
3.Insensitive to object rotation around the vertical axis (important for vehicles, boats, UAVs)
4.Ability to operate in point-to-multipoint networks

Disadvantages:

1.Lower gain compared to directional antennas of the same size
2.Energy radiates in all directions, including "unnecessary" directions (up, down, backward), which reduces range and contributes to interference with other systems
3.Vulnerable to interference from all directions (noise, jamming)
4.At the same transmitter power, provide shorter range than directional antennas

Practical range example. Using omnidirectional antennas with 5 dBi gain at both ends, transmitter power +30 dBm, and receiver sensitivity -99 dBm (QPSK 1/2), the maximum range in free space (no obstacles) is approximately **6–8 km** (depending on mounting height and terrain). In urban conditions, due to reflections and shadowing, the actual range drops to 1–3 km.

5.3 Directional Antennas

Operating principle. Directional antennas concentrate energy into a relatively narrow sector through design features: the use of multiple radiators (antenna arrays), reflectors (metal screens), or dielectric lenses. The most common types:

•**Yagi–Uda (wave channel):** a series of parallel radiators on a boom – one active, others passive (directors and reflector). Gain 6–15 dBi, beamwidth 30–60°
•**Horn antenna:** used primarily at very high frequencies (>5 GHz)
•**Parabolic dish:** a reflector in the form of a paraboloid of revolution, with a feed at the focus. Gain up to 30–40 dBi, beamwidth down to 3–5°
•**Patch antenna (planar):** flat antenna with microstrip elements, compact, gain 5–20 dBi, widely used in MIMO systems
•**Rhombic antenna:** broadband, gain up to 10–15 dBi, less commonly used

Radiation pattern: has a pronounced main lobe and side lobes (usually significantly weaker). The width of the main lobe at the -3 dB level defines the angular sector within which the antenna transmits/receives with no more than 3 dB loss relative to the maximum.

Advantages:

1.High gain with relatively small dimensions (especially for Yagi antennas)
2.Significantly longer communication range at the same transmitter power
3.Better interference immunity – side lobes "reject" interference from unwanted directions
4.Ability to operate at lower power to achieve the same range (energy savings)

Disadvantages:

1.Require precise aiming at the correspondent (angular position is critical)
2.Unsuitable for moving objects without direction tracking systems
3.If misaligned, perform worse than omnidirectional antennas
4.Large dimensions at high gain
5.In simple implementations (Yagi) – lower bandwidth

Practical range example. If omnidirectional antennas with 5 dBi gain are replaced with Yagi directional antennas with 12 dBi gain (both ends), the system gain increases by 14 dB (from 5 dBi to 12 dBi is +7 dB per side, total +14 dB). Under the same conditions, the maximum range in free space increases approximately 5 times (each +6 dB doubles free-space range). That is, from 6–8 km to **30–40 km** at the same power. In practice, due to terrain and Earth's curvature, the actual range rarely exceeds 25–30 km, but this is still a dramatic improvement.

5.4 Sector Antennas (Intermediate Type)

Sector antennas occupy an intermediate position between omnidirectional and highly directional antennas. They radiate into a sector from 60° to 120° with a gain of 8–18 dBi. They are often used at base stations in point-to-multipoint systems to serve multiple subscribers in a specific direction without wasting energy on 360° coverage.

5.5 Antenna Selection for Moving Objects

Vehicle ↔ Fixed station:

•**On the moving object (vehicle): omnidirectional antenna** (5–8 dBi) or a combination of multiple omnidirectional antennas for MIMO.
•**At the fixed station: directional antenna** (Yagi 12–15 dBi, patch 10–20 dBi, or parabolic up to 25–30 dBi) to maximize range. If a zone is being served rather than a specific direction – a sector antenna.
•**Explanation:** The fixed station can be aimed once during installation, while the vehicle rotates arbitrarily, so an omnidirectional antenna is required on the vehicle.

Vehicle ↔ Vehicle:

•**Optimal choice: omnidirectional antennas on both vehicles.** Neither object has a fixed position, so directional antennas are impossible without complex automatic tracking systems.
•**Drawback:** Range will be limited because the gain of omnidirectional antennas is low. This is a fundamental limitation of the moving-moving scenario.
•**Exception:** If vehicles are moving in a convoy and the direction between them is relatively stable, antennas with weak directivity (e.g., 60–90° patch) aimed along the convoy can be used. This requires precise mounting and maintaining body orientation.

UAV ↔ Ground station:

•**On the ground: directional antenna** (patch or parabolic) – the operator aims at the flight zone.
•**On the UAV: omnidirectional** (with circular polarization) because the drone's orientation constantly changes (roll, pitch). Circular polarization is less sensitive to antenna rotation.

5.6 Polarization (an additional important factor)

Linear (vertical / horizontal). Omnidirectional whips radiate vertical polarization. For maximum power transfer, both antennas must have the same polarization. When a vehicle moves, polarization is preserved only on a flat road – on inclines/declines additional losses occur.

Circular (LHCP / RHCP). Better suited for moving objects (especially UAVs), as losses under arbitrary orientation do not exceed 3 dB, whereas with linear polarization, a 90° rotation can cause signal fade of 20–30 dB. **Disadvantage:** circularly polarized antennas have slightly lower gain for the same dimensions and higher cost.

6. Radio Communication on Moving Objects

The operation of a radio channel under moving conditions (vehicle-to-vehicle, vehicle-to-fixed station) involves a number of specific problems that do not arise or have less impact when operating with stationary objects. Below are the main physical effects and practical aspects of their compensation.

6.1 Doppler Effect and Intersymbol Interference

Physical nature. When the transmitter and receiver move relative to each other, the frequency of the received signal differs from the transmitted frequency. The frequency shift (Doppler shift) is determined by the relative speed of approach or recession and the operating frequency:

$\Delta f = (v / c) \cdot f_0$

where v – relative speed (m/s), c – speed of light, f_0 – carrier frequency.

Implications for communication. At speeds of 60–120 km/h at 2.4 GHz, the Doppler shift can reach tens to hundreds of Hertz. This leads to a phenomenon known as frequency spreading: the signal at the receiver is "smeared" across the frequency spectrum. In OFDM-based systems (which form the basis of most modern radio modems), this causes loss of orthogonality between subcarriers, generating Intersymbol Interference (ISI) and Inter-Carrier Interference (ICI).

> **Practical manifestation:** at speeds exceeding 80–100 km/h, even with sufficient signal level, the Bit Error Rate (BER) increases sharply, perceived as "dropouts" in communication, reduced data throughput, or periodic reconnections.

Special considerations for vehicle-to-vehicle scenario. In this case, the relative speed is the sum of the speeds of both vehicles. For example, when moving towards each other at 60 km/h each, the relative speed is 120 km/h. Accordingly, the Doppler shift will be twice as large as in the vehicle-to-fixed-station scenario. Furthermore, channel estimation and tracking of its changes over time become more difficult.

6.2 Multipath Propagation and Fast Fading

Physical nature. In urban conditions, the signal propagates not only via the direct path but also reflects from buildings, other vehicles, road surfaces, and trees. As a result, multiple copies of the signal arrive at the receiver with different delays, phases, and amplitudes. As the vehicle moves, the geometry of these paths constantly changes.

Fast fading. Interference between paths causes the amplitude of the composite signal to vary by tens of decibels when the vehicle moves only half a wavelength (for 2.4 GHz – about 6 cm). This phenomenon is called fast fading. In the absence of a direct path (e.g., in dense urban areas), the amplitude distribution follows the Rayleigh distribution; in the presence of a strong direct signal, it follows the Rice distribution.

Practical manifestation: even when the vehicle is stationary but the engine is running, body vibration can cause signal level fluctuations. When moving, fast fading makes the signal level "noisy" and unstable, complicating the operation of automatic rate control systems (ARQ, adaptive modulation).

6.3 Shadowing Effect (Slow Fading)

In addition to fast fading, there is the effect of shadowing – a change in the average signal level when passing behind large obstacles (buildings, hills, forest belts). Such variation follows a log-normal distribution with a standard deviation of 3–4 dB under typical conditions.

Practical manifestation: as the vehicle moves, it may enter "dead zones" behind large objects where communication is lost completely, and then regain signal when exiting the shadow. This requires radio modems to have the ability to quickly re-synchronize after signal loss.

6.4 Antenna Challenges: Mutual Influence and Space Constraints

Physical limitation. On modern mobile communication points, a large number of antennas are placed: for cellular communication (2G/3G/4G/5G), satellite navigation (GPS/GLONASS), satellite radio (SiriusXM), radio communication (UHF/VHF), as well as for V2X systems and drone communication. All these antennas must operate simultaneously, sometimes in closely spaced bands.

Implications for the radio channel. When antennas are placed densely, mutual coupling occurs – energy from one radiator enters the input of another, which can cause intermodulation distortion in receivers. This directly affects channel throughput: with low isolation between antennas, the gain from MIMO is reduced or completely negated.

> **Recommendation from experience:** radio transceivers should be placed on the roof (the metal plane acts as a "ground"), not inside the cabin or trunk of the vehicle. The distance between MIMO antennas should be at least half a wavelength (≈60 mm for 2.4 GHz). To reduce mutual coupling, it is advisable to use a combination of vertical and horizontal polarization or circular polarization.

6.5 Performance Dependence on Speed and Modulation Type

Different modulation types have different resistance to Doppler shift. Higher modulations (64QAM) require more stable channel estimation than BPSK/QPSK.

Scenario	Typical Speed	Doppler Shift (2.4 GHz)	Recommended Modulation
Vehicle–fixed station (highway)	60–90 km/h	≈130–200 Hz	QPSK–16QAM (depending on SNR)
Vehicle–fixed station (city)	30–60 km/h	≈70–130 Hz	16QAM–64QAM (with good LOS)
Vehicle–vehicle (oncoming)	up to 180 km/h	up to 400 Hz	BPSK–QPSK (auto-rate fallback)

At speeds exceeding 120 km/h, even QPSK may operate unstably due to rapid channel changes that exceed the tracking capabilities of the system.

6.6 Configuration Recommendations for Moving Objects

1. **Antenna orientation.** For the vehicle-to-vehicle scenario, antennas with circular polarization (LHCP/RHCP) are recommended. They are less sensitive to mutual tilting of vehicles (e.g., when driving on a hill) and provide more predictable attenuation under arbitrary body orientation.
2. **Bandwidth selection.** Narrowing the channel from 8 MHz to 4 MHz improves receiver sensitivity by ≈2–3 dB, which partially compensates for fading losses. On high-speed highways, it is advisable to use 4 MHz.
3. **Auto rate configuration.** It is recommended to enable Auto Rate in the range from BPSK 1/2 to 16QAM 3/4 (excluding 64QAM). This prevents attempts to switch to high modulations under rapidly changing channel conditions, which would be unstable anyway.
4. **Using MIMO in challenging conditions.** In urban environments with multipath, MIMO performs better than single-channel mode, despite slightly worse sensitivity. On an open highway (LOS), the MIMO gain is smaller but still useful for combating Rayleigh fading.

7. Comparison of 2.4 GHz and 900 MHz Bands

Understanding the physical differences between the 2.4 GHz band (2.402–2.478 GHz) and the 900 MHz band (902–928 MHz) is critical for proper equipment selection for specific operating conditions. Each of these bands has fundamental advantages and disadvantages that directly affect range, penetration capability, antenna installation requirements, and global applicability.

7.1 Fundamental Difference: Free-Space Path Loss

Physical nature. According to the Friis equation for free-space transmission, path loss is a function of the square of distance and the square of frequency. This means that, all else being equal, the higher the frequency, the greater the attenuation the radio wave experiences over the same distance. Loss is calculated by the formula:

$$\mathbf{L = 20 \cdot \log_{10}(4\pi r/\lambda)\ dB}$$

where r – distance, λ – wavelength.

Quantitative difference. For the 900 MHz band, the wavelength is approximately 0.33 meters; for the 2.4 GHz band, it is approximately 0.125 meters. Due to the shorter wavelength, the 2.4 GHz signal experiences 8.5 dB higher loss over the same distance compared to 900 MHz.

> **Practical consequence:** An 8.5 dB increase in loss means that the maximum communication range in the 900 MHz band is approximately 2.7 times greater than in the 2.4 GHz band, with the same transmitter power and receiver sensitivity.

7.2 Comparison of Key Characteristics

Parameter	900 MHz Band	2.4 GHz Band
Wavelength	≈ 33 cm	≈ 12.5 cm
Typical LOS range (open area)	up to 7–20 miles (≈11–32 km)	up to 3–10 miles (≈5–16 km)
Typical indoor range	up to 1500 ft (≈450 m)	up to 600 ft (≈180 m)
Loss through concrete wall	≈ 10 dB	≈ 20 dB
Antenna height requirements (Fresnel zone)	Higher (larger zone radius)	Lower (smaller zone radius)
Typical receiver sensitivity	down to -110 dBm	down to -105 dBm
Power consumption (receive)	≈ 70 mA	≈ 90 mA
Global availability	Limited (North America, Australia)	License-free worldwide
Typical antenna size (λ/4)	≈ 8.25 cm	≈ 3.1 cm

Data based on comparison of typical industrial radio modems.

7.3 Penetration Through Obstacles

Buildings and structures. Lower frequency signals (900 MHz) have better ability to penetrate building structures compared to 2.4 GHz. This is because longer radio waves interact less with materials that have inhomogeneities comparable to the wavelength. For example, a 700–900 MHz band signal loses approximately 15 dB less when passing through walls than a 2.5 GHz signal.

Foliage and vegetation. Both bands experience significant attenuation when passing through dense vegetation, but for 2.4 GHz this effect is significantly more critical. Studies show that even at a depth of 80 meters in a bamboo forest, a 2.4 GHz signal can still be received with sufficient antenna height (3 m), but attenuation is substantial. In most cases, 2.4 GHz communication through dense vegetation without line-of-sight is practically impossible at distances exceeding 100–200 meters.

Humidity and precipitation. Higher frequency signals are more sensitive to weather degradation. Heavy rain at 10 GHz causes attenuation of about 0.1 dB/km, while at 40 GHz it is already 5 dB/km. For the 900 MHz and 2.4 GHz bands, this effect is negligible and is usually not considered in engineering calculations.

7.4 Fresnel Zone

Concept. The Fresnel zone is an ellipsoidal region of space between the transmitting and receiving antennas within which the main part of the radio wave energy is concentrated. Even in the presence of line-of-sight (LOS), if a significant part of this zone is blocked by obstacles (ground, trees, buildings), the signal level can drop significantly.

Fresnel zone radius calculation. The radius of the first Fresnel zone at its widest point is determined by the formula:

$r = \sqrt{(\lambda \cdot d_1 \cdot d_2 / (d_1 + d_2))}$

where λ – wavelength, d_1 and d_2 – distances from each antenna to the measurement point.

Practical example. For a distance of 1.6 km (1 mile) at the widest point of the Fresnel zone:

- **2.4 GHz band ($\lambda \approx 0.125$ m):** zone radius ≈ 7.1 meters
- **900 MHz band ($\lambda \approx 0.33$ m):** zone radius ≈ 11.6 meters

This means that to ensure Fresnel zone clearance (no more than 40% blockage), 900 MHz band antennas must be mounted significantly higher above ground and obstacles: approximately 46 meters over a 32 km distance versus 15 meters for 2.4 GHz. In rough terrain, this can be a significant problem for lower frequency systems.

7.5 Antenna Constraints

Antenna dimensions. Wavelength directly determines the minimum dimensions of effective antennas. A quarter-wave whip for the 900 MHz band has a length of ≈ 8.25 cm, while for 2.4 GHz it is ≈ 3.1 cm.

Spatial diversity for MIMO. For operation in MIMO (2×2) mode, antenna spacing of at least half a wavelength is important to ensure uncorrelated channels. For the 900 MHz band, this requires a distance of at least ≈ 16.5 cm between antennas, which imposes constraints on the minimum size of the device or mounting panel. For 2.4 GHz, a distance of ≈ 6 cm is sufficient, which is much easier to implement in compact devices.

7.6 Regulatory Constraints (global availability)

The most important practical difference is the global availability of the bands. The 900 MHz band is license-free only in North America (FCC Part 15) and Australia. In most other regions of the world (Europe, Asia, Africa), this band is occupied by cellular communication (GSM) or other licensed services.

The 2.4 GHz band, in contrast, is a global ISM band (Industrial, Scientific, Medical) and is permitted for license-free use in virtually all countries of the world. This makes it the only viable option for equipment operated outside North America and Australia.

7.7 Band Selection Recommendations

Conditions / Scenario	Recommended Band	Justification
Maximum range in open area (North America)	900 MHz	2.7 times greater range at same power
Communication through building walls / dense vegetation	900 MHz	Better penetration through obstacles
Fixed systems with low antenna heights (ground-level)	900 MHz	Less critical to antenna height (although Fresnel zone is larger, the signal better bends around terrain)
Operation outside North America and Australia	2.4 GHz	900 MHz is prohibited or licensed in most countries
Compact devices, portable devices, UAVs	2.4 GHz	Ability to use small-form-factor antennas
Latency-sensitive systems (video conferencing, VoIP)	2.4 GHz	Larger available bandwidth and potentially higher speeds
Operation in dense urban environments (multipath)	2.4 GHz	with MIMO – better utilizes reflected signals

Important note on throughput: Although modulation schemes can provide comparable speeds within a single channel, the total available bandwidth in the 2.4 GHz band is generally larger than in the 900 MHz band. This allows the implementation of wider channels (8 MHz and above) and achieving higher peak data rates, which is critical for high-definition video streaming. For telemetry and small data volume transmission, the speed difference is not decisive.

Appendix C. Glossary

This glossary defines key technical terms and abbreviations used throughout this document.

BER (Bit Error Rate)

The ratio of incorrectly received bits to the total number of transmitted bits, expressed as a decimal or exponent (e.g., 10^{-6}). BER is a direct measure of link quality. For reliable communication, typical targets are BER ≤ 10^{-6} (one erroneous bit per million). Higher BER indicates poor SNR, interference, or hardware issues.

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dBi (Decibels relative to isotropic radiator)

A unit of antenna gain referenced to an ideal isotropic radiator (a theoretical point source that radiates uniformly in all directions). An antenna with 3 dBi gain radiates twice the power density in its preferred direction compared to an isotropic antenna. Higher dBi values indicate more directional radiation.

Doppler Effect / Doppler Shift

The change in frequency of a wave when the transmitter and receiver move relative to each other. At 2.4 GHz, a relative speed of 100 km/h produces a Doppler shift of approximately 220 Hz. This can cause intersymbol interference (ISI) and inter-carrier interference (ICI) in OFDM systems, degrading performance at high speeds.

Fade Margin (FM)

A safety margin added to the receiver sensitivity to account for signal fading due to multipath, weather, component aging, and other unpredictable factors. Typical values: 10–15 dB for fixed LOS links, 15–20 dB for urban conditions, 20–25 dB for moving objects. Higher fade margin increases reliability but requires higher transmit power or shorter distance.

Fast Fading (Multipath Fading)

Rapid fluctuations in received signal amplitude caused by interference between multiple signal paths (direct and reflected). At 2.4 GHz, moving a receiver by only 6 cm can change signal level by tens of decibels. Fast fading is a major challenge for moving objects.

Fresnel Zone

An ellipsoidal region of space between transmitting and receiving antennas where most of the RF energy propagates. For reliable communication, at least 60% of the first Fresnel zone must be clear of obstacles. If blocked, additional loss of 3–20 dB occurs.

ISI (Intersymbol Interference)

A phenomenon where one transmitted symbol interferes with subsequent symbols due to multipath propagation (delayed copies of the signal) or Doppler-induced time spreading. ISI corrupts demodulation and limits data throughput, especially in high-speed mobile scenarios.

ISM Band (Industrial, Scientific, Medical)

Frequency bands reserved internationally for industrial, scientific, and medical applications. These bands are license-free but subject to power and duty cycle restrictions. The 2.4 GHz band (2.400–2.4835 GHz) is a global ISM band, while 900 MHz ISM availability is limited to North America and Australia.

LOS (Line of Sight)

A direct, unobstructed path between transmitting and receiving antennas. LOS is not strictly required for communication (reflected paths can work), but it provides the best possible signal strength and stability. For moving objects, maintaining LOS is often difficult.

MIMO (Multiple Input Multiple Output)

A wireless communication technology using multiple antennas at both transmitter and receiver to improve performance. MIMO 2×2 (two transmit, two receive antennas) provides two benefits: **spatial diversity** (combating multipath fading) and **spatial multiplexing** (increasing data rate). S-Radio MIMO uses MIMO 2×2 in all modes.

MRC (Maximal Ratio Combining)

A diversity combining technique used in MIMO receivers. Signals from multiple antennas are weighted and summed to maximize the output SNR. MRC improves sensitivity by 2–4 dB compared to single-antenna reception, especially in multipath conditions.

NLOS (Non-Line of Sight)

A propagation condition where the direct path between antennas is obstructed. Communication relies on reflected, diffracted, or scattered signals. NLOS scenarios (e.g., urban canyons, dense forests) typically have 10–30 dB higher path loss than LOS and are more sensitive to fading.

OFDM (Orthogonal Frequency Division Multiplexing)

A modulation scheme that transmits data over many closely spaced, orthogonal subcarriers. OFDM is robust against multipath interference and is used in most modern radio modems (including S-Radio MIMO). Its main weakness in mobile applications is sensitivity to Doppler shift, which breaks subcarrier orthogonality.

Path Loss (L)

The reduction in power density of an electromagnetic wave as it propagates through space, expressed in decibels (dB). For free space, path loss increases with distance and frequency. In real environments, obstacles, ground reflections, and atmospheric effects add extra loss.

Receiver Sensitivity

The minimum received signal power (in dBm) required for the receiver to achieve a specified BER (typically 10^{-6}). For S-Radio MIMO with 4 MHz bandwidth, sensitivity ranges from –102.5 dBm (BPSK 1/2) to –83.5 dBm (64QAM 5/6). Higher sensitivity (more negative) allows longer range but lower data rate.

RSSI (Received Signal Strength Indicator)

A measure of the power level of the received signal, typically expressed in dBm. RSSI is useful for link alignment and troubleshooting, but it does not distinguish signal from noise. For link quality assessment, SNR is more meaningful than RSSI alone.

Shadowing (Slow Fading)

Gradual changes in average signal level caused by large obstacles (buildings, hills, forest belts). Shadowing varies slowly as the transmitter or receiver moves (over meters to tens of meters), following a log-normal distribution with typical standard deviation of 3–4 dB.

SNR (Signal-to-Noise Ratio)

The ratio of desired signal power to background noise power, typically expressed in decibels (dB). Higher SNR enables higher modulations (e.g., 64QAM requires SNR > 22 dB, while BPSK works at SNR > 6 dB). SNR is the most reliable indicator of link quality.

Spatial Diversity

A MIMO technique where multiple antennas receive (or transmit) the same signal through slightly different paths. The receiver combines the copies to combat fading. Spatial diversity improves robustness, especially in multipath environments, but does not increase data rate.

Spatial Multiplexing

A MIMO technique where different data streams are transmitted simultaneously over multiple antennas. Spatial multiplexing increases data rate (up to 2× for 2×2 MIMO) but requires sufficiently uncorrelated channels (antenna spacing ≥ λ/2) and high SNR.

Two-Ray Ground Reflection Model

A propagation model that accounts for the direct ray and a single ground-reflected ray. For distances beyond the interference zone, path loss increases at 40 dB/decade (vs. 20 dB/decade for free space). This model is more accurate than free-space for low-height ground links but has significant uncertainty (±5–10 dB in real environments).

TX Power (Transmitter Power)

The output power of the transmitter, expressed in dBm or watts. S-Radio MIMO supports TX power from 7 dBm (≈5 mW) to 30 dBm (1 W) in 1 dB steps. Excessive power at short distances causes receiver saturation; minimum sufficient power is recommended.

Wavelength (λ)

The physical distance between successive peaks of an electromagnetic wave. For 2.4 GHz, λ ≈ 12.5 cm; for 900 MHz, λ ≈ 33 cm. Wavelength determines antenna dimensions (typical antennas are λ/2 or λ/4), Fresnel zone size, and spatial diversity requirements (antenna spacing ≥ λ/2).