# Enhancing Competitiveness, Resilience and Sustainability of Remote Farming, Forestry and Rural Areas through Holistic Assessment of Smart XG, Last-mile and Edge Solutions' Gains

## XGain – Technological Handbook

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# 1 Introduction

Digital transformation in rural and remote areas is no longer a distant aspiration—it is a pressing need. From sustainable agriculture to smart aquaculture and resilient rural communities, connectivity and computing technologies are the backbone of innovation. Yet, rural environments pose unique challenges: sparse populations, difficult terrain, and limited existing telco infrastructures. The XGain Knowledge Facilitation Tool (KFT) has been developed to help bridge that gap. The KFT enables users to obtain adapted infrastructure and technology mix proposals to implement their digital services and according to their needs, while being provided assessment for techno-economic and socio-environmental factors.

This handbook complements the KFT and serves as a practical and accessible guide for farmers, rural planners, local authorities, cooperatives, and engineers who are engaging with the KFT. Its purpose is to extend the information provided in the KFT via key radio and computing technologies that can be deployed in rural contexts, and to explain their capacities and limitations.

Rather than being a purely technical manual for the KFT on how to use it, this handbook elaborates on core concepts such as radio connectivity types (e.g., Wi-Fi, 4G/5G, LPWAN), computing approaches (e.g., edge and far-edge processing), virtualization, orchestration, and the use of renewable energy. It explains how these technologies can be used in combination through shared infrastructure models like neutral hosting, and how performance and sustainability can be evaluated using standard metrics and KPIs.

In doing so, the handbook aims to support users in understanding and applying digital technologies that can strengthen rural services, stimulate innovation, and promote inclusive growth.

Disclaimer: This document has been used partially with generative AI, feeding the XGain project's technical deliverables D3.1 and D3.2 to the model to produce the content.

# 2 Radio Technologies

Radio technologies are the invisible highways that allow data to travel through the air. They are what connect sensors in the field, your smartphone, or your drone to a broader digital network. They also can enable connections between buildings or relevant sites, when cabled solutions are not an option. In rural areas, choosing the right radio technology is critical — some technologies work better for long distances, while others are more suitable for short-range, high-speed connections.

The goal of this section is to help you understand the basic types of radio connectivity options available in the KFT, so that you can choose the best ones for your services and local conditions.

Common Radio Technology Overview

## 2.1 Types of Radio Access Technologies

Radio access network (RAN) technologies are used to connect end devices, such as smartphones, drones and sensors to a local service and/or the Internet. Some technologies are of generic use, such as Wi-Fi and cellular technologies, and some are designed for very specific uses, like Internet of Things (IoT) radio technologies for connecting low-power sensors.

Transport technologies, on the other hand, are used to interconnect specific (fix) points in an area. In urban areas, more often than not wired technologies like fibre and Ethernet are used to connect households or businesses.

In the following, we present a brief overview of the radio technologies that are considered by the KFT.

### 2.1.1 Wi-Fi

**What it is:** Wi-Fi is a local wireless technology commonly used in homes and offices that can also be used to connect other types of devices for rural services. Currently (2025) the 7th iteration of Wi-Fi is available on the end consumer market, offering data rates up to Gigabit per seconds. It is a technology that is continuously updated with newer versions that are backwards compatible. Generic use cases that require mid-high transmission rates and low-medium range coverage can consider the use of Wi-Fi.

**When to use it:** For example, for connecting devices like computers, tablets, or cameras on a farm or building. Indoor and outdoor usage is possible, but efficient (high-performing) range is limited. Not a good option if mobility is required, since handovers (seamless switching from one Wi-Fi access point to another) are not natively supported.

**Strengths:**

- Low cost
- Established technology that is supported by many devices and has many vendors
- Supports various use cases due to high capacity
- Easy to set up

**Limitations:**

- High-capacity limited to short range (tens of meters)
- Not suitable for open fields unless you deploy many access points; and then, mobility might not be supported if handovers occur.

### 2.1.2 4G/5G Cellular


**What it is:** The current de-facto technology to connect phones to the network for speach and daat transmissions. Mobile networks are mainly used by smartphones, but might have other uses, if end devices are equipped with a 4G/5G modem. While 4G is widespread and available in many regions, 5G is newer and faster, but the rollout is slower in European countries. Since 4G and 5G can be deployed in many different bands, the capacity and range of this technology are very varied. At low frequencies (sub-GHz), long-range communications are possible (10-15km per cellular base station). The data rates are low at low frequencies, but it has other advantages, such as being able to also provide indoor coverage. As the frequencies get higher, the possible data rates increase, however at the cost of reduced coverage and less capacity to penetrate buildings and across dense vegetation. As such, there is a trade-off between range and transmission capacity. Further, the use of small cells and macro cells can be differentiated. Small cells are designed to cover small areas with dedicated 4G/5G connectivity, whereas macro cells, as used often by public mobile network operators, can cover wide areas. The compact format of small cells is suitable for a seamless integration in a rural landscape, not requiring a telco tower, and this format consumes less energy, which makes them a much more sustainable option. However, for covering larger areas, a macro cell can be more efficient, as it will just require a single installation.

It is important to note that cellular technologies work over licensed spectrum and each European country uses the spectrum differently, meaning that public mobile network operators own different parts of the spectrum to implement their connectivity services. The availability of private spectrum to set up private cellular networks is also different for each country. In some countries, like Germany or UK, certain bands are available to be used for private cellular networks.

**When to use it:** The cellular technologies offer great flexibility for connecting mobile devices, sensors, or machines that move or are spread over a large area.

**Strengths:**

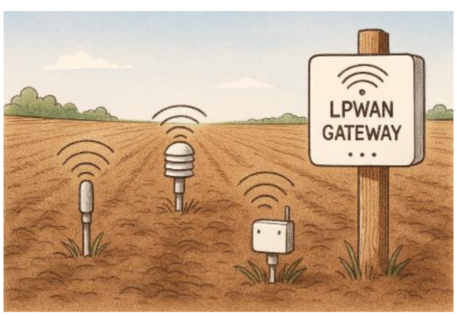
- Good coverage (especially 4G)
- Suitable for voice, video, and data
- Can work with public networks or private installations

**Limitations:**

- High cost for private deployment
- Requires good line-of-sight to towers for high frequencies (5G)

### 2.1.3 LPWAN (Low Power Wide Area Networks)

**Technologies:** LoRa, Sigfox, NB-IoT, LTE-M




**What it is:** LPWAN networks have been designed to enable the transmission of small amounts of data over long distances. The Internet of Things (IoT) is the main use case for these technologies: sensor and actuators of all kinds that are battery powered and do not require any large amount of data to be transmitted (mostly just sensor reports or control messages to activate/deactivate a device). Within the LPWAN networks, there exist proprietary technologies like LoRA and Sigfox that use their own types of radios and NB-IoT and LTE-M networks, that are cellular technologies and are designed to operate along existing technologies (4G).

While LoRA works in unlicensed spectrum, it is not the case for the other technologies. This means that for the creation of private networks, there are limitations, just like for the cellular technologies.

**When to use it:** For example for environmental sensors, soil moisture readings, livestock trackers.

**Strengths:**

- Very low power (battery-powered for years)
- Long range (up to 10–30 km)
- Low cost for deployment

**Limitations:**

- Very low data speeds and potentially large delays
- Not suitable for video or real-time applications

### 2.1.4 Satellite

**What it is:** In cases where connectivity is necessary even in very remote areas, where public network coverage is unlikely, the use of satellite connections is an option. Generally speaking, devices equipped with satellite transceivers can connect to the internet via satellites in orbit. While there are various types of constellations using satellites in different orbits, for the end-user there are two key satellite connectivity types to be distinguished: broadband satellite and IoT satellite. While broadband satellite services offer high data rates and small-medium latencies, IoT- satellite connections offer low data rates with potentially high latencies. The coverage via satellite, generally speaking is excellent (depending on the operator), but a major drawback of satellite-based service deployments are generally high costs for the infrastructure, such as satellite dishes, and the subscriptions can be costly.

**When to use it:** Areas with no mobile or fiber coverage — e.g., remote farms or coastal zones.

**Strengths:**

- Connectivity available almost anywhere
- Useful for backup or emergency links

**Limitations:**

- Higher latency (slower response times)
- Expensive hardware and subscription
- Signal affected by heavy rain

### 2.1.5 Microwave/mmWave Links (PtP/PtMP)

**What it is:** Mircrowave and millimeter wave links can form directional wireless links between two or more fixed points. These technologies operate in the medium-high GHz bands and are both available for licensed and unlicensed bands. These technologies are beneficial, when a site or a building needs to be connected with another site and using fibre is too expensive or impractical, or depliying fibre infrastructure is not feasible due to regulatory regulations (e.g., e.g. in protected sites, like NATURA-2000 habitats). The wireless links established by the microwave/mmwave devices are normally static and with a proper alignment, they can reach very high performance with high data rates and low latencies. However, these links can easily be affected by obstructions of line of sight between the devices (e.g., foliage of trees) or meteorological effects (e.g., fog) can affect the quality of the link. As such, careful planning is required. Beyond simple point-to-point connections, there are options for point-to-multipoint connections that can connect several points to a single concentrator.

**When to use it:** Connecting two or more buildings, access radio sites, or sending data from a local tower to a central hub.

**Strengths:**

- High speed
- Long distances (PtP)
- Can serve many users (PtMP)

**Limitations:**

- Requires clear line-of-sight
- Sensitive to rain and terrain

### 2.1.6 Summary

| Feature | Wi-Fi | 4G/5G | LPWAN | Satellite | Microwave/ mmWave |
|---|---|---|---|---|---|
| Range | Short | Medium | Long | Very long | Long (if LoS*) |
| Data Speed | High | High | Very low | Medium | High |
| Power Use | Medium | Medium | Very low | High | Medium-High |
| Cost (setup) | Low | Medium-High | Low | High | Medium |
| Terrain Impact | High | Medium | Low | Medium-High | High |
| Access/Backhaul | Access | Access | Access | Access/Backhaul | Backhaul |

*LoS = Line of Sight

## 2.2 Public vs. Private Networks

When connecting devices or services to the internet or a local system, it's important to understand the difference between public and private networks. Some technologies can be set up and managed privately—such as installing your own Wi-Fi network or deploying a LoRa gateway on your farm. Others rely on public services, like connecting through national mobile networks (e.g., 4G/5G from operators such as Vodafone or Orange) or using commercial satellite connections.

**Private Networks**

Private networks give users more control. They can be customized to local needs, configured to prioritize specific applications, and managed directly by the organization or user. For example, a private 5G or LTE network can be deployed in a rural area to serve only a group of farms, enabling fast and reliable communications with no dependency on external providers. However, setting up and managing private networks requires more technical expertise, initial investment in hardware, and sometimes spectrum licenses (especially for cellular technologies).

**Public Networks**

Public networks are offered by telecom or satellite operators, and users subscribe to them as a service. They are simple to access and usually available in many locations, especially in urban areas. Cellular technologies like 4G and 5G are often used this way: farmers or planners can simply use a SIM card and connect a device. The drawback is less control over network performance and coverage—especially in remote areas where signal strength may vary or be limited.

A comparison of the main advantages and disadvantages of private and public networks is given below:

**Private:**

- You control the network
- Better for sensitive data or guaranteed quality
- Requires setup and maintenance
- Licensed spectrum technologies require permissions

**Public:**

- Quick to use (like a SIM card)
- No own installation needed
- May have limits in speed or availability (especially in areas with low coverage)

## 2.3 Environmental and Physical Constraints

Radio signals can be weakened or blocked by various environmental and terrain-related factors. The KFT includes models to estimate this signal loss and displays warnings when necessary. Here's an overview of the most relevant elements:

**Rain and Fog**

High-frequency signals, such as those used in millimetre wave (mmWave) 5G or satellite links, are especially vulnerable to rain and fog.

- **Rain** causes "rain fade," where the signal is absorbed or scattered by raindrops, leading to a significant loss in quality, especially above 10 GHz (e.g., point-to-point links) but also on lower frequencies at around 2-6 GHz (e.g., cellular, WiFi). This can happen even if it's not raining directly at your location—rain along the signal's path can still have an impact
- **Fog**, which consists of tiny water droplets suspended in the air, also affects higher frequencies. The density and moisture content of the fog play a key role in how much signal is lost

Lower transmission frequencies have better propagation properties and are less affected by Rain & Fog.

**Trees and Vegetation**

Vegetation causes signal loss through absorption, reflection, and scattering. The impact varies depending on:

- Leaf density (e.g., trees with leaves block more than leafless ones),
- Moisture level (wet foliage absorbs more),
- Tree type and height,
- Wind, which can cause branches to sway and introduce further variation. Signals at higher frequencies like 5G and microwave are more affected than lower frequencies such as LoRa or NB-IoT.

The KFT merges these concepts into a single option, which is to indicate if there is vegetation and introduce the height of the vegetation. For a conservative estimation of supported technologies, the user should introduce a conservative estimate for the height.

**Mountains and Terrain**

Hills, rocky areas, and mountainous terrain can block the line-of-sight (LoS) path needed by many radio systems. In such cases, the signal might:

- Reflect off nearby surfaces,
- Bend around obstacles (diffraction),
- Scatter in different directions.

These effects reduce signal strength and reliability, especially for technologies like point-to-point microwave and mmWave. Non-LoS systems like some satellite or low-band cellular links can sometimes help, but terrain remains a major challenge.

**Other Factors**

- **Freezing temperatures** can affect equipment rather than the signal itself—batteries might lose capacity and cables may suffer mechanical damage due to ice formation.
- **Water bodies** like rivers and seas reflect signals, creating interference (multipath effects), especially for high-frequency systems. Lower-frequency technologies (like NB-IoT or the lower bands of 5G) and satellite are usually more stable in such environments

**In the KFT:**
All these factors are taken into account during network planning simulations. If signal loss is expected to be too high due to rain, fog, trees, terrain, or other factors, the KFT provides warnings to guide users toward more reliable configurations—like selecting lower frequencies, alternative locations for antennas, or switching technologies.

## 2.4 Radio Virtualization

Radio virtualization is the concept of using software to manage and share the physical parts of a radio access network (RAN). Instead of each network or service provider building their own infrastructure, multiple services can run over the same physical radio equipment — increasing efficiency and reducing costs.

This is especially useful in rural areas where infrastructure can be expensive and underused.

### 2.4.1 Virtualization for Wi-Fi

Wi-Fi virtualization refers to the ability to create multiple distinct networks from a single physical Wi-Fi access point. This is typically achieved using technologies like multiple SSIDs (Service Set Identifiers) or VLANs (Virtual Local Area Networks). These techniques allow one Wi-Fi device to behave as if it were several separate networks, each with its own settings and purpose.

**How It Works**
A single Wi-Fi router can broadcast several SSIDs—for example:

- "FarmNet" for agricultural sensors and automation,
- "GuestNet" for visiting workers or tourists,
- "AdminNet" for farm staff and secure operations.

Each of these virtual networks can be tied to a VLAN, meaning that even if the traffic shares the same airwaves and physical device, it remains separated and managed independently behind the scenes.

**Key Benefits**

- **Efficient use of equipment**: There is no need to install multiple routers or access points for different tasks. One device does it all.
- **Traffic separation**: Data from sensors won't interfere with video calls or guest internet usage, because each network can have its own bandwidth limits, priority levels, and security settings.

- **Security and access control**: Users of one virtual network can be restricted from accessing the devices or data of another. For example, guests can browse the internet but won't see internal sensor systems.
- **Flexibility for rural services**: A local municipality, for instance, could deploy a Wi-Fi router that simultaneously serves public internet in a town square, connects smart parking sensors, and allows remote management of irrigation—all virtually separated.

**Example Use in Rural Environments**

In a small village, a local cooperative might deploy a single Wi-Fi router in the community center:

- Farmers use the "AgriData" SSID to upload sensor data from nearby fields.
- Tourists and locals access "RuralFreeWiFi" for browsing.
- The cooperative's private administrative systems connect through a secure "OfficeNet" VLAN.

This setup provides isolated, purpose-driven networks without the cost or complexity of multiple physical deployments. It also simplifies maintenance, as updates or changes can often be managed from a single dashboard.

### 2.4.2 Virtualization in Cellular Networks (4G/5G)

Modern cellular networks (like 4G and 5G) are designed to be more flexible and efficient thanks to virtualization—this means that multiple mobile network operators (MNOs) can share the same physical infrastructure while still offering independent services. This is especially important in rural areas, where building full infrastructure for each operator can be costly and redundant.

There are two main types of network sharing enabled by virtualization:

**MORAN (Multi-Operator Radio Access Network)**

In MORAN setups:

- Multiple operators share the same antennas, towers, and base stations.
- Each operator still uses its own radio frequencies and connects to its own core network (the part of the system that handles routing, billing, etc.).

This means that two or more operators can reduce costs and simplify installation by using a common physical setup, while maintaining full independence in how they manage their services.

### MOCN (Multi-Operator Core Network)

MOCN goes a step further:

- Operators not only share the physical infrastructure (as in MORAN),
- They also share the radio frequencies and some parts of the core network.

This requires more coordination between operators, but it allows for even greater efficiency, and can be a strong solution in areas with low population density or where spectrum availability is limited.

### Why this matters for rural connectivity

Virtualized deployments in rural areas bring several advantages:

- **Lower infrastructure costs**: By avoiding the duplication of towers and radio equipment, rural coverage can be extended at a much lower investment.
- **Reduced energy use**: Fewer towers and devices mean lower electricity consumption, which is especially important in areas powered by solar or generators.
- **Greater choice for end-users**: Even with limited infrastructure, people can access services from multiple operators, improving competition and service quality.

### Supporting Technologies

These models are increasingly supported by:

- **Cloud-native architectures**: where network functions run as software on general-purpose hardware, increasing flexibility.
- **Open RAN (O-RAN)**: a new approach where equipment from different vendors can be mixed and matched, reducing vendor lock-in and enabling more cost-effective deployments.

### Considerations for Private or Cooperative Deployments

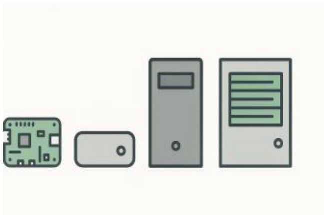
In community-led or private cellular setups—such as those on farms or in rural cooperatives—virtualization can also play a role if multiple operators are willing to collaborate. Key factors include:

- **Spectrum availability** for each operator,

- **Hardware capabilities** to handle multiple virtual networks,
- **Agreements on costs, maintenance, and governance**,
- **Willingness to coordinate** between parties.

When successful, such shared cellular infrastructure can bring robust, affordable, and sustainable mobile connectivity to underserved regions.

# 3 Computing Technologies



Modern rural services—from drone surveillance to smart irrigation—depend on computing resources to process data locally or remotely. This section introduces the core technologies that enable such processing, especially when using edge computing systems that operate close to the source of data.

In the XGain project, computing technologies are grouped into several types based on where and how they process data. These systems can range from tiny computers inside a sensor to regional servers or remote cloud platforms.

## 3.1 Edge and Cloud Computing: What They Are and Where They Fit

In today's digital world, computing doesn't always happen in a central server or faraway data center. Depending on the situation—especially in rural environments—processing data locally (at the *edge*) can be faster, cheaper, and more efficient. This section explains the key differences between edge computing and cloud computing, and highlights the types of devices typically used in each case.

### 3.1.1 What Is Edge Computing?

**Edge computing** means processing data close to where it's generated—on the farm, in the village, or even on a moving drone. Instead of sending everything to the cloud, smart devices or small computers handle tasks locally. This can include:

- Reading and analyzing data from sensors,
- Running AI models on videosto detect issues (e.g. pests or irrigation needs),
- Making decisions automatically (e.g. opening a valve).

Edge computing is often categorized by how close the processing happens:

- **Extreme Edge**: On the device itself (like a drone or a camera),
- **Far Edge**: On a radio node, i.e., the infrastructure element that provide connecitivy to end device.
- **Near Edge:** On a nearby gateway, small server, or cooperative hub.

### 3.1.2 What Is Cloud Computing?

**Cloud computing** is when data is sent to a remote server—often located in a large data center, sometimes far away—and processed there. The cloud generally spekaing offers powerful computing capabilities, useful for:

- Storing large amounts of data over time,
- Running heavy analytics or training AI models,
- Coordinating services across many sites or regions.

However, cloud computing relies on a good internet connection and can introduce latency (delays) and higher data traffic—two challenges in rural environments.

### 3.1.3 Comparing Edge and Cloud

| Feature | Edge Computing | Cloud Computing |
|---|---|---|
| Location | Near the data source | Remote data centers |
| Speed (Latency) | Fast (few milliseconds) | Slower (depends on connection) |
| Connectivity Needed | Limited or intermittent | Reliable high-speed required |
| Power Use | Lower (localized) | Higher (centralized) |
| Data Privacy | Stays local | Leaves site, higher exposure |
| Use Cases | Real-time control, monitoring | Storage, large-scale analytics |

Edge and cloud are complementary: edge handles fast, local tasks; cloud handles global, heavy tasks. Together, they form a hybrid model that is supported by the KFT.

### 3.1.4 Typical Edge Devices

Different edge tiers use different hardware. Here are some examples:

- **Microcontrollers** (e.g. Arduino, STM32).
- **Raspberry Pi 4 or 5**: Small, flexible computers ideal for local dashboards or data pre-processing.
- **NVIDIA Jetson Nano / Xavier**: AI-capable devices for tasks like object detection or video analysis.

- **Intel NUC** or **industrial mini-PCs**: For running local services, Kubernetes clusters, or web servers.

These devices can be solar-powered and are suitable for rough environments. Some models are enclosed in waterproof or dustproof casings for outdoor use.

### 3.1.5 Typical Cloud Platforms

Cloud services used in rural deployments may include:

- **Public cloud**: Amazon Web Services (AWS), Microsoft Azure, Google Cloud.
- **Private cloud**: Local data centers managed by regional authorities or cooperatives.
- **Federated cloud**: Shared infrastructure operated across multiple stakeholders.

In the KFT, cloud computing is suggested when many services are deployed or high-processing demands are present.

### 3.1.6 Choosing the Right Level

The KFT helps users select the most appropriate computing level based on:

- Bandwidth availability,
- Service requirements (e.g., real-time vs delayed),
- Energy efficiency,
- Cost and maintenance considerations.

In many rural deployments, edge computing is prioritized for resilience, efficiency, and autonomy, while cloud computing supports scalability and regional collaboration.

## 3.2 Computing Virtualization

**What is it?**
Virtualization allows a single computing device (like a small computer or server) to run multiple tasks or services at once, using software to simulate multiple separate computers. This means different applications can share the same hardware efficiently.

**Why is this useful in rural areas?**
Instead of buying many physical devices, farmers or local cooperatives can use one device to do multiple jobs—like monitoring crops, controlling irrigation, or analyzing weather data.

**How does it work?**
There are three main approaches:

- **Containers** (e.g., Kubernetes or K3s): Lightweight, fast, and perfect for small devices at the edge.
- **Virtual Machines** (e.g., OpenStack): More suited for larger setups, like near-edge or cloud.
- **Serverless**: Runs short tasks automatically in the cloud, but is less predictable and harder to manage locally—so it's not used in XGain's approach.

In XGain, Kubernetes (K8s) and its lightweight variant K3s are used to virtualize tasks efficiently on various computing platforms.

## 3.3 Orchestration and Management

**What is it?**
Once you virtualize computing tasks, you need to manage them—decide which device runs what, monitor energy use, and adapt when things change. This is called *orchestration*.

**What tools are used?**

- Kubernetes is a key orchestration platform used in XGain.
- It allows us to coordinate tasks across devices, restart services if they fail, and scale up or down depending on demand.

**Why does it matter?**
Imagine running video analysis on drones or controlling 10 different weather sensors—managing all this manually would be a very work intense task. Orchestration automates and optimizes it. This is specially important in setups where multiple service are hosted together on top of the same infrastructure.

**XGain Integration:**
The “Tech-mix Dimensioning Solver” used in the XGain KFT proposes the best combinations of computing and network devices, assuming that orchestrated and virtualized setups are used in multiservice deploymnets and adapted to local needs (e.g., agriculture, aquaculture, health monitoring).

## 3.4 AI and Service Deployment at the Edge

**What is it?**
Edge AI means using small computers (often with dedicated chips) to run AI tasks—like recognizing people in images or detecting crop disease—right where data is collected.

**Benefits for rural areas:**

- **Faster response times:** No need to send data to a faraway cloud.
- **Reduced data traffic:** Only processed results (like alerts or summaries) are sent to a cloud service, if desired.
- **Improved privacy:** Sensitive data (e.g., health info, images) doesn't leave the site.

**Common devices:**

- NVIDIA Jetson boards
    - These are small, energy-efficient, and powerful enough to run tasks like image or audio recognition in real time.

By using AI at the edge, XGain improves performance and reduces costs, while making systems more reliable—even in areas with poor internet connectivity. Larger servers, with high processing capacities, can also be deployed at the edge in case that multiple services have to be served or for very intense processing tasks.

# 4 Tiered Topology Concept

Modern digital services in rural and remote areas face unique challenges due to limited infrastructure, long distances, and scarce resources. To address these challenges, the XGain project proposes a tiered topology model, which organizes digital infrastructure into different levels, or tiers, based on their roles, capabilities, and proximity to end users. It further assumes different types of connectivity between each of the tiers. This model provides a systematic way to plan, deploy, and manage digital services efficiently across varied geographic and connectivity conditions. It allows for flexible combinations of computing, communication, and energy systems to suit the specific needs of each area or use case.

## 4.1 The Four Tiers of the Topology

**Extreme Edge Tier**

This is the closest level to the data source. It includes devices such as smart sensors, agricultural machinery, drones, or handheld terminals that interact directly with the physical environment. These devices often perform basic data acquisition or even pre-processing (e.g. filtering, alert generation), minimizing the need for continuous communication with upstream systems.

**Far Edge Tier**

Far edge nodes include local gateways, edge servers, or micro data centers that aggregate and process data from extreme-edge devices. They are typically installed in farms, cooperative hubs, or village centers. These nodes may host virtualized applications, run AI models (e.g. crop disease detection), and offer service continuity even when upstream connectivity is interrupted.

**Near Edge Tier**

This tier encompasses regional computing facilities with greater processing capacity. Located at municipality buildings, regional exchanges, or telecom hubs, they bridge local deployments with national or cloud infrastructure. They support tasks that require more power or coordination between multiple far-edge systems, such as orchestration or regional data analytics.

**Core or Cloud Tier**

Centralized facilities or public cloud platforms form the top level of the topology. These are used for long-term data storage, heavy computation, training of AI models, and coordination across regions. While powerful, they are less suitable for real-time operations due to latency and potential backhaul constraints in rural areas.

## 4.2 The Networks that Connect the 4 Tiers

In any digital deployment—whether on a farm, in a rural school, or across a village—connectivity depends on several types of networks working together. Each one serves a different function in ensuring that data can flow between devices, users, and services. In XGain, these networks are modelled and planned using the KFT to ensure efficient and cost-effective deployments.

### 4.2.1 Access Networks

**Access networks** are the first layer of connectivity—the part that links end devices (like sensors, smartphones, or drones) to the local or wider network. In rural areas, access networks often rely on:

- **Wi-Fi**: For connecting devices within buildings or small outdoor areas. It's low-cost and supports high speeds but has limited range.
- **4G/5G Cellular**: Offers wide-area connectivity for mobile devices, vehicles, or distributed sensors. Can be public (via operators) or private (set up locally).
- **LPWAN (LoRa, NB-IoT)**: Enables very low-power, long-range connections for small data applications like environmental sensing.
- **Satellite**: Used when no other access option is available, particularly in remote locations.

Each technology has its strengths and weaknesses, and choosing the right one depends on the application's data needs, power availability, and coverage area (see Section 2.2).

### 4.2.2 Local Networks

**Local networks** interconnect access points within a defined area—such as a farm, cooperative, or small village. They aggregate or distribute the data between points in deployment and come into play in distributed deployments, where several access network connectivity points need to connect with each other or a centralized service. Technologies for local networking may include:

- **Ethernet or fibre** (where feasible),
- **Microwave or mmWave point-to-point links**, especially when connecting buildings or installations across a property.

### 4.2.3 Internet Connectivity (Backhaul)

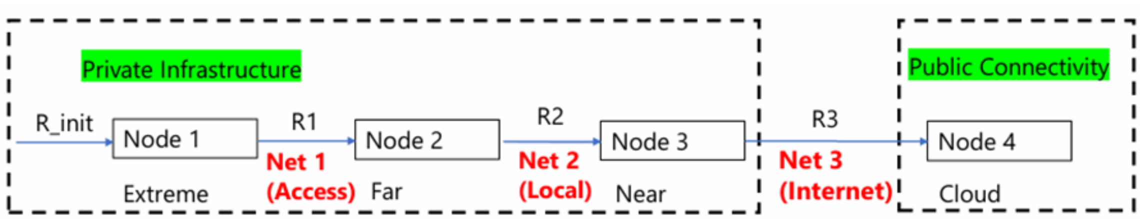
To connect rural systems with the wider digital world—including remote servers, cloud platforms, or national databases—backhaul or internet connectivity is required. This connection typically links the local network to:

- **Fiber-optic lines**, where available, offering high-speed and reliable connections.
- **Cellular networks** (4G/5G), used for sending aggregated data or remote monitoring.
- **Satellite links**, when no terrestrial infrastructure exists.
- **Fixed wireless links**, like microwave or mmWave backhaul to a network hub.

Backhaul is critical for syncing data with the cloud, enabling remote support, software updates, or external dashboards. However, its cost and reliability can be a limiting factor in remote regions—another reason why edge computing and local processing are essential in XGain's approach.

## 4.3 Why a Tiered Topology Matters

The logical topology assumed by the KFT, shown in the figure below from Deliverable D3.2, features the Nodes (tiers) and networks explained in the previous subsections.




The main reasons for adopting this model are

- **Adaptability**: Different services can adopt different tiers based on local conditions—some may only need extreme and far-edge layers, while others can benefit from connecting to near-edge or cloud services.
- **Resilience**: By distributing functionality across tiers, systems can continue operating even if one tier becomes temporarily unavailable.

- **Efficiency**: Local processing reduces data traffic, improves latency, and can cut energy costs—especially important in low-bandwidth or off-grid environments.
- **Scalability**: The modular structure allows the gradual expansion of digital infrastructure without disrupting existing services.

The tiered topology is an underlying assumption made in the KFT, in helping users simulate deployments that match their specific needs. By applying this model, XGain enables rural communities to plan sustainable, high-performing, and locally adapted digital infrastructures—without requiring one-size-fits-all solutions.

# 5 Neutral Hosting / Shared Infrastructure

Neutral hosting is a model in which infrastructure for telecommunications and digital services is owned and operated by a third party—the neutral host—who provides access to multiple service providers. Instead of each operator deploying its own network equipment in rural areas (which may be economically unviable), they share the same infrastructure, reducing costs and accelerating deployments. This concept is especially important in rural and remote regions, where low population density and difficult terrain make traditional, operator-specific deployments inefficient.

Neutral hosting can include both:

- **Passive infrastructure**: towers, power supplies, shelters, masts, fiber backhaul.
- **Active infrastructure**: radio units, baseband units, switches, routers, and even cloud-native virtual network functions.

## 5.1 Why It Matters in Rural Areas

Deploying digital infrastructure in rural zones presents several challenges:

- Sparse populations result in lower revenue per $km^2$, making traditional deployments unattractive.
- Harsh terrain or lack of grid electricity increases the cost of deployment and maintenance.
- There is often little coordination between public or private stakeholders, leading to duplicated or underused infrastructure.

Neutral hosting offers a solution:

- **Cost-effective deployments** by sharing CAPEX/OPEX across operators and services.
- **Better service availability**, as multiple mobile operators can serve the same area via a shared site.
- **Scalability and modularity**, using shared cloud infrastructure to support different service types (e.g., mobile broadband, IoT, smart agriculture).

## 5.2 Technologies Enabling Neutral Hosting

Neutral hosting leverages several advanced technologies to function efficiently:

### 5.2.1 Passive Sharing

Shared use of non-electronic infrastructure:

- **Towers and poles**
- **Cabinets and shelters**
- **Backhaul and power systems** (solar, battery, diesel)

This is the simplest form of sharing and often the first step in multi-tenant deployments.

### 5.2.2 Active Sharing

Operators share parts of the radio access network (RAN):

- **Multi-Operator RAN (MORAN)**: shared radio units, but each operator keeps its own spectrum and core.
- **Multi-Operator Core Network (MOCN)**: shared radio units and shared spectrum; partial core network sharing.
- **Virtual RAN (vRAN)** and **Open RAN (O-RAN)** architectures allow remote and virtualized operation of shared radio infrastructure using general-purpose hardware.

### 5.2.3 Virtualization and Orchestration

Shared infrastructure benefits from:

- **Network Function Virtualization (NFV)**: radio and core functions run as software on shared servers.
- **SDN (Software Defined Networking)**: enables dynamic network control, traffic slicing, and service differentiation.
- **Orchestration platforms**: coordinate resource usage between tenants (operators), enabling efficient network slicing, service chaining, and SLA enforcement.

These technologies allow a neutral host to isolate each operator's service while ensuring fair resource allocation.

## 5.3 Challenges in Rural Neutral Hosting

Despite its potential, neutral hosting in rural areas faces several hurdles:

**Spectrum Management**

- Operators must agree to share spectrum (especially under MOCN), which may require regulatory adaptation.
- In some cases, local private spectrum licenses may be used to create community-owned networks.

**Operational Complexity**

- Multi-tenant orchestration needs mature platforms to prevent conflicts.
- Hardware must support multi-domain configurations (e.g., different backhaul policies, security zones).

**Business and Governance Models**

- A neutral host must define clear service-level agreements (SLAs), pricing models, and governance frameworks.
- Trust and coordination between stakeholders—operators, municipalities, cooperatives—can be a barrier.

**Technical Standardization**

- Not all hardware is O-RAN compliant.
- Legacy operator equipment may not interoperate easily in a shared environment.

## 5.4 Looking Ahead: A Sustainable Model

In the context of rural innovation hubs or smart agriculture zones:

- Local cooperatives or public bodies can become neutral hosts.
- Using solar-powered passive infrastructure, virtualized RAN, and local cloud services, these hosts can offer robust connectivity with minimal ecological footprint.
- Open-source orchestration tools (e.g., Open Source MANO, Kubernetes-based solutions) can be adapted for managing shared resources.

Neutral hosting is not just about sharing towers—it's a technological framework for inclusive, scalable, and efficient rural connectivity. Through a combination of modern radio virtualization, cloud-native management, and shared investment, rural areas can achieve digital parity without overbuilding or underutilizing infrastructure.

# 6 Edge and Far-Edge Computing Use Cases

Edge and far-edge computing play a central role in enabling responsive, efficient, and sustainable digital services in rural areas. By processing data closer to where it is generated—rather than relying on distant cloud servers—these technologies help overcome connectivity limitations, reduce latency, and enable local decision-making. This section outlines the concepts, technical characteristics, and practical use cases of edge-based deployments, with a focus on their relevance to rural connectivity as supported by the XGain project: The KFT focuses on promoting edge-based deployments—especially at the far and extreme edge levels—to enable better performance and service reliability in rural environments.

## 6.1 Why is edge compute important in rural scenarios?

Rural areas often face connectivity limitations due to weak backhaul links, scarce bandwidth, or long distances to the cloud. As a result, pushing all data to the cloud for processing can lead to delays, interruptions, or high operational costs.

Edge and far-edge computing allow critical data processing to occur locally, which results in lower latency, improved resilience, and better use of bandwidth. This is particularly valuable for applications that require immediate feedback or operate in areas with poor connectivity.

## 6.2 Typical use cases in rural environments

Smart agriculture is a key area for edge deployments. For example, extreme-edge devices like soil sensors or weather stations can pre-process measurements locally, reducing the amount of data sent. At the far edge, servers hosted on-site or at a cooperative hub can run AI models to detect irrigation needs or crop diseases.

Autonomous or remotely operated farm machinery requires fast response times. Video feeds and telemetry can be processed at the far edge to detect obstacles or optimise navigation, avoiding the delays of round-trip communication to the cloud.

Environmental monitoring systems deployed in forests, rivers, or remote pastures can perform early data filtering at the edge to detect anomalies such as fires, flooding, or unusual pollution levels. Edge analytics can trigger alerts even in the absence of constant connectivity.

In emergency and safety scenarios, such as wildfire detection or rural security, video data captured by drones or camera networks can be analysed by mobile edge platforms. These systems support decision-making in real time without waiting for cloud processing.

Smart villages can also benefit. Public lighting control, parking sensors, or community notice systems can be operated using local edge platforms, reducing dependence on external networks and cloud subscriptions.

## 6.3 Technical considerations

Extreme-edge nodes are typically constrained devices with limited power and compute, such as Raspberry Pi units, microcontrollers, or embedded AI boards. They are suitable for sensor filtering, threshold detection, or simple control tasks.

Far-edge nodes include more capable devices, such as Intel NUCs, Nvidia Jetson boards, or rugged industrial servers. These can support AI inference, image analysis, or local service hosting, and may integrate with mobile or fixed access networks (e.g. 4G/5G or fibre).

Key parameters to consider include latency (usually under 5 ms for real-time use cases), power availability, environmental resistance, and ability to run containerised or virtualised workloads. In some cases, accelerators like GPUs or FPGAs may be required to support specific computing tasks.

## 6.4 Benefits

Edge computing reduces the amount of data sent through rural networks, lowers latency, and improves system autonomy. It also enhances data privacy, as sensitive information does not need to leave the premises. In energy-constrained environments, processing data locally can also reduce the energy consumption associated with communication.

## 6.5 Challenges

There are still important technical challenges. Devices at the edge may have limited processing capacity or storage, requiring efficient software design. Ensuring secure operation (including software updates and data protection) can be more difficult in decentralised, unattended environments. Finally, orchestration of services across a distributed network of edge devices—especially when mobility or power constraints are present—requires robust planning and management tools.

The KFT developed within XGain supports simulation and planning of such deployments, helping users estimate energy consumption, latency, and service behaviour at different levels of the compute continuum.

## 6.6 Conclusion

Edge and far-edge computing are central enablers for rural digital transformation. They support real-time, efficient, and autonomous operation of services, while reducing dependence on external infrastructure. With the right planning and technology choices, edge computing allows rural communities to gain access to advanced services previously limited to urban settings.

# 7 Typical Performance Metrics and KPIs

To evaluate and compare different technologies and deployment options, it is useful to track performance metrics or Key Performance Indicators (KPIs). These help assess how well a network or service performs under real-world conditions. In rural deployments—where cost-efficiency, reliability, and coverage are essential—KPIs provide the technical foundation for planning and optimization.

Below are the most common performance metrics used in radio and computing infrastructure deployments:

## 7.1 Coverage and Availability

- **Signal Strength (RSSI / RSRP)**
  Measures how strong the received signal is. In rural areas, weak signals often occur due to long distances, terrain, or vegetation.
- **Coverage Area**
  Indicates how much land a radio base station or gateway can serve. This depends on frequency, antenna height, power level, and topography.
- **Availability (%)**
  Shows how often the network is operational and accessible. A typical goal is 99% or higher, but rural systems may tolerate slightly lower availability if alternative paths or fallback systems exist.

## 7.2 Throughput and Capacity

- **Downlink / Uplink Throughput (Mbps or kbps)**
  Measures the actual speed of data transfer. Important for applications like video monitoring or real-time data collection.
- **Network Capacity**
  Refers to the number of users or devices that can be served simultaneously. Technologies like LoRa or NB-IoT are designed for many low-bandwidth devices, while 5G supports both high and low data-rate use cases.

## 7.3 Latency and Responsiveness

- **Latency (ms)**
  The time it takes for data to travel from sender to receiver and back. Low latency (e.g., <10 ms) is critical for real-time control (e.g., drones or autonomous machinery). Higher latencies (100–500 ms) may be acceptable for sensing or alerts.
- **Jitter (ms)**
  Variation in latency. A low jitter ensures smoother performance for voice and video applications.

## 7.4 Reliability and Error Rates

- **Packet Loss (%)**
  The percentage of data packets that never reach their destination. This impacts application performance—especially for video, control systems, and industrial IoT.
- **Bit Error Rate (BER)**
  Measures how many bits are received incorrectly. Important for long-range or noisy environments.

## 7.5 Energy and Sustainability

- **Power Consumption (W or kWh)**
  Relevant in off-grid deployments (e.g., solar-powered base stations). Tracking energy use helps optimize uptime and sustainability.
- **Energy Efficiency (bits per Joule)**
  Shows how much data is transmitted per unit of energy. Useful when comparing different technologies or configurations.

## 7.6 Service-Specific KPIs

- **Sensor Network Update Rate (seconds)**
  How often a sensor transmits data. Critical for time-sensitive applications like irrigation control.
- **User Satisfaction / QoE (Quality of Experience)**
  A broader measure combining availability, speed, latency, and application performance—often collected through user surveys or application logs.

## 7.7 Virtualization and Cloud Metrics

In virtualized or shared infrastructures, additional KPIs may apply:

- **CPU and Memory Usage (%)**
  Helps identify overloaded nodes or virtual functions.
- **Orchestration Response Time**
  Time taken to spin up, migrate, or adjust services across virtual infrastructure.
- **Container / VM Uptime (%)**
  Important in edge computing and network slicing contexts.

# 8 Use of Renewable Energy (PV)

In many rural and remote regions, connecting digital infrastructure to the electrical grid can be expensive or even impossible. To ensure reliable operation of communication and computing systems in these areas, renewable energy—especially solar power using photovoltaic (PV) panels—is a highly viable solution.

PV systems convert sunlight into electricity, offering a sustainable, decentralized energy source that aligns with both environmental goals and rural development needs.

## 8.1 What Can Be Powered by PV in Rural Networks?

Photovoltaic systems can support various components of rural digital infrastructure:

- **Wi-Fi routers and LPWAN gateways** (e.g., LoRa, NB-IoT)
- **5G small cells** or 4G base stations (low-power models)
- **Edge computing nodes** (e.g., mini servers or SBCs)
- **IoT sensor hubs**
- **Battery charging systems** for backup power or hybrid use

Depending on the setup, PV systems may power the equipment directly, or store energy in batteries for use during the night or cloudy conditions.

## 8.2 System Components

A typical PV-powered connectivity node includes:

- **PV panels** (to generate electricity)
- **Charge controller** (to manage battery charging)
- **Battery bank** (for energy storage, often $LiFePO_4$ or lead-acid)
- **DC/AC converters** or **regulated DC supplies** (to power the network equipment)

These systems can be modular and compact, making them suitable for rooftop installations, poles, or mobile units (e.g., mounted on trailers or farm vehicles).

## 8.3 Technological Considerations

**Power Requirements**

- A Wi-Fi router or LPWAN gateway may only require 5–15W, which is easily met with small PV panels.
- A 4G/5G small cell or edge server might need 30–200W, requiring larger panels and battery capacity.
- Macro cellular stations might require 1kW or more.

**Sizing the System**

- Proper dimensioning is critical. This includes:
    - **Daily energy consumption**
    - **Sunlight availability** (based on location and season)
    - **Battery autonomy** (typically sized for 2–5 days of storage)
- Tools and calculators (or planning platforms like the KFT) can assist with estimating these parameters.

**Hybrid Power**

- PV systems can be combined with wind turbines, diesel generators, or grid fallback to create hybrid energy systems, improving reliability in areas with variable weather or high energy demands.

## 8.4 Benefits of Using PV in Rural Digital Infrastructure

- **Energy independence**: Works without reliance on the power grid.
- **Low operational costs**: After initial installation, sunlight is free.
- **Sustainability**: No emissions or fuel transport needed.
- **Scalability**: Can be expanded with additional panels or batteries.
- **Resilience**: Useful in disaster recovery or remote emergency deployments.

## 8.5 Challenges and Mitigations

| Challenge | Mitigation |
|---|---|
| High initial cost | Community funding, EU support programs |
| Weather variability | Battery storage, hybrid systems |
| Theft or vandalism | Secure mounting, alarms, visibility |
| Maintenance in remote locations | Remote monitoring, modular hardware |

## 8.6 Integration with Smart Infrastructure

PV-powered nodes can host:

- **IoT sensors for precision agriculture**
- **Edge processing units** for local analytics
- **Neutral-host small cells** to serve multiple operators

All of this can be done off-grid, enabling fully autonomous digital islands in areas where connectivity and electricity were once impossible.

**Conclusion**
Photovoltaic energy is a cornerstone of sustainable digital transformation in rural areas. By coupling clean energy with intelligent connectivity infrastructure, rural regions can build systems that are not only technically robust and cost-effective, but also environmentally responsible and future-ready.

# 9 Glossary and Acronym Index

**Access Network**
The part of a network that connects end-user devices (like sensors or smartphones) to a local or central network. Examples include Wi-Fi, 4G/5G, and LPWAN.

**AI (Artificial Intelligence)**
Software that can perform tasks requiring human-like decision-making, such as image recognition or anomaly detection. In XGain, AI is often run at the edge.

**Backhaul**
The connection between a local network and the internet or central data center. It typically uses fibre, cellular, satellite, or point-to-point wireless links.

**Cloud Computing**
Processing and storing data on remote servers located in data centers, often accessed via the internet. Useful for large-scale analysis and long-term storage.

**Container**
A lightweight software unit that packages an application and its dependencies, allowing it to run reliably across computing environments. Often used in edge computing.

**Edge Computing**
Processing data close to where it is generated, rather than sending it to a remote cloud. Improves speed, reduces traffic, and supports offline operation.

**Extreme Edge**
The computing layer that runs directly on end devices (e.g., smart sensors, drones). Suitable for simple, fast processing tasks.

**Far Edge**
The layer of computing that takes place near the source, such as on-site gateways or local servers. Suitable for AI inference and data aggregation.

**Internet Network**
The global network of interconnected servers and devices. In rural projects, internet access is often provided via satellite, 4G/5G, or fibre.

**Kubernetes (K8s)**
An orchestration platform that manages containerized applications across a network of computers. Used to automate deployment and scaling in XGain.

**K3s**
A lightweight version of Kubernetes, optimized for resource-constrained environments such as edge devices.

**Latency**
The time delay between sending and receiving data. Lower latency is essential for real-time applications.

**Local Network**
A private network within a defined location (like a farm or village) that connects local devices and services. Can use Ethernet, Wi-Fi, or point-to-point wireless links.

**LPWAN (Low-Power Wide-Area Network)**
Wireless technologies (like LoRa or NB-IoT) used to connect battery-powered sensors over long distances with minimal data needs.

**Microcontroller**
A compact computer embedded in devices like sensors or actuators. Used for simple control or data collection tasks at the extreme edge.

**NVIDIA Jetson**
A family of small computing boards with AI processing capabilities, commonly used in edge AI applications.

**Orchestration**
The automated coordination of computing tasks across devices, ensuring services run reliably and efficiently.

**Private Network**
A locally managed network that is not part of a public telecommunications service. Offers more control, security, and customization.

**Public Network**
Telecommunications infrastructure provided by commercial operators (e.g., Vodafone, Orange) and accessible via subscription.

**Raspberry Pi**
A small, low-cost computer used for various computing tasks, often at the far edge in rural settings.

**Tiered Topology**
A hierarchical structure for organizing computing resources in levels: extreme edge, far edge, near edge, and cloud. Each tier plays a specific role in data processing.

**Virtual Machine (VM)**
Software that emulates a physical computer, allowing multiple VMs to run on a single device. Used in more powerful edge or cloud setups.

**Virtualization**
Technology that allows multiple applications or systems to share the same physical hardware by isolating them through software.

**Wi-Fi**
A wireless technology for short-range communication between devices. Common in homes and local access networks.