Technology: Wirepas Mesh 2.4 GHz

Abstract

Wirepas Mesh 2.4 GHz (WM) is a wireless decentralized mesh network technology. It is designed to support massive-scale, reliable, and robust mesh networks for industrial use. The WM devices (sensors or actuators) can act as routers and enhance network connectivity. Every WM device takes local decisions on where to route data and how to act as a router. The WM devices can be either configured in low-power mode or in a high-performance, low-latency mode. Both modes can be used in one single network.

One single Wirepas Mesh network can have hundreds of thousands of WM devices and one or more gateway devices that route the traffic into and from the WM network. Wirepas supports multi-gateway topologies and self-healing routing. Wirepas Mesh networks, by design, do not have a single point of failure since multiple gateways are enabling connectivity to external systems.

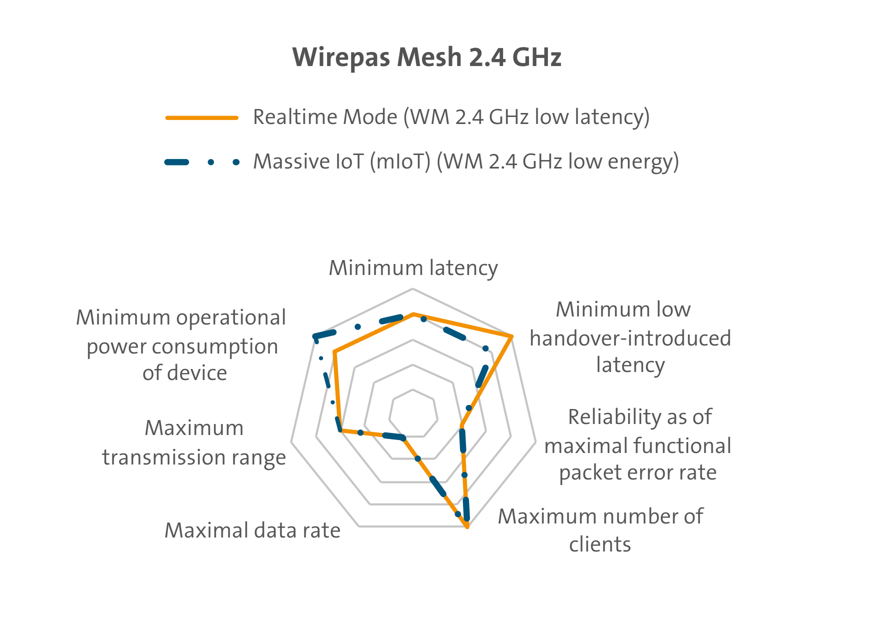
WM is a technology that enables operation in the 2.4 GHz ISM (Industrial, Scientific and Medical) frequency band and uses the same modulation scheme (GFSK – Gaussian Frequency Shift Keying) and channel allocation as Bluetooth® Low Energy for its physical layer. WM can be run on standard affordable SoC's. In addition to wireless communication, WM supports positioning services.

WM design principle foresees the utilization of any locally available frequency channels, i.e. those that a WM device can sense as non-occupied, when routing data from one WM device via the other in the direction of a gateway. Together with a hop-by-hop acknowledgement method and adaptive transmit power adjustments, very high reliability can be obtained in the already saturated 2.4 GHz ISM frequency band.

Solution providers have adopted WM to:

- Sensor solutions in industrial facilities
- Asset tracking, large-scale inventory, and positioning
- Building energy management and lighting control
- Energy metering

Technology Briefly



Note: Scale value “5” = best performance; scale value “0” = not specified. Source: Wirepas

The properties in this diagram have been defined by consensus within WCM-Working Group 2.

In addition to a consensual definition, the property values refer to requirements described in reference use cases. This is done to ensure a degree of comparability between wireless communication systems.

The reference use cases have been described by the WCM-Working Group 1, providing specific requirements for:

- Realtime / Ultra low latency communication (e.g. discrete manufacturing)
- Streaming/high data rate (e.g. video streaming)
- Massive Industrial Internet of Things (mIIoT) / Sensor Networks (e.g. valve status)

Property Definitions

Minimum Latency

Nominal achievable latency for the given reference use case and the associated functional packet error rate (FPER) property.

- Assuming that all clients are able to fulfill this latency requirement at the same time
- The latency is measured from reference input interface to reference output interface of the wireless communication system (e.g. Layer2/3)
- The latency and FPER of the spider diagram need to be achievable at the same time as they are linked together

Minimum Handover-Introduced latency

Minimum latency added to the nominal latency when a handover of a single device occurs for the given use case. Handover assumes operation of all devices of the usecase with the associated FPER.

Reliability as of maximal Functional Packet Error Rate, where Functional PER:

Percentage of data that is delivered later than the nominal latency for a given reference use case due to errors on the channel, late channel access, scheduling, or whatever other reason.

- Assuming that all clients are at the maximum range and at line of sight
- Assuming that all devices have to fulfill the same latency requirement (provided by the minimum latency property)
- Assuming that all clients fulfill the same FPER requirement
- FPER and latency of the spiderdiagram need to be achievable at the same time as they are linked together

Maximum number of clients

The maximum supportable number of clients for the given reference use case. This means the number of clients servable by one access point/base station/node in a meshed network/relay.

- Assuming that all devices in that scenario have the same communication requirements
- The available spectrum for the property is defined by the maximum bandwidth supported by the technology.
  It needs to be in line with the data rate property
- Per default the frequency regulation of Germany is referenced

Maximum Data Rate

The maximum/peak user data rate (payload) achievable per device for the given reference use case. Assuming that all devices in that scenario have the same communication requirements.

Minimum Operational Power Consumption of Device

Mean power consumption in Watt [W] for the given reference use case.

- This references the power consumption of a known device/node for that use case
- The time duration for the averaging is defined by the use case

Maximum Transmission Range

Maximum distance from a single transmitter to a single receiver

- Assuming maximum allowed transmission power (EIRP)
- Assuming typical receive antennas for the application
- The frequency band is also defined by the application
- Assuming line of sight communication

The “Technical Parameters” chart in the “Detailed Technology Description” section provides further information on these properties and other Key Performance Indicators (KIPs).

A brief description of the reference use cases can be found in the Appendix.

Disclaimer: This graph is based on the information provided by the authors of this chapter – a list of authors can be found at the end of the publication – available at the time of publication. It reflects an approximate performance of the communications system at a high level, based on the requirements specified in reference use cases.

This performance may of course vary depending on the degree of customization possible in defining the specific requirements for each industrial application and on the specific implementation. Thus, dialogue between the industrial user and wireless experts is encouraged to explore all possibilities.

High-level Technology Description

Topology

WM operates by default in a mesh topology but can also be used in a star or point-to-point topologies. WM devices form a clustered tree routing topology under a device in sink role integrated in a gateway, and towards external systems. Devices automatically form the clustered tree communication structure and optimize it during the system operation. In this optimization process, each device autonomously decides whether to operate in router or non-router role and chooses the frequency channel to operate. Also, each device chooses which other device to associate with to obtain the optimum route towards a sink and gateway to gain external connectivity. No role-specific hardware is required for devices in sink, router or non-router roles.

WM supports multi-gateway (multi-sink) systems, i.e., the selection of optimum route involves also routes to different sinks. The route selection is based on routing cost calculation, including the number of hops, traffic load and link quality, introducing automatic load balancing to the network. If a sink or gateway goes down or connectivity to the sink is lost, WM devices will find a route to another sink device integrated in a gateway.

WM devices support Low-Energy (LE) and Low-Latency (LL) operating modes. LE mode is designed for low energy consumption for battery-operated power devices with the capability to route other devices' traffic. LL mode is designed for real-time and high-capacity applications. Additionally, devices can be set to operate in a non-router role for ultra-low-power applications such as asset tracking tags. Both LL and LE devices can operate in the same network.

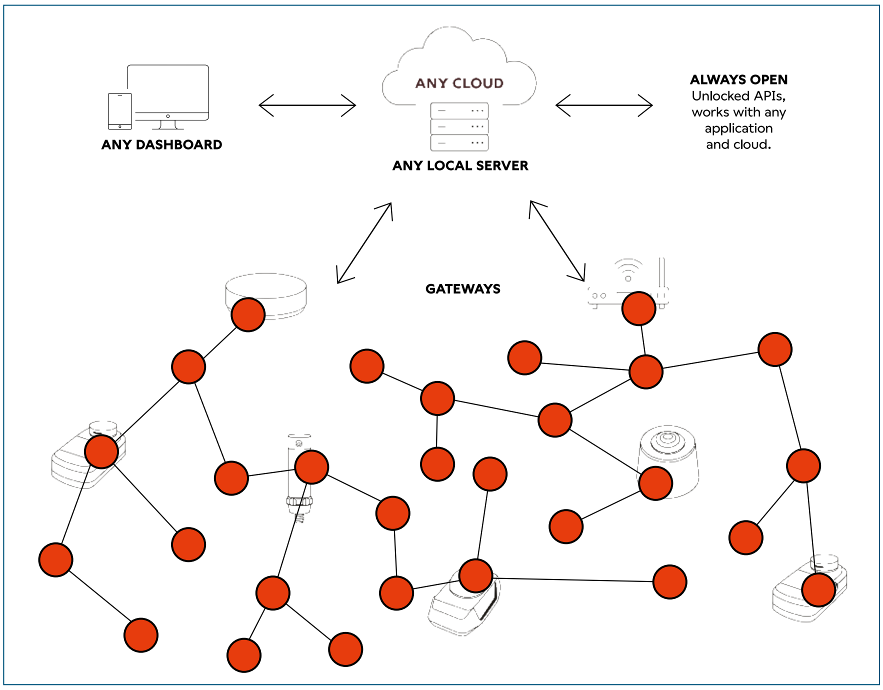


Figure 1: Wirepas Mesh 2.4 GHz system architecture. Source: Wirepas

Interfaces

Wirepas Mesh 2.4GHz provides the following services for the mesh network:

- Reception and transmission of the (application) data (payload)
- Shared network-wide configuration for the application(s)
- Provisioning functionality to provide network credentials for a new WM device(s)
- Over-the-air programming (OTAP) to update the WM firmware and the application(s) in a network
- Monitoring functionality to see the health and key parameters of a network

WM allows to build new interfaces to communicate with the WM devices. The interfaces can be built in the radio module, gateway level as well as backend level. Wirepas interfaces are, e.g.:

At device level:

- Single-MCU (microcontroller unit) interface for application operating in the same processor with WM
- UART (universal asynchronous receiver transmitter) and USB (universal serial bus) interfaces to communicate with a WM radio module

At gateway level:

- Gateway's and gateway-to-cloud APIs (Application Programming Interface)

At backend level:

- Backend services plus direct access to the MQTT broker to communicate and get the data from the WM network
- Clustered MQTT might also be used to differentiate routing payload data and WM diagnosis data
- Wirepas Network Tool (WNT) to monitor and configure networks

Time Behaviour

WM provides connectivity by establishing time synchronization for the network. The synchronization is maintained by beaconing with 2, 4, or 8-second intervals. The beaconing, i.e. broadcasting network control information is the duty of the devices in sink and router roles. The time synchronization is local among those devices able to communicate each other, which enables wide area operation with relatively simple synchronization requirements. In LE mode, data is forwarded using a time-slotted access protocol, obeying the beaconing intervals. In LL mode, data proceeds with typically tens of milliseconds per hop latency using CSMA-CA (Carrier-Sense Multiple Access with Collision Avoidance) protocol for real-time applications with delay budgets under 200 milli-seconds in multi-hop mesh environment.

Spectrum

WM uses a 2.4 GHz license-free ISM frequency band at 2400 – 2483.5 MHz. The band is divided into 40 (1 MHz) frequency channels.

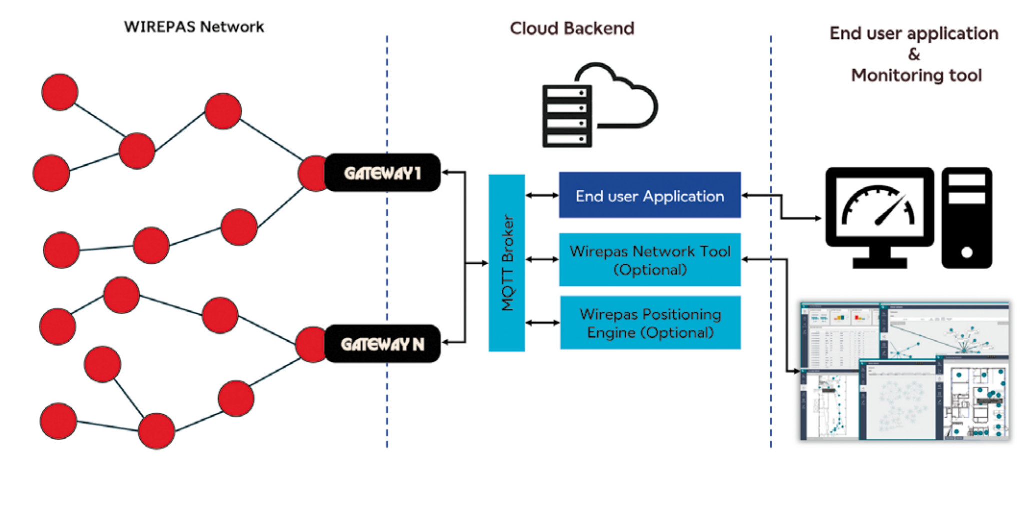


Figure 2: WM system topology. Source: Wirepas

Coexistence

Each WM sink and router can locally select the most optimum operating for the cluster where interference from non-WM systems and other WM clusters is minimized. Further, each WM device continuously evaluates the best cluster for maintaining a connection toward a sink.

Through these time and operating channel selections for the mesh networking, WM can avoid local interference caused by Wi-Fi, Bluetooth LE transmissions, or any other interference at the 2.4 GHz ISM frequency band.

The local frequency channel selection and blacklisting of interfered frequency channels and next hop selection are automatic continuous processes in each mesh WM device, enabling the network to adapt to changing interference conditions locally. As this process is done by each WM device automatically in synchronous manner with other devices, there is no need for network or frequency planning.

Maturity

The first version of the WM was published in 2014, having been implemented since then in different verticals and being in active use in the field.

Detailed Technology Description

Technical Parameters

Parameter	General KPIs
Protocol	Propietary - Wirepas Mesh 2.4 GHz
Frequency bands	2.4 GHz
Un-licensed frequency band	Yes
International coverage	Global
Real-Time capability	No
Network topology	Mesh, Star, Point-to-Point
Handover (mobility) support	Seamless
Voice support	No
Localization support	Yes
Coexistence mitigation mode	LBT, dynamic channel selection Dynamic channel and time selection per hop. Low duty cycle*
MiMo capability	No
Typical range BS - MS	Single link: up to 50 m indoor Up to a maximum of 200 m outdoor
Typical range mesh	Campus wide
Typical latency BS - MS	< 10 ms
Typical latency with one hop in a mesh	< 20 ms, < 6 s*
Typical data rate	1 Mbps
Maximal number of active clients	> 4 billion
Maximal lifetime when using a battery	n/a, Ten years*
Expected interference immunity	Good
Likelihood of coexistence	Good
Signal bandwidth	1 MHz
Coexistence relevant bandwidth	1 MHz
Localization accuracy	3 – 10 meters
Technology maturity level	Mature
Product availability	2016, 2014*
Standardization	ETSI TG 11 [1]
Standard availability	May 2021
Required Infrastructure on site	Wirepas Mesh battery-operated devices form the network, Gateway(s) needed as access point(s)

Parameter	General KPIs
Realtime Mode	**WM 2.4 GHz low latency**
Nominal latency	<10 ms**
Handover introduced latency	Seamless
Cycle time	n/a
Roundtrip time	30 ms
Maximal Functional Packet Error Rate	$<10^{-3}$
Maximum number of clients	>20.000
Telegram size	<102 Bytes
Maximal data rate MS downlink	120 kbps
Maximal data rate MS uplink	120 kbps
Data payload per MS downlink (net)	Flexible, up to 1500 Bytes (IPv6 packet)
Data payload per MS uplink (net)	Flexible, up to 1500 Bytes (IPv6 packet)
Maximal RF power [EIRP] downlink	10 dBm
Maximal RF power [EIRP] uplink	10 dBm
Required SNR	Automatically adjusted by power control to obtain 12dB SNR
Mean power consumption in usecase	21 mW per node (on average)
Maximum transmission range	Single link 200 m
Maximum velocity of an MS	3 km/h and 30 km/h
Massive IoT Mode (mIoT)	**WM 2.4 GHz low energy***
Nominal latency	< 5 s
Handover introduced latency	< 5 s
Cycle time	2, 4, or 8 s
Roundtrip time	Depends on configuration. <20 s
Maximal Functional Packet Error Rate	10^{-3}
Maximum number of clients	> 4 billion devices in single network. One Router can handle 14 members. Number of routers can theoretically be unlimited. Max. 256 hops to single Gateway. Multi Gateway load balancing built in - determining throughput. Networks >20.000 devices in operation.
Telegram size	<102 bytes
Maximal data rate MS downlink	1,2 – 4,6 kbps
Maximal data rate MS uplink	1,2 – 4,6 kbps
Data payload per MS downlink (net)	Flexible, up to 1500 Bytes (IPv6 packet)

Parameter	General KPIs
Data payload per MS uplink (net)	Flexible, up to 1500 Bytes (IPv6 packet)
Maximal RF power [EIRP] downlink	10 dBm
Maximal RF power [EIRP] uplink	10 dBm
Required SNR	Automatically adjusted by power control to obtain 12dB SNR
Mean power consumption in usecase	On average between 0.12 to 0.75 mW for router device On average 0.05 to 0.08 mW for non-router device
Maximum transmission range	200 m per hop / >10km (50 hops times 200 m) coverage
Maximum velocity of an MS	< 6 km/h

* Wirepas Mesh 2.4 Low Energy Mode

** To meet <10ms latency system needs to be configured with single link or star network operation.
If the delay requirement is relaxed, the coverage can be significantly extended by means of multi-hopping.

Technology Description

Wirepas Mesh 2.4 GHz has two different modes of operation, which can be configured at the node level:

- Low Energy mode (LE) is optimized for router device power consumption with the capability to form a network with only battery-operated devices.

- Low Latency mode (LL) is designed for real-time and high-capacity applications.

To support both LE and LE requiring applications, the network can also be built by mixing devices using the different modes together. Devices in LE mode wake up synchronously while the devices in LL mode are all the time ready to route traffic from either LE or LL mode devices.

WM network is reliable and resilient because there is no single point of failure. If one WM device fails, the rest of the devices re-organize automatically to find an alternate route to a gateway. Even battery-operated devices can start to operate as a router device at any time. If a gateway breaks down, the WM device are able to find a route to another gateway. A WM network is reliable also because each packet can be sent point-to-point to the next hop with acknowledgment and automatic re-transmissions. This assures 99,9% packet reliability in end-to-end transmissions in feasible deployments.

A WM network is also secure. It uses industry-standard AES-128 encryption and CMAC for integrity protection in all messaging (FIPS PUB 197: “Advanced Encryption Standard (AES).”; NIST Special Publication 800-38B: “Recommendation for Block Cipher Modes of Operation: The CMAC Mode for Authentication.”). An unauthorized party cannot join the network, modify messages, or read the message content. Different key-pairs (encryption and integrity) can be set to each separate network.

A WM network has also maximum scalability. The network uses cost-based routing, wherein each WM device in router role exposes the (cumulated) cost value; thus, each WM device finds the best route to the gateway by choosing the available router with lowest cost. Because the routing is cost-based, no routing tables are required to store in devices' memory. That means that extremely large networks can be built.

WM is very adaptive so that it can be used in geographically large-scale and extremely dense networks. The network can use 40 different channels, and the nodes independently select the least crowded ones. Communication between nodes is also split into time slots to optimize the channel usage of multiple nodes while minimizing power consumption. Short transmission time on-air reduces the risk of collisions. WM devices adjust transmission power between each connection, maximizing spatial reuse of the channels and minimizing power consumption.

WM has built-in provisioning and node device update features. WM provides a secure way to add new devices to a network. The nodes will get the network parameters and security keys to become network members. The whole network can be updated later on using Over-The-Air Programming (OTAP), which provides a long device lifecycle. With OTAP, multiple applications in the same network can be updated remotely, including the WM stack firmware. Also, the The firmware update is possible so that all the devices in the network are compatible with the new releases of the WM stack.

WM provides positioning of devices by using the concept of tags and anchors. Tag is a WM radio device attached to the moving asset. Anchor is a WM device in WM mesh network at a known location, transmitting regularly beacon messages. Tags wake up regularly, collect Received Signal Strength Indication (RSSI) information based on the received beacons from different anchors and send the measurement data over the WM mesh network to a Wirepas Positioning Engine (WPE). WPE computes the physical location of the tags using the RSSI information and location of the measured anchors. Location accuracy and speed are configurable within the properties of the technology (see Technical Parameters chart).

WM radio characteristics and compatibility are analysed in (ETSI TR 103 665 v.1.1.1 (2012-05), " System Reference document (SRDoc); Data Transmission Systems using Wideband technologies in the 2.4 GHz band"), listing multiple technologies applying harmonized standard EN 300 328.

Application Reference

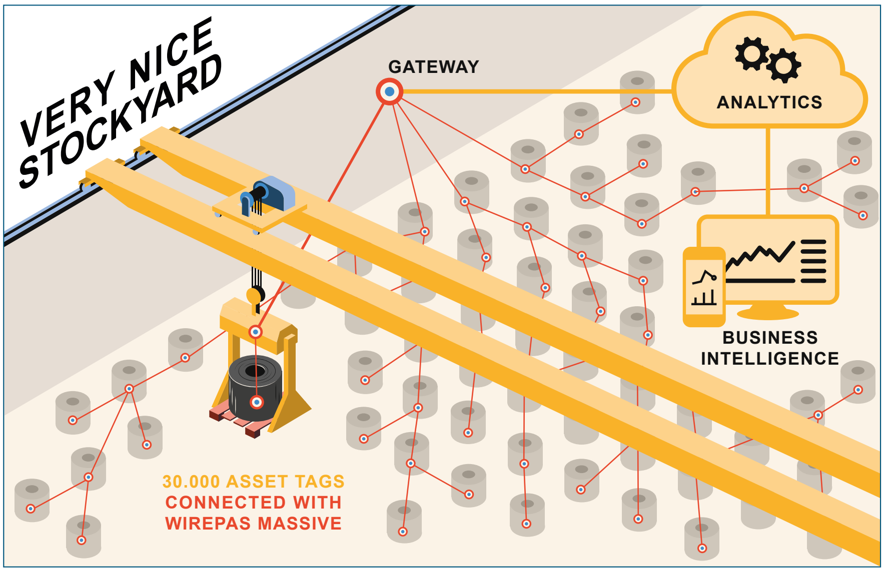


Figure 3: WM network used to track steel coils. Source: Wirepas

Application Specific Technology Description

Localization and Inventory

Tracking steel coils

Current Situation

Flat steel production facilities are filled with steel materials and big machinery. This kind of industrial environment have been considered extremely hard for wireless tracking systems as there are continuous reflections and unstable signal levels.

Pain Point

The enormous task of manually addressing all work in process, finished goods, and raw materials in the vast stockyards highlighted inefficiencies using cranes, forklifts, and operators. Because of the ongoing process of movement of the coils, there were always a number of coils missing from their location as they had been repositioned while handling other coils in shipment or production.

Inevitably this led to long truck loading times because of search and find activities inside the stockyard. But also, time losses on the production side for finding the right raw material or work in process material as operators would go inside the stock area to continuously address coils on a daily basis. Not to mention inventory counting that had to be carried out by large numbers of operators working physically on the field.

Wireless Solution

The solution was "making the steel coils talk". Solving this problem was realized through the use of WM for end-to-end tracking of the steel coils and sheets, starting from the entry of raw material to shipment of the finished products.

The system permits digital asset tracking of steel coils and sheets in the form of raw material, work in process, and finished goods used for automatic location tracking for material handling, shipment operations, and inventory counting.

Real World Example

A flat steel producer started commercial production in 2017 from a new site spanning 250,000 m². With products meeting the demands not only in Turkey but also in a region spanning Europe, Caucasus, the Middle East, and North Africa, the plant has a rolling capacity of 1 million tons of steel.

The WM-based smart tracking solution is provided by an Integrator/Solution. It includes nearly 30 000 asset tags and IoT devices being used without causing or experiencing significant interference in this extremely difficult environment area size of over 250 000 m^2 including more than 30 industrial cranes and forklifts.

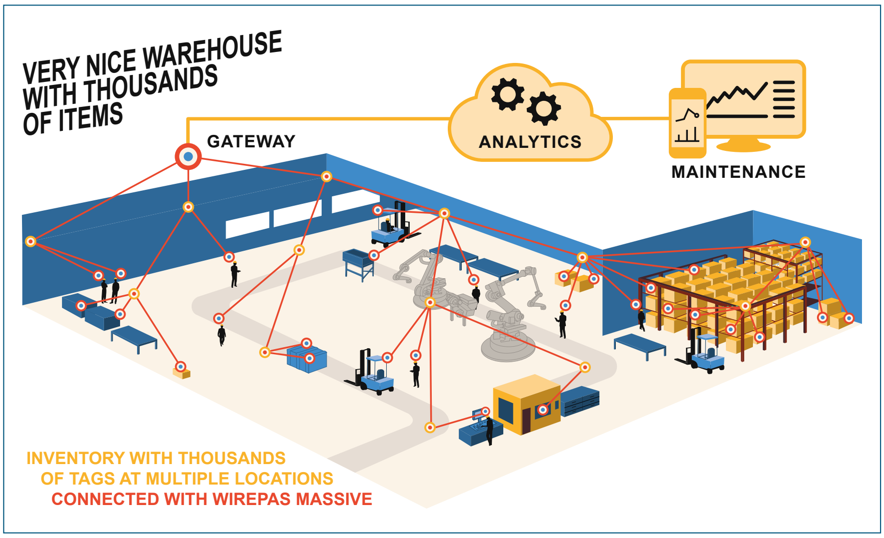


Figure 4: WM used for inventory in industrial environments. Source: Wirepas

Inventory and localization in industrial environments

Current Situation

Assets that do not serve mission-critical production processes are often only statically inventoried or tagged with location information in ERP (Enterprise Ressource Planning) systems and are not automatically tracked or continuously inventoried.

Pain point

Important information like rest times at certain places (e.g., for further assembly of semi-finished goods) or incomplete manual registrations cause long search times and high costs. The common outcome of not having inventory up to date is a lack of assets or over-dimensioned inventory, even with possible damaged or outdated assets. It results in production delays and thus reduction of sales or extensive use of capital investment to maintain an extensive inventory. In many cases, this also results in high manual labour costs and a waste of time for highly skilled workers.

Many times, the effort of building the coverage for cable-based location systems with asset tags is too complex and costly for having an up-to-date inventory and location information.

Wireless Solution

WM offers a tracking mode using the RSSI-based location solution, enabling battery-operated anchor devices in the respective warehouses. The resulting latencies (minutes) and accuracy (3-4 m) fit the requirements.

In addition, the technology had to comply with the manufacturer's very strict rules for frequency deployment and radio interference, where introducing new technology on the 2.4 GHz spectrum is considered a big challenge. By design, WM operates in a very spectrum-friendly manner.

Many users conducted successful independent testing for coexistence and approved WM operation in industrial shop floor environments.

Real World Example

When the design department of a car manufacturer needs to locate cars or component prototypes in a hurry, there's no time to search its warehouses. Locked-in with an end-of-life barcode-based inventory system, this was the problem facing one world-leading German automotive OEM. As the proposed in-house solution proved not fit-for-purpose as it derived from a very infrastructure-intense, high accurate, and low latency real-time location system (RTLS), the search was started for a more fit-for-purpose option.

The solution now in place makes each stored prototype carry an RTLS tag autonomously connecting with battery-operated anchors through to a gateway. The anchors form an efficient, robust mesh network where each anchor acts as a relay to the next – with a battery life of more than five years. All on available frequencies without influencing existing Wi-Fi 2.4 GHz networks. Data is delivered via tags and gateways to the positioning engine, which calculates location and interfaces to the automaker's own secure cloud environment.

Tests in simulated environments were run from an independent test house, resulting in the whitelisting of WM technology with the manufacturer.

Industrial Monitoring
Condition monitoring system and predictive maintenance

Current Situation
Unplanned downtimes are one of the largest and most costly challenges an operator of an industrial plant is facing.

Pain Point
In many cases, these are a surprise because only a small percentage of machines are monitored online in real-time. The complexity and effort to constantly monitor every turning or rotating device is very high and cannot be obtained with cabled solutions. In addition, revolving temporary sanity checks, e.g., ultrasound or other sensor devices surging the machines, are also causing planned downtimes that are intended to be reduced.

Wireless Solution
WM enables service providers wireless condition monitoring. Data collection can be done with low-power, battery-operated devices that can operate for years. The design principle of decentralized and autonomous networks created by the radio devices themselves makes any extensive planning redundant. It permits the condition monitoring sensors to be commissioned by any plant worker. The robustness of the mesh that is constituted and permanently adapted to local radio environments reduces the onsite maintenance effort to a very minimum.

Real World Example
A leading global supplier to the automotive and industrial sectors, deployed its solution for Industry 4.0 using WM as the wireless IoT connectivity. The solution offers wireless condition monitoring that helps any production reduce downtime. The mobile app provides visual monitoring over the condition of the machines, which in turn allows for fast reaction to possible issues in their operation. Continuous development and innovation based on the machines' analytics will enable improvements in production and less downtime.

Fast and easy installation that does not require specifically trained technicians or engineers. Several hundred measuring sensors can be installed in a single day, and activation happens through a simple NFC-based mobile end-device app. WM also allows to envision multiple use cases beyond condition monitoring, installed sensors, and gateways being used as a backbone.

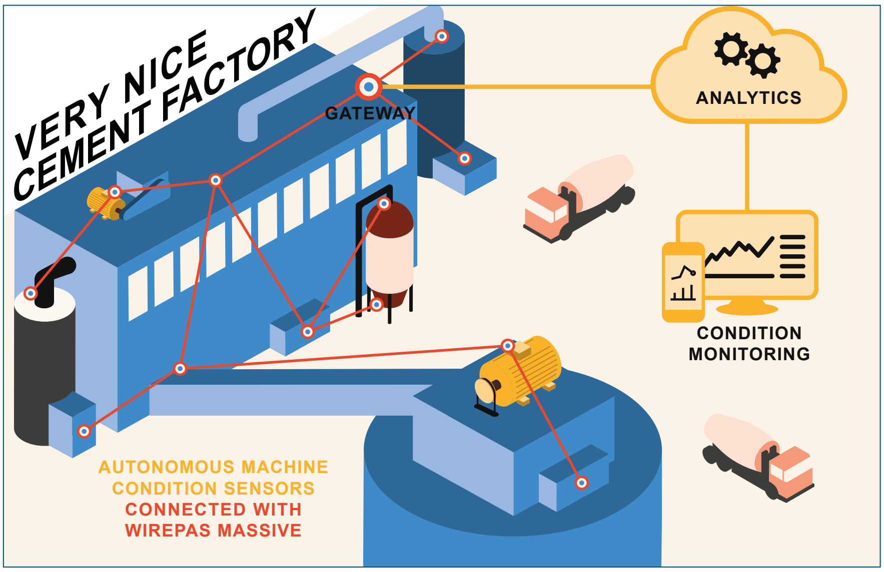


Figure 5: WM used for condition monitoring Source: Wirepas

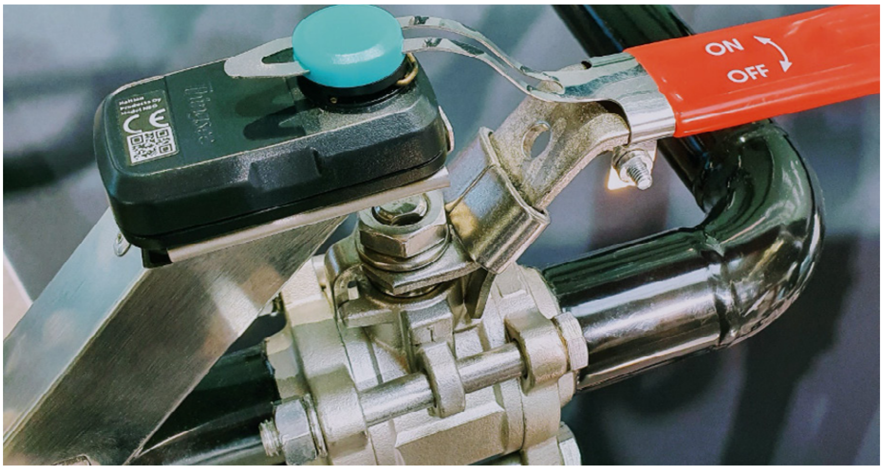


Figure 6: WM-enabled valve sensor Source: Wirepas

Remote Monitoring system
for manual control valves

Current Situation
Ensure monitoring of manual control valves in an industrial installation, for example, to avoid any environmental damage due to hazardous substance leaking, can't be done through cabling for understandable cost and complexity reasons.

Pain Point
In many cases, only critical points of the installation will be prone to inspections, leaving a probability of defects in many parts of the system, whose impact can be very important.

Ensuring manual control of the critical valves in the installation may also have, for consequence, a rundown of the activity. In addition, many technologies have challenges in scaling the number of devices in one installation.

Wireless Solution
Installing WM based sensors on each and every valve in the installation, regardless of the type of the valves, which can be ball or butterfly ones. Configuration is done onsite and is not time-consuming. WM device installations (and with this, the network implementation) are made by regular maintenance staff.

Real World Example
A WM-based sensor is simply attached to any manual valve to provide real-time visibility over valve positions. This makes maintenance work safer and the subsequent production ramp-up faster, saving CAPEX & OPEX.

Stable communication was assured even in harsh production conditions, which was difficult for wireless technologies.

Bibliographic Handlist

ETSI TR 103 665 v.1.1.1 (2012-05), “System Reference document (SRDoc); Data Transmission Systems using Wideband technologies in the 2.4 GHz band”.

FIPS PUB 197: “Advanced Encryption Standard (AES).”

NIST Special Publication 800-38B: “Recommendation for Block Cipher Modes of Operation: The CMAC Mode for Authentication.”