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LoRa connectivity for Condition-Based and Predictive Maintenance in Smart Industry

Industrial IoT (IIoT) is driving continuous technological innovation and advancement in production systems as dated manufacturing processes transition into more connected systems offering greater flexibility and control. This transition implies an overhaul of the largely approximative maintenance schedules for industrial machinery based on historical data and vendor recommendations, which do not account for the actual condition of articulated or moving components.

Condition-Based Monitoring (CbM) represents a paradigm in maintenance as it is based on real data about the state of rotating and moving components, usually by monitoring physical measures (vibration, current, temperature, etc.) at selected points on or around process machinery. CbM can also represent the first phase in Predictive Maintenance (PdM) strategies aimed at reducing downtime and optimizing maintenance strategies.

Edge computing is a key element in wider scale CbM and PdM implementations, as multiple sensor data streams can easily exceed network bandwidth limits and even the processing capacities of centralized servers and cloud systems. Local microcontrollers and microprocessors on sensor nodes and gateways can help streamline such data intensive flows by immediately filtering and processing captured data, and latest generation sensors can implement decision trees to ensure only exceptional data is processed.

Complex monitoring systems with multiple nodes and gateways, however, present substantial cabling issues over short and long ranges, with wireless communication often representing the preferable alternative.

This paper presents an Edge node configuration for condition-based monitoring solutions using LoRaWAN architecture to take advantage of the features that render the LoRa communication protocol highly suitable for large scale Smart Industry scenarios.

The distances seen in heavy industry and energy farming systems are better serviced by Low Power Wide Area Networks like cellular and LoRaWAN.

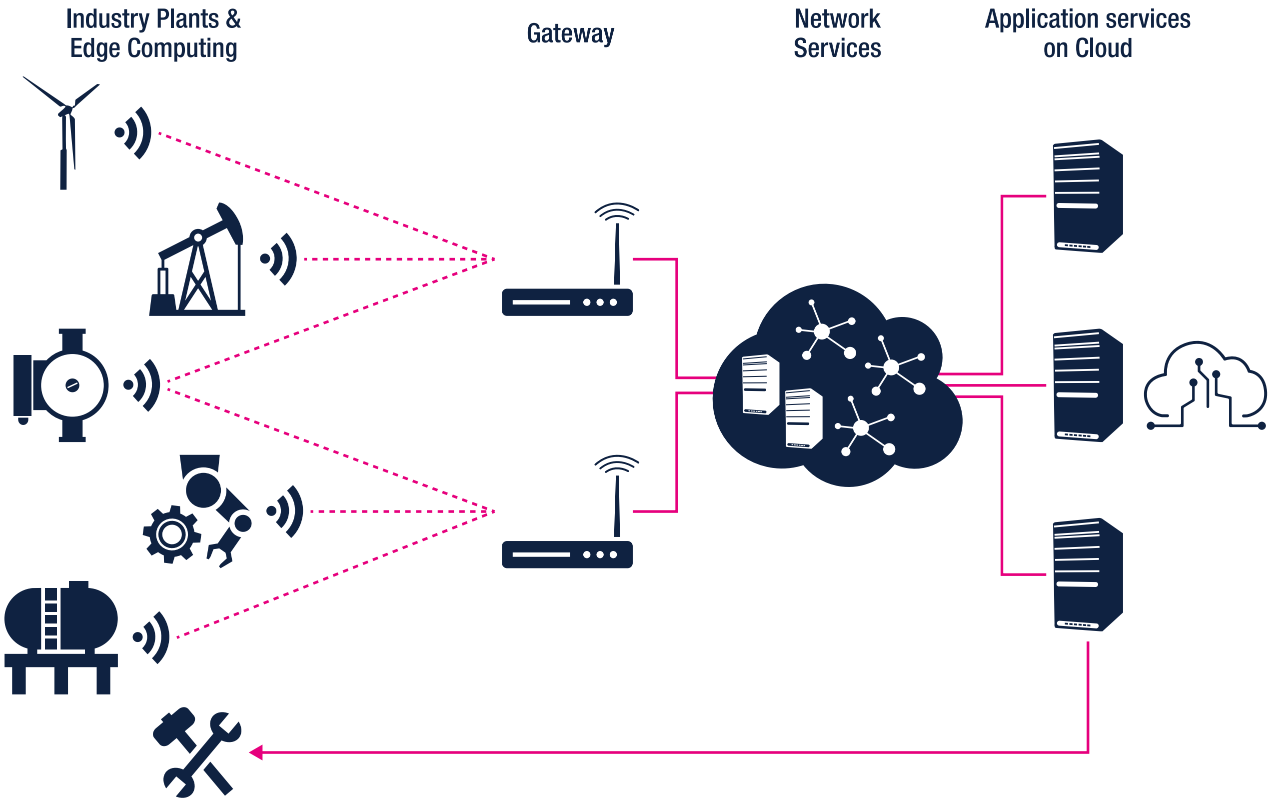


Figure 1: LoRaWAN Architecture for Smart Industry

INDUSTRIAL APPLICATION SCENARIOS FOR LoRa

Some of the industrial activities requiring extended coverage in remote and often hostile climates include:

- Oil & Gas extraction and transportation
- Wind farms and solar parks
- Mineral mining plants

Figure 2: Industry plants in remote areas

The size and scale of such installations do not lend themselves well to cable connectivity, leaving wireless communication as the best option. An appropriate wireless technology must, however, offer extended transmission ranges at sufficient data rates and remain cost effective in order to facilitate a viable condition-based monitoring system.

Low Power Wide Area Network (LPWAN) technologies such as LoRaWAN™ offer a range of features able to support typical industrial application requirements, including:

- low power consumption to support battery operation
- flexibility and scalability over wide area private and public networks
- cost-effective long distance communication even in harsh climates
- simple and secure protocols
- support for a large number of simultaneous network connections

The crucial network security aspect is based on rigorous key exchange procedures during device activation and authentication, and is integral to the Edge node project discussed herein.

INTRODUCING LoRa AND LoRaWAN

LoRa (Long Range) is a Semtech patented modulation technique, based on chirp spread spectrum (CSS) modulation. This physical layer delivers low-power, long-range communication in license-free sub-gigahertz radio frequency bands.

LoRaWAN™ (Long Range Wide Area Networks) is the open standard developed and supported by the **LoRa Alliance** to allow LoRa communication over long-range, bi-directional networks in star topologies consisting of end-devices, gateways, network servers and application servers.

Network architecture

End-devices are often the remote sensor nodes located on or around monitoring points in the system. Gateways, also known as concentrators and base stations, receive data packets from one or more end nodes and forward them via the Internet (Ethernet, Wi-Fi, cellular, etc.) to a designated network server. This server, representing the center point of the star network, manages a series of tasks, including gateway and dataflow management, data filtering, security checking, acknowledgment scheduling, and adaptive data rate implementation. The resulting data is then sent to dedicated application servers for processing, logging and conversion into useful, human-interpretable information.

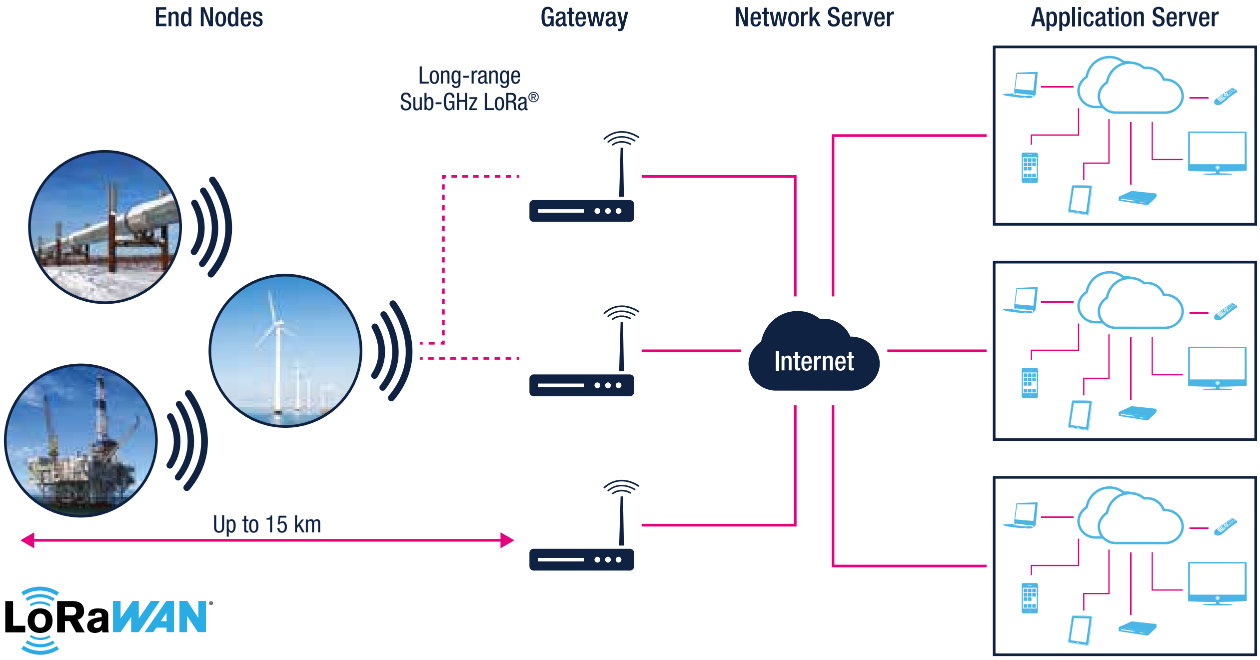


Figure 3: LoRaWAN star topology architecture

Cost-effective infrastructure and security

LoRaWAN uses license-free spectra, usually ISM (Industrial, Scientific, Medical) frequency bands, which are established and controlled by the specific regions (e.g., 868 MHz in Europe, 915 MHz in North America), with certain limitations in terms of allowable traffic volumes.

LoRaWAN network security is implemented through the exchange of keys and identifiers to establish mutual authentication between the LoRaWAN end-device and the LoRaWAN network during a device registration event. The user can choose between Over The Air Activation (OTAA) or Activation By Personalization (ABP), which performs end-device personalization and activation in a single step.

Both of these activation methods allow the exchange of keys and identifiers to establish secure end-to-end communication. When a device is registered, the user selects the activation method and provides the appropriate security keys. The network join procedure then establishes mutual authentication between the LoRaWAN end-device and the LoRaWAN network (visit **LoRa Alliance** for more information).

Unlicensed spectra allow companies to build and implement private networks without having to acquire frequency licenses. Companies can also subscribe to public networks and use the antennas made available by telecom operators.

EDGE PROCESSING FOR CONDITION-BASED MONITORING AND PREDICTIVE MAINTENANCE

Wear and failure detection

The degradation of equipment is a gradual process that can be observed in the progressive change in certain parametric values over time. For maintenance purposes, the lifecycle of rotating equipment can be divided into three distinct phases: installation **(I)**, the point where failure signs manifest **(P)**, and full failure **(F)**.

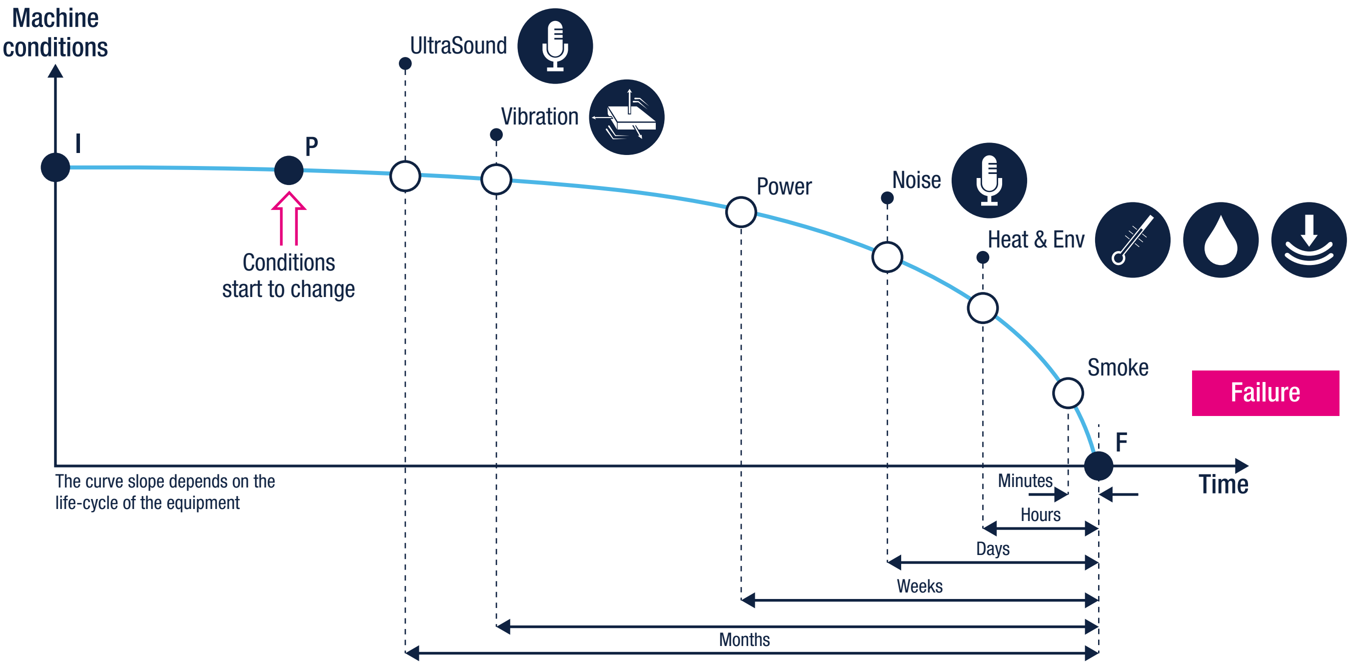


Figure 4: Equipment lifecycle (IPF curve)

Ultrasound and vibration sensing and analysis in combination with supporting ambient temperature, pressure, and humidity data are among the most suitable for monitoring the condition or status of moving equipment and under varying loads.

Such data can be analyzed both over time to reveal unexpected excursions beyond set thresholds, and over frequencies to track trends in rotary or linear dynamics as they evolve. These parameters can be interpreted together to map changing equipment condition patterns across operational lifecycles.

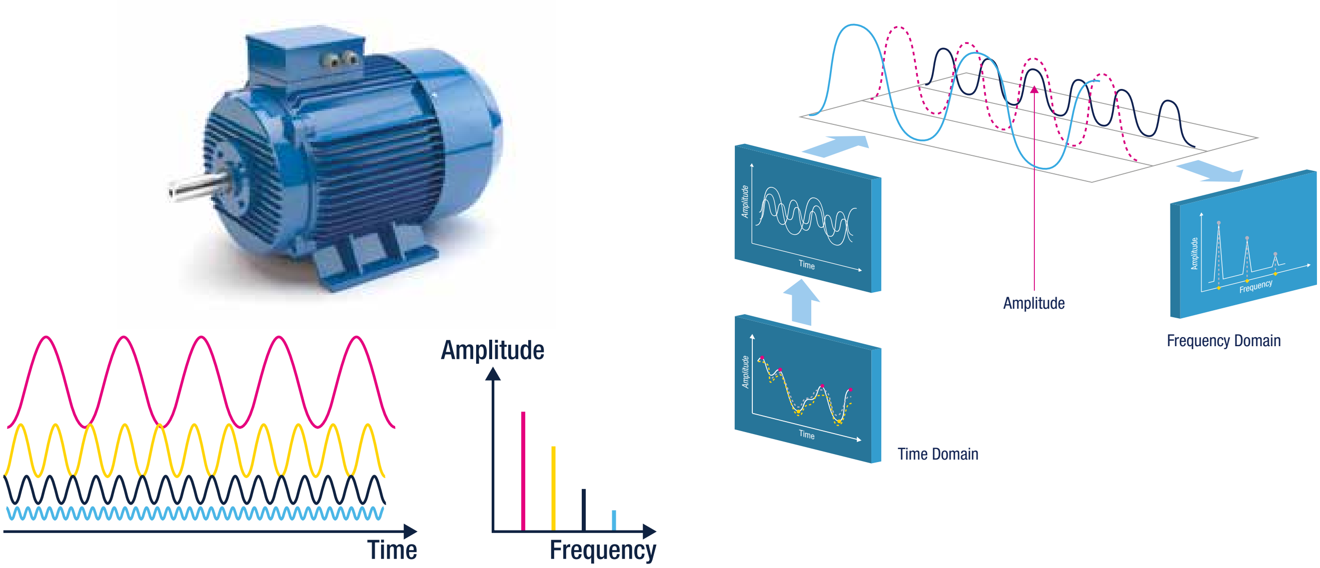


Figure 5: Vibration analysis in time and frequency domains

Time and frequency domain analyses

Time domain (TD) analyses of vibrational data acquired over specific time frames can be integrated with external data and processed to reduce offset or noise, derive RMS moving averages, and isolate peak values. The resulting data can then be compared with corresponding model or signature data to determine the effective status of the measurement data.

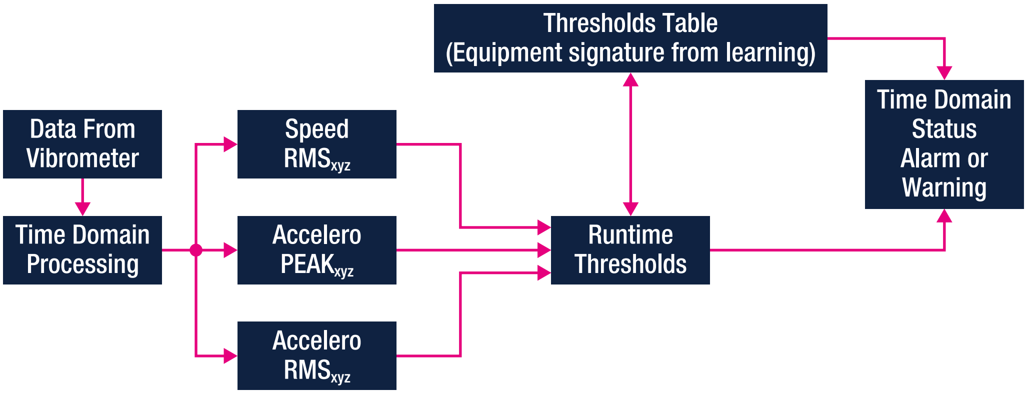


Figure 6: Time domain processing architecture

Time domain analyses continuously monitor operating conditions at different working loads to detect sudden events such as cracks, breakages or shocks. They also help isolate gear and bearing defects over time to allow prediction of the end-life of moving components.

Frequency domain (FD) analyses implement Fast Fourier Transforms (FFT) to derive acceleration power spectra over specific sample sizes through various windowing (rectangular, Hanning, Hamming, flat top), overlapping, output buffering and averaging techniques. Transformed data is then adapted and classified in subranges, which can be compared with signature threshold tables to determine the status of the measurement data.

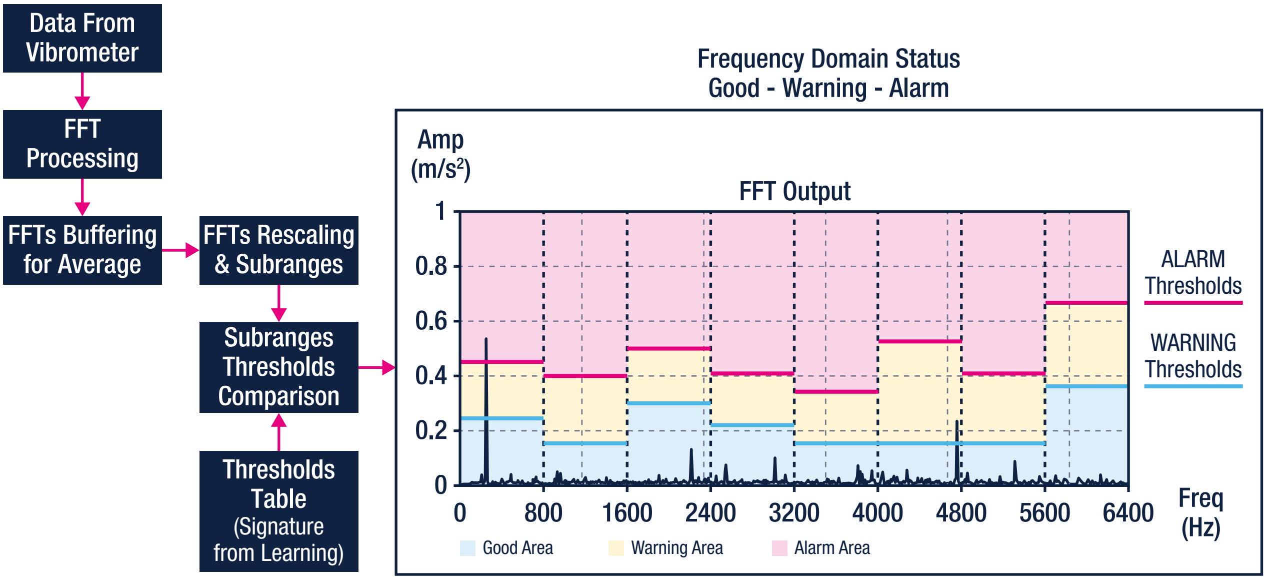
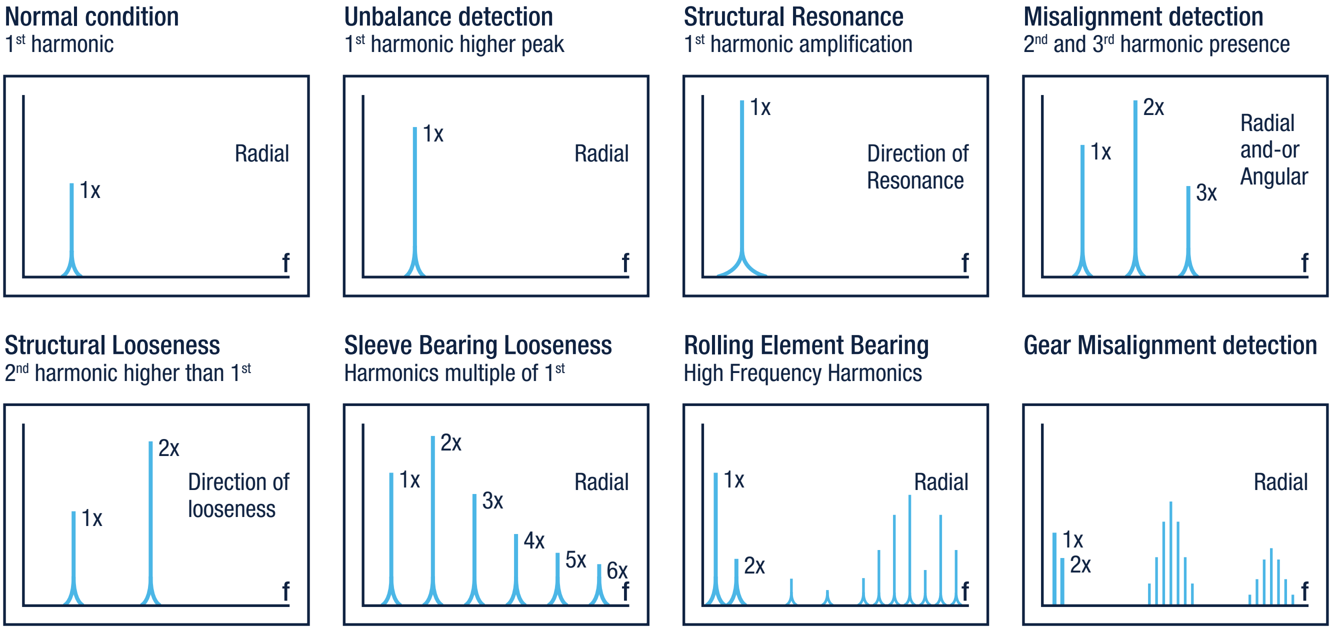


Figure 7: Frequency domain processing architecture

Frequency domain analyses can ultimately reveal various mechanical assembly (tightness, misalignment) and structural (failure, fatigue) issues, which can severely impact critical operating conditions.



Normal condition
1st harmonic

Unbalance detection
1st harmonic higher peak

Structural Resonance
1st harmonic amplification

Misalignment detection
2nd and 3rd harmonic presence

Structural Looseness
2nd harmonic higher than 1st

Sleeve Bearing Looseness
Harmonics multiple of 1st

Rolling Element Bearing
High Frequency Harmonics

Gear Misalignment detection

Figure 8: Typical fault indications through FFT analysis

The process involves comparing real machinery condition data with historical time and frequency domain (or custom statistical) data in order to classify the good, warning, or alarm condition of equipment signiture data.

More details regarding this process can be found in the whitepaper:
Capacitive MEMS accelerometer for conditioning monitoring.

Advanced data processing

The data collected from machinery is categorized in extensive databases according to the various operating conditions, ready for comparison in conventional diagnostic processes or used to seed more innovative diagnostic models based on Artificial intelligence (AI).

The databases or functional tables can be updated and integrated with other specific information pertaining to specific machinery or wider production processes such as total machine operating time, primary functions, and previous maintenance interventions in order to generate status KPI for mechanical condition evaluation and maintenance planning.

More innovative predictive methodologies deploy neural network models and machine learning algorithms to allow systems to learn continuously from up-to-date source data and refine the applicable models accordingly.

The learning techniques for deriving the functional model from database information may be supervised or unsupervised. Supervised learning uses comprehensive databases that include fault, process and maintenance information, while unsupervised learning is limited to unclassified data such as process information. Semi-supervised learning uses both database types.

The scenario may be further extended with diagnostic algorithms able to evaluate the Asset Health Index (AHI) of machinery using real-time and historical data or predicting Remaining Useful Life (RUL) to avoid unrecoverable failures.

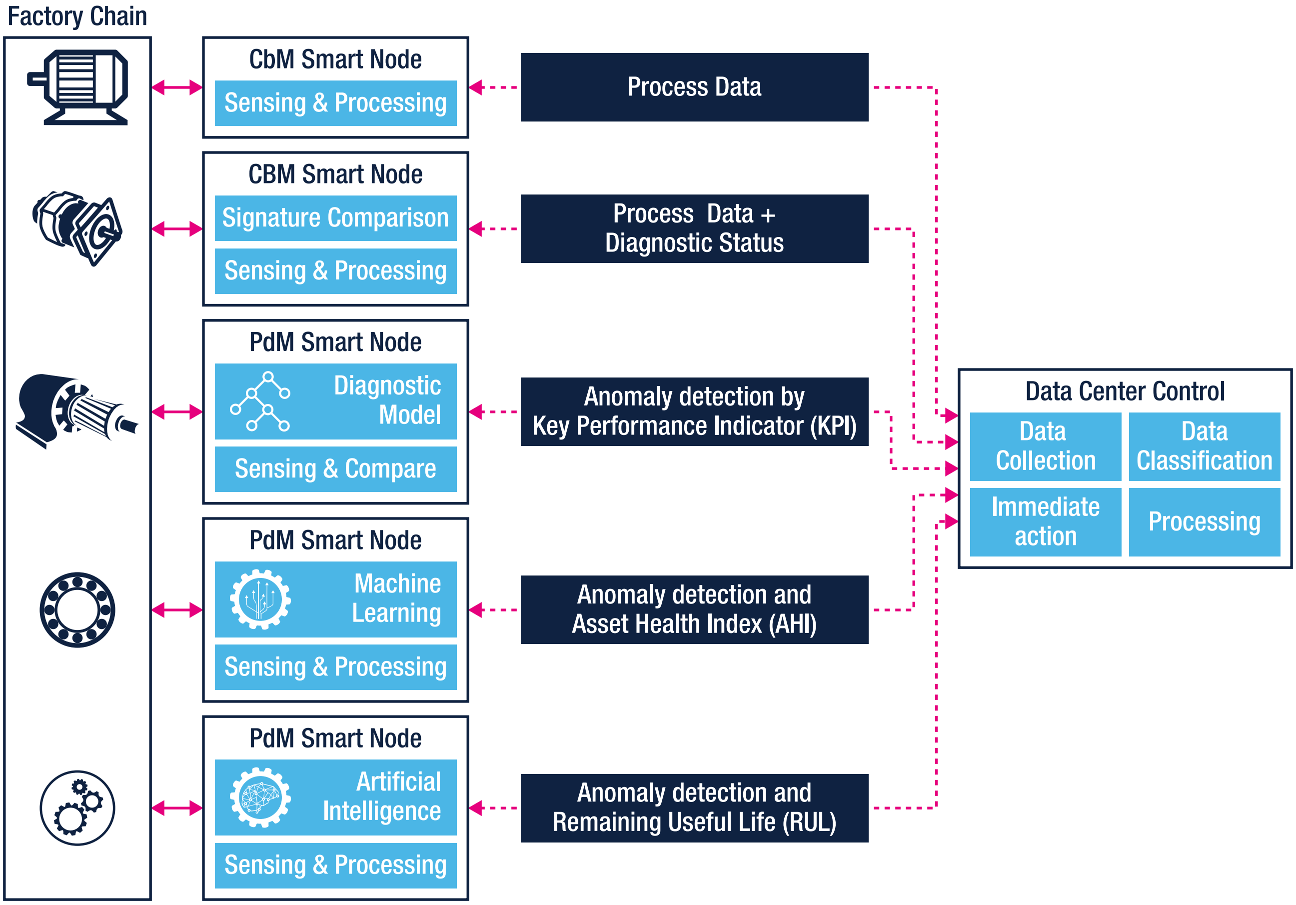


Figure 9: Possible scenarios for data processing

LoRa TRANSMISSION CHARACTERISTICS

Transmission rates

For each world region, the LoRaWAN Regional Parameters document specifies the maximum data payload size, which varies by Data Rate (DR) – primarily a function of bandwidth and spreading factor – due to the maximum on-air transmission time allowed by Region [RP002-1.0.3 LoRaWAN® Regional Parameters, 2021 Lora Alliance] (Table 1, Table 2).

DataRate	MACPayload size (M)	Maximum application payload size (N)
0, 1, 2	59	51
2	123	115
4, 5, 6, 7	230	222
8	58	50
9	123	115
10	58	50
11	123	115
12:15	Not defined	

Table 1: Data rates and payload sizes for Europe (EU863-870) in the absence of FOpts control field

DataRate	MACPayload size (M)	Maximum application payload size (N)
0	19	11
1	61	53
2	133	125
3, 4	230	222
5	58	50
6	133	125
7	Not defined	
8	61	53
9	137	129
10:13	230	222
14:15	Not defined	

Table 2: Data rates and payload sizes for US (US902-928) in the absence of FOpts control field

The data rate of an end-node may also be varied via the Adaptive Data Rate (ADR) mechanism, which optimizes communication between each device and gateway in terms of energy consumption and time-on-air, according to the RF conditions.

LoRa communication performance depends on the spreading factor, which is an integer value between 7 and 12. A larger spreading factor increases the time-on-air, which increases energy consumption, reduces the data rate, and widens communication range.

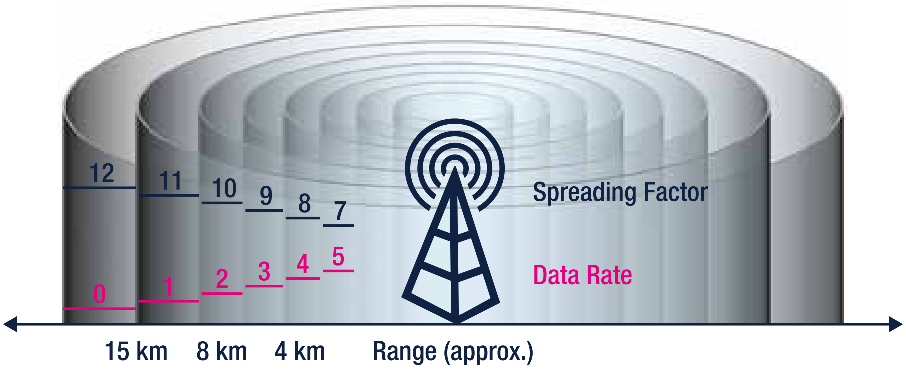


Figure 10: Range vs. Spreading Factor

A fragmentation and recovery solution to payload limitations

While the ceilings on LoRa payload sizes may be sufficient for certain IIoT applications, more intensive scenarios such as condition monitoring with frequency domain acceleration and subrange data will almost always exceed maximum allowable packet sizes, regardless of the region.

This limitation may be managed through the fragmentation of data packets into multiple frames that are reassembled on the application servers. Unfortunately, the increased use of ack messages to recover lost partial frames may significantly increase network activity and perhaps exceed network server limits regarding the number of allowable downlink messages.

Our research into this problem has uncovered a better alternative for frame recovery using only two additional fields per uplink fragment. The fields indicate the total number of fragments in the current data block and the index of the current fragment in terms of fragment length, with the exception of the last fragment. Upon completion, the end-node sends a *Downlink Request* frame to trigger a cumulative ack by the application server containing any indexes of missing frames. To open a receiving window for this downlink message from the application server, the device sends another *Downlink Request* frame.

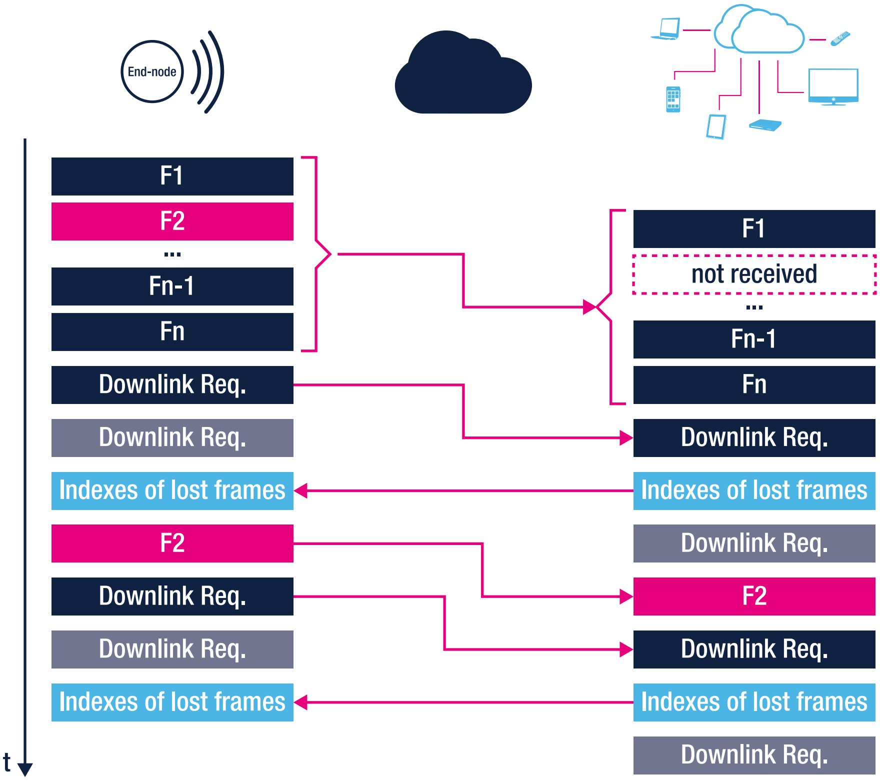


Figure 11: Downlink for fragmented data

Once the downlink message is received and decoded, the end-node resends the missing frames, and the entire process is reiterated until the end-node receives a zero index value for missing frames, effectively confirming that the whole message has been recovered at application server level, or until the maximum number of attempts is reached, in order to render the mechanism more reliable.

This approach is consistent with the underlying LoRaWAN principle of low band occupation, even when large payloads are involved, and can still respect airtime limits as industrial nodes in CbM and PdM contexts only need to generate longer messages in certain circumstances, such as when anomalous activity is detected or when FFT frames are involved.

The method carries advantages even when frames do not exceed maximum packet limits, as it can help improve goodput in denser and slower networks.

APPLICATION SERVER IMPLEMENTATION FOR CbM

All the processed data generated by the LoRa CbM system is decoded and manipulated in the application server that provides the human interface functionality on a suitable dashboard to complete the comprehensive monitoring scenario.

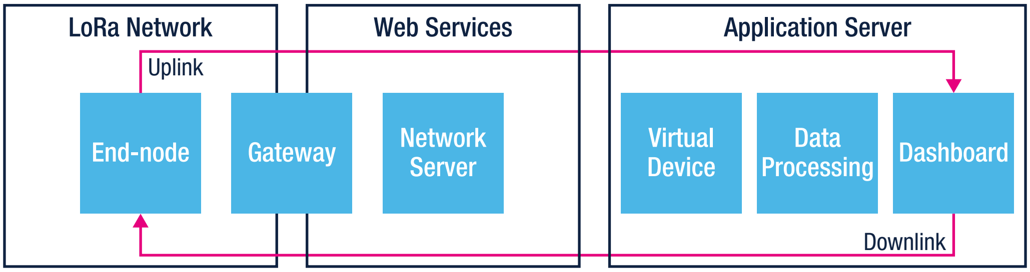


Figure 12: Application server architecture for CbM

The application server interfaces with the network server through virtual devices or software objects that reflect any status changes on corresponding real end-node devices. A data processing component then parses, extracts, modifies, and aggregates any information contained in the payloads and returns downlink messages to the device.

Single payloads are simply decoded to extract and store measurement data in buckets for subsequent representation on the dashboard interface. Multiple payload messages are instead analyzed to verify fragmentation sequences before storing and presenting measurement data on the dashboard once all the frames have been collected. Lost frames will, of course, trigger downlink message requests for the end-node to retransmit the missing frame.

TYPICAL APPLICATION EXAMPLE

ST solutions for LoRa end-node designs

STMicroelectronics offers one of the widest ranges available for end-node combinations of sensors, processors, long range RF communication and power management solutions.

3-axis digital MEMS vibration sensors generally represent the primary sensing elements and ST offers highly suitable devices in terms of design versatility, accuracy, bandwidth, and robustness in high temperature environments. Pressure, humidity and temperature data are common inclusions, and ST again features a comprehensive range of compact, low-power environmental sensors fully compatible with STM32 microcontrollers and wireless systems-on-chip.

ST offers a dedicated AI framework and design services, including machine learning implementations in **sensors with Machine learning cores** and in MCUs running software based on **NanoEdge AI Studio** and **STM32 Cube.AI**, both allowing new levels of intelligent power management and algorithm performance optimization.

STM32 microcontrollers (MCU) with ARM® core architecture and extended peripheral set represent ideal end-node application and communication processors for LoRa end-node solutions in condition-based monitoring scenarios.

In terms of managing and processing high-speed sensor data, the processing capacity and ultra-low power architecture of the **STM32L4+ series** render this MCU the perfect application processor for building IIoT nodes. To increase the level of integration, the **STM32WL Series** MCU embeds a sub-GHz radio that supports LoRa modulation. This MCU is an ideal network processor for long range, bidirectional wireless communication over a LoRaWAN network.

Alternatively, a dual-core STM32WL MCU can fulfil both application and network processor roles, with benefits in terms of integration, computational power, available resources and security features for application development.

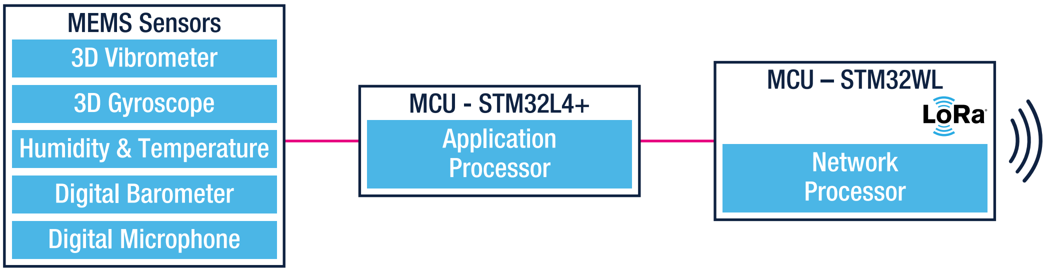


Figure 13: IIoT node block diagram

Application scenario

The envisioned condition-based monitoring scenario involves certain data types, including temperature, pressure, relative humidity, battery charge status, and the following analytical outputs:

- Time domain values (peak acceleration and speed RMS) with related status.
- Frequency domain results in terms of maximum amplitude detected in power spectrum (FFT) and related frequencies.
- Frequency domain status derived from comparison with pre-defined signatures.

Supposing a LoRaWAN public or private network with 10 industrial nodes generating environmental data along with the analytical outputs, the standard LoRaWAN transmission duty-cycle constraints would be satisfied using the following strategy:

1 The end-node tracking normal operation periodically sends inertial TD and FD analyses over 15 minute intervals or greater, depending on the monitored equipment.

2 After each N transmissions (e.g., N = 3 = once per hour), the analytical data is accompanied by environmental data.

3 If equipment warning or alarm states are raised in the frequency domain, subranges are immediately scheduled for transmission using the same fragmentation strategy (once per hour), until the equipment returns to its normal status.

4 Once per day, or on user request, a complete power spectrum array can be transmitted, generally using fragmentation to manage the larger payload size.

5 Fragments are timed to respect access policies imposed by the network server provider, but their transmission interval must be in the order of seconds in order to complete the full FFT frame as rapidly as possible on the application server side.

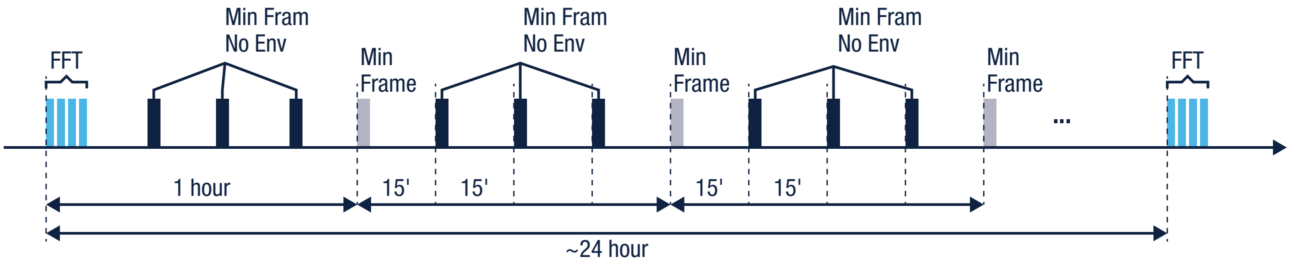


Figure 14: Single and multiple frame LoRaWAN transmission example for CbM

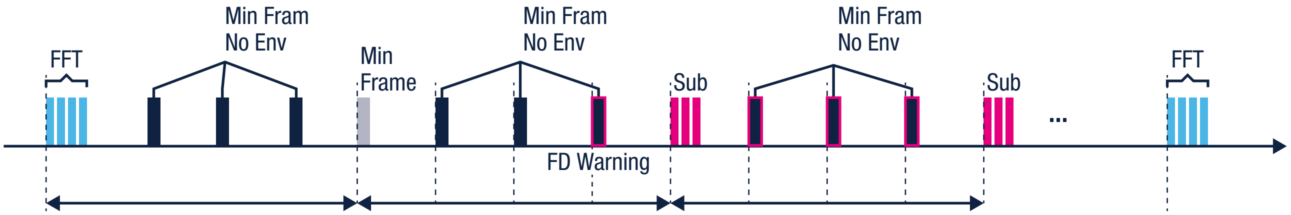
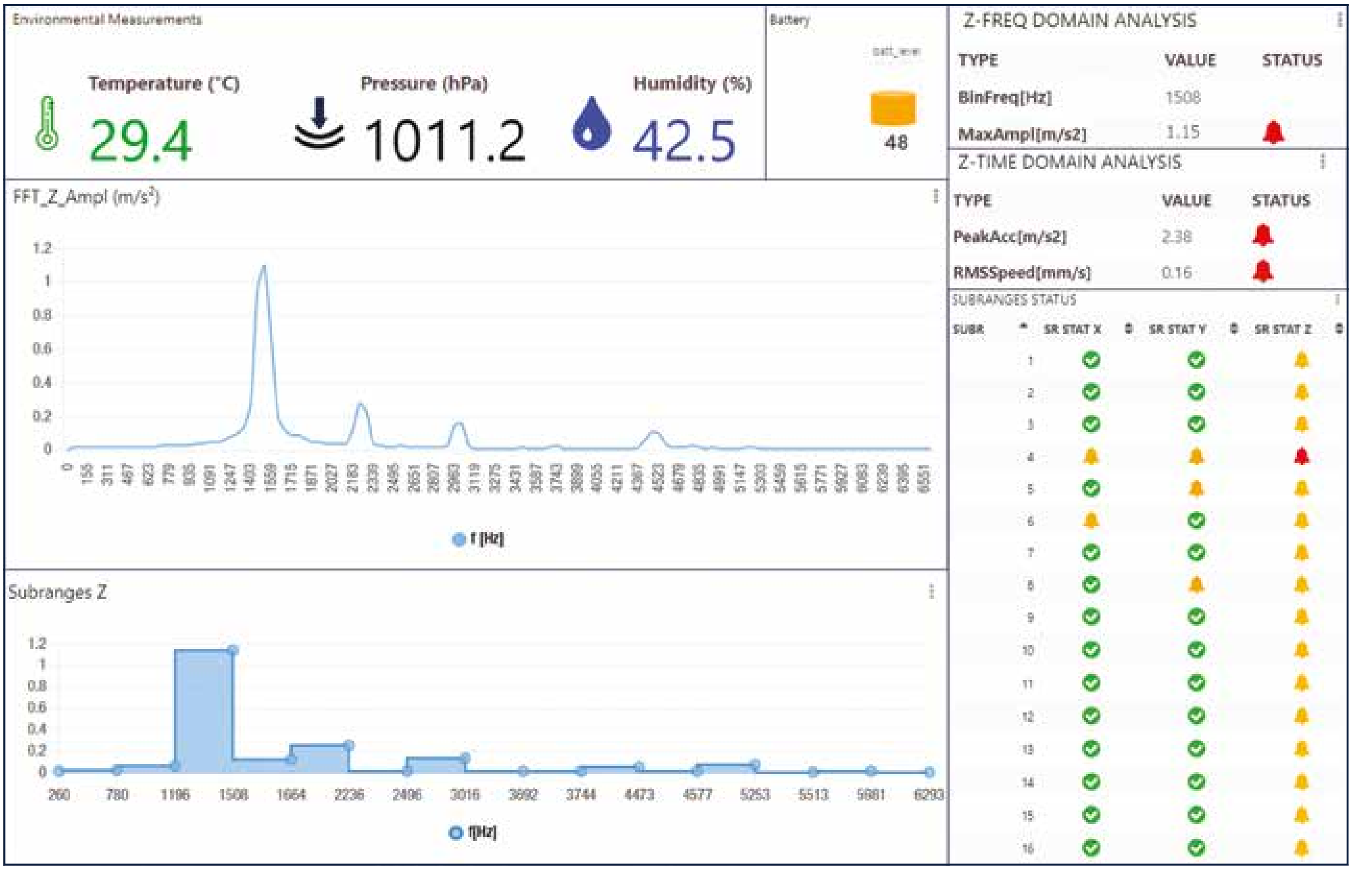


Figure 15: LoRaWAN transmission example for CbM in Warning or Alarm events

To emulate typical use cases, a sensor node can be mounted on a shaker or a motor with bearing to evaluate its performance using the LoRaWAN message scheme indicated above. In a complete system, the results are sent to the application server via the network server, and the LoRa messages are stored, decoded, analyzed, and displayed on a personalized dashboard using custom widgets, in order to present the user with intelligible and useful equipment status information.


Environmental Measurements

Temperature (°C) 29.4

Pressure (hPa) 1011.2

Humidity (%) 42.5

Battery

batt_level 48

Z-FREQ DOMAIN ANALYSIS

TYPE	VALUE	STATUS
BinFreq[Hz]	1508	
MaxAmpl[m/s2]	1.15	🔔

Z-TIME DOMAIN ANALYSIS

TYPE	VALUE	STATUS
PeakAcc[m/s2]	2.38	🔔
RMSSpeed[mm/s]	0.16	🔔

SUBRANGES STATUS

SUBR	SR STAT X	SR STAT Y	SR STAT Z
1	✓	✓	🔔
2	✓	✓	🔔
3	✓	✓	🔔
4	🔔	🔔	🔔
5	✓	🔔	🔔
6	🔔	✓	🔔
7	✓	✓	🔔
8	✓	🔔	🔔
9	✓	✓	🔔
10	✓	✓	🔔
11	✓	✓	🔔
12	✓	✓	🔔
13	✓	✓	🔔
14	✓	✓	🔔
15	✓	✓	🔔
16	✓	✓	🔔

Figure 16: CbM results in a dashboard on Application Server

CONCLUSION

Much of the present Industry 4.0 industrial revolution revolves around the greater use of digitization along production chains to improve control through innovative processes, tools, and practices.

LoRa technology represents one of the most promising communication technologies surrounding Industrial Internet of Things and is integral to this proposal for a viable predictive maintenance strategy for even the most remote installations and harshest conditions.

ST products and technologies are equally pivotal in this context, with sensing, data processing and connectivity solutions designed specifically for monitoring process conditions, along with comprehensive hardware and software tools and environments aimed at helping professionals accelerate proof of concept and field testing phases.

RESOURCES

LoRa Alliance [Official Web Page]

Mobius Institute [Official Web Page]

Capacitive MEMS accelerometer for Condition Monitoring [Download Page]

Condition Monitoring and Predictive Maintenance at a glance [Application page]

ST's Industrial sensors [Application page]

STM32WL microcontrollers [Product Page]

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Order code: **BRWPCBMLORA1121**