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Functional QoS Metric for LoRaWAN Applications in Challenging Industrial Environment

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***Abstract*—Industry 4.0 applications rely upon timely and accurate data about plant and process within a production site. Whilst modern facilities tend to have this capability as a matter of course, older equipment may lack network connectivity. A lack of data-gathering capability represents a significant barrier-to-entry when undertaking any data-driven investigation or improvement programs. Wireless sensor networks (WSNs) can be used as a flexible and low-disruption technique to acquire data at the point of interest, however the data stream is often lossy when deployed in harsh conditions without costly adaptations to the environment.**

This paper introduces the F-QoS metric which is able to classify the quality of the data stream from a WSN (using only packet reception timestamps), at user-defined sampling rates with a constraint placed upon the maximum amount of missing data. The resulting classifications can be used in an offline fashion to select periods of high-quality data for modelling, or, in an online manner to assess the realtime performance of a WSN.

The F-QoS metric is applied to a LoRaWAN network in a large commercial bakery with a low-disruption installation - the network links are strained by large metal obstructions and the endpoints are installed inside metal cabinets. Each node transmits on a 10s cycle, and the analysis shows that $>$70% of the data is suitable for sampling at a 30s rate. The results indicate that LoRaWAN is capable of data acquisition in an unadapted and challenging environment, with the recommendation that the raw sample rate should be triple the desired final sample rate.

***Index Terms*—LoRa, QoS, F-QoS, WSN, Industrial IoT**

I. Introduction and Motivation

Essential to Industry 4.0 (and to automation in general) is the idea of networked plant and process control. The idealised network could be considered as a comprehensive and real-time view of the whole process at different levels of granularity, with the aid of a massive number of sensors - aggregated and available via a centralised access point for use at any end-device that requires this information. There are other considerations to this paradigm - accurate modelling of systems and processes, inclusion of the human-in-the-loop and resilience to exogenous disturbances.

Modern factories and plants tend to have rich networking capabilities available as a matter of course, and in this case the focus can be put upon analytics, data lake technologies and working practice evolution. However older sites with outdated equipment often have insufficient networking - without these data links they cannot effectively develop modern manufacturing solutions. There is a danger of SMEs (small-to-medium enterprises) being left behind in the Industry 4.0 revolution, the barrier to entry for updating older equipment and locations with Industrial Internet-of-Things (I-IOT) technologies is significant.

Practical communication networks in this environment will have different requirements, depending upon their purpose. For control of plant the latency must be bounded and the reliability must be sufficient. For data acquisition the requirements are less stringent, variable latency and some amount of missing measurements are acceptable in many cases. For a manufacturer to undertake an improvement project, the first step will often be a survey of existing practices and equipment to identify the most promising opportunities for improvement.

The costs to undertake a data-driven investigation can be high and the return on investment is, by definition, unknown at this stage. Whilst there are a large number of facilities equipped with data gathering infrastructure in the form of wired SCADA systems and networked plant there is also a significant portion of smaller businesses or older sites that have limited or no capability in gathering production information. It is also a common case that an important measure exists in a controller or piece of equipment that has no integral networking capability.

Wireless Sensor Networks (WSN) are able to gather the required data whilst remaining independent of any existing network infrastructure or specific interfacing requirements of controllers/equipment. By negating the need for expensive and troublesome rewiring, they can be deployed at the location of the quantity of interest which greatly reduces the burden of installation and interfacing.

Installations of WSNs can range from low-overhead (using the existing environment as-is) to high-effort (survey of environment with suitable modifications made to ensure signal quality). The effort that is put into setting up the wireless communications infrastructure is generally correlated with the performance of the resulting system. However, this effort can also be almost directly related to the monetary cost - and as an initial investigation will generally be dealing with data of unknown value, this cost should be minimised.

Performance analysis and the building of models can be achieved with a dataset that exhibits some degree of missing information (the particular bounds of which depend upon the specific techniques being applied). The common scenario of

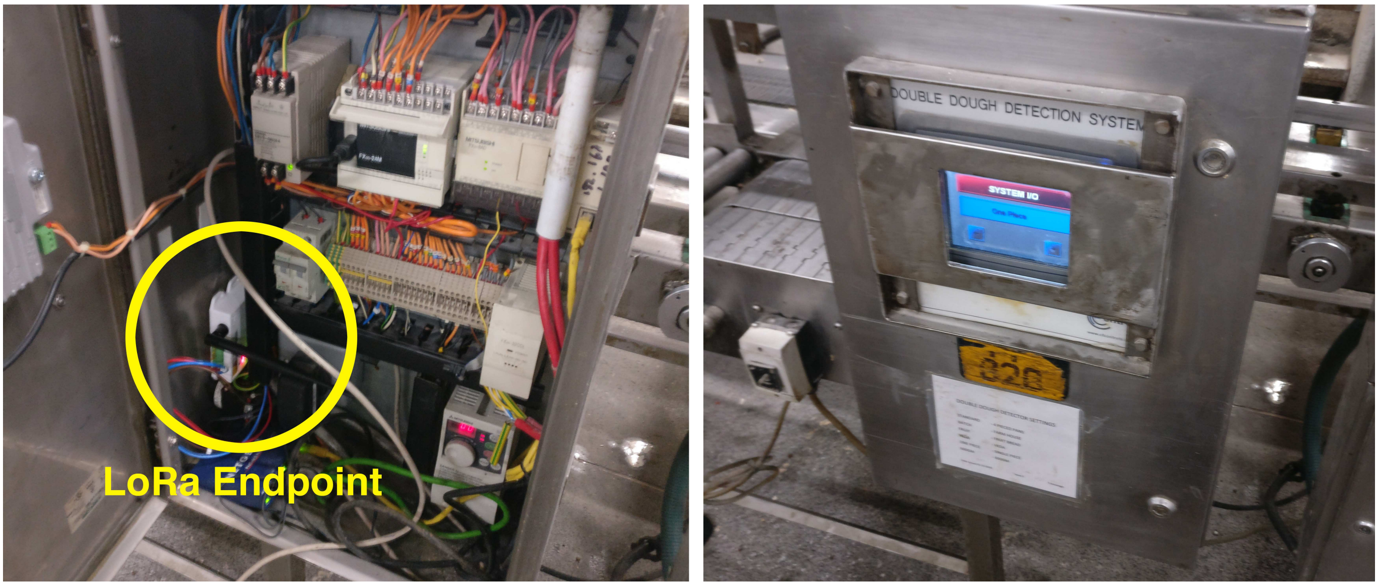

Fig. 1. Typical installation of node sealed within metal cabinet

	LoRa (EU)	BLE (802.15.1)	Wifi (802.11)	Zigbee (802.15.4)	NBIOT	LTE-M	Sigfox
Topology	*Star*	Star/Mesh	Star	Star/Mesh	Star (cellular)	Star (cellular)	Star (third party)
Frequency	*<1 GHz*	2.4GHz	2.4GHz, 5GHz	2.4GHz	GSM Bands	LTE Bands	<1GHz
License	*ISM, Public*	Public	Public	Public	Susbcription	Subscription	ISM (Private)
Data Rate	*250bps-11kbps, 50kbps*	125kbps-2Mbps	6MBps-1GBps	250kbps	20-250kbps	1Mbps	100-600bps
Range	*1-2km, 15km LoS*	10-100m LoS	30-70m LoS	10-100m LoS	~14km LoS*	~12km LoS*	3-10km Urban, 50km Rural
Hub Cost	*€ 100‡‡*	N/A	€ 50**	€ 180§§	N/A	N/A	N/A
Node Cost	*€ 35†*	€ 5‖	€ 5‖	€ 15§	€ 44‡	€ 44‡	€ 35†

TABLE I
COMPARISON OF RADIO TECHNOLOGIES USED IN WIRELESS SENSOR NETWORKS, INCLUDING APPROXIMATE (BAREBONES) DEVICE COSTS
*RANGES ARE ESTIMATES ACCORDING TO FIELD TESTING BY NORDIC SEMICONDUCTOR [1]
† PYCOM LOPY4, ‖ GENERIC ESP32-WROVER-X, §XB3-24XXXX-X, §§ XM-X9-5P-U, ‡ PYCOM GPY, ‡‡TTIG-868, **GENERIC 802.11.AC ROUTER

missing samples is dealt with by interpolation (eg. curve fitting) or more advanced imputation (for instance with a generative Autoencoder or probabilistic tools), however these techniques are nevertheless limited to being some expression of the information that has actually been gathered. It is often better to work with a high quality subset of the data that has very few missing points, with the caveat that any necessary compensations are performed to ensure that distribution and bias is not unduly distorted.

This paper is motivated by the need to assess the quality of data being produced by a WSN. Conventional networking performance measures arguably do not reflect the usefulness of the data produced by a WSN as its raw output is usually resampled and/or subject to further processing [2].

There are various motivations in resampling and processing industrial time series data : removing noise from measurements, detecting trends and patterns at various time horizons, building and verifying models from experimental information, event detection (eg. stoppages, breakdowns and changeovers on a production line). The time resolution of the data under investigation should be suitable for the horizon of interest and the duration of the features that are being identified - too many data points slows down computation and may even cause algorithms to diverge, whilst a resolution that is too low will distort or even eliminate features of interest. After these requirements have been considered, a suitable resampling rate (or range thereof) can be arrived at.

Functional QoS (F-QoS) is introduced as a technique to classify the quality of fixed-frequency time-series data for onward processing, or to make an online assessment of a WSN's performance. The evaluation is based upon the timestamps of the dataset and does not require radio signal information.

Section II places QoS and LoRaWAN in the context of industrial WSNs, Section III describes the on-site experimental setup, Section IV gives the F-Qos Formulation, and Section V presents the Results and Conclusions.

II. QoS IN INDUSTRIAL WSN

The goal of a Quality of Service (QoS) metric is to quantify a network's overall performance in terms of application requirements. In the context of industrial WSNs this is a multi-objective function that usually incorporates: end-to-end packet delay (timeliness), delivery reliability and energy efficiency [3].

Multi-route networks (using multi-hop topology) will often use QoS as an objective function to optimise routing or design the network layout [4] [5]. Adaptive routing protocols (ROL/NDC [6], MMSPEED [7]) for demanding applications are able to modify the network's behaviour in response to the QoS specification of individual packets.

Probabilistic techniques have been applied to networking questions of control and estimation, contemporary examples in the literature include: identification of optimal node placement in order to provide sufficient network coverage during the design phase [8], estimation of throughput and backlog in node-dense environments with latency-restricted traffic [9], and estimation of outages under different network conditions [10]. These approaches tend to be used when exhaustive solutions become computationally intractable or when there is insufficient information to use first-principles models. It has been shown that probabilistic models perform well in comparison to their analytical counterparts and are a viable approach to the design and assessment of wireless networks. In fact, a probabilistic approach can offer greater generality and flexibility if it is structured to require less specific information about radio signals.

LoRaWAN is an LPWAN (Low-Power Wide-Area-Network) radio technology that claims extreme improvements on range compared to classical WSN technologies, as shown in Table I. Sigfox, NBIOT and LTE-M are similar contemporary developments in this space, however they rely upon third party network providers' infrastructure and levy an ongoing subscription cost [11].

The star topology of LoRa greatly simplifies the routing of packets, with the result that QoS becomes primarily defined by the link quality between source and sink. Link Quality Estimation (LQE) model inputs are typically selected from: packet delivery rate (PDR), signal-to-noise-ratio (SNR) and received signal strength indication (RSSI) [12].

Work by Srinivasan et al. [13] has shown that the long- and short-term link quality can be estimated by examining the distribution of PDRs at various Inter-Packet-Intervals (IPIs).

F-QoS analyses timeliness and link quality by examining a windowed distribution of IPIs (which are variable due to failed transmissions). This distribution is then used to classify the quality of the data service - in terms of feasible sampling periods (sufficient raw data points are available to sample at the specified rate) and data completeness (a bounded acceptable level of missing measurements).

III. Experimental Setup

Experimental data is provided by a data acquisition network developed by the researchers and then installed on-site at a commercial bakery. A base station (Multitech Conduit LoRa concentrator, generic Linux server and 4G router) is situated in the roofspace and separated from the production floor by a metal-clad ceiling.

The radio technology's performance is challenged by deliberately deploying the WSN with minimal adaptation of the environment. The nodes are each enclosed within metal electrical/control panels with significant metal obstructions along the path to the base station. Figure 2 shows the layout of the system.

The full LoRa server stack is on-site, which receives the LoRa frames; processes and buffers the data; then transmits it via the MQTT protocol to an off-site database for logging and analysis.

A complete LoRa network implementation (from nodes upwards) will include: endpoint(s), LoRa concentrator(s), gateway(s), network server(s) and application server(s). The LoRaWAN specification allows for a significant degree of customisation in the behaviour of the network communications, therefore the particular configuration of this network will be detailed to enable interpretation of the results.

The experimental installation uses a Multitech Conduit configured as a packet forwarding LoRa Concentrator and a Docker stack composed by the open source LoraServer project [14]. The endpoint nodes are Multitech MDOT microcontrollers running mbed-os implementing a certified LoRaWAN network stack.

Each node operates on a fixed schedule, sending a single 22 byte transmission every 10 seconds. ACKs are disabled by default (avoiding network congestion and reflecting the raw link quality more accurately) [15] and using the 3 default EU frequency channels (868.1MHz, 868.3MHz, 868.5MHz). Join status is confirmed every 60 packets by a single ACK enabled transmission, and the nodes will rejoin the network after 5 consecutive failed ACKs. Time is not synchronised across the nodes, therefore packet collisions are a possibility.

LoRa uses a chirp spread spectrum modulation, and is capable of transmitting at a range of data rates shown in Table II. Assuming that the radio is being operated with a 1% duty cycle (typical EU implementation in line with ETSI regulations EN-300-220), the effective throughput is in the range of 2.5bps-110bps (500bps FSK). This particular application targets 26.7bps throughput which can be achieved with data rate of 4 or greater.

IV. F-QoS Formulation

F-QoS parameter choice enables a flexible assessment of the data - for instance, selecting a high quality period from a large and variable data set to use for modelling. The constraints that describe high-quality are dependent upon the user's specifications, and are defined by the parameters P (data completeness: the required percentage of timely data points) and QoS_{C-Th} (a list of target resampling periods, ordered from slowest to fastest).

Data Rate	Bits/s	Max Payload
0	250	51 bytes
1	440	51 bytes
2	980	51 bytes
3	1760	115 bytes
4	3125	222 bytes
5	5470	223 bytes
6	11000	224 bytes
7 (FSK)	*50000*	*225 bytes*

TABLE II
LoRa Raw Throughput at various data rates

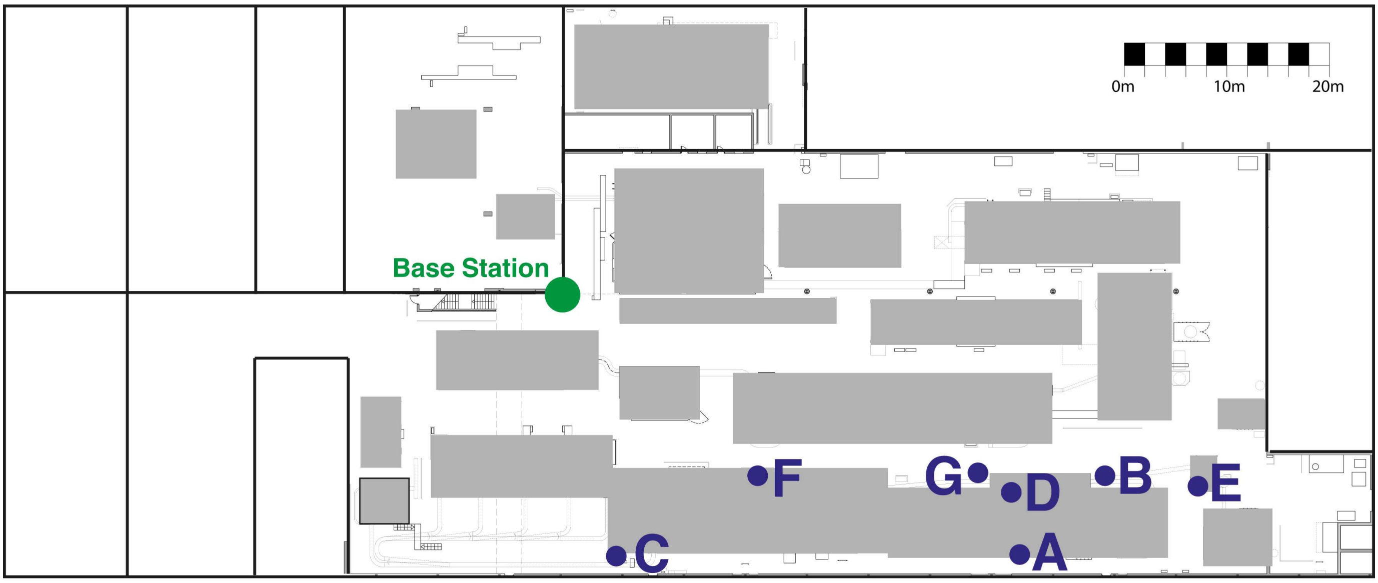

Fig. 2. Layout of Base Station and Nodes on Factory Floor

The output of the algorithm classifies regions that meet the specified constraints in terms of data completeness and rate of arrival. F-QoS can also be used in an online fashion to define the functional performance of a deployed sensor network.

The steps to calculate F-QoS are divided into pre-processing and metric formulation:

Pre-Processing

1) Calculate Inter-Packet Intervals (IPIs)
2) Define Rolling Time Windows, across the time series
3) Classify network as online/offline for each time interval

F-QoS Formulation

1) Calculate distribution of IPIs within each window
2) Find the Pth Percentile Time (the inter-message delay time by which $P\%$ of values have arrived)
3) Classify each window by its percentile time into the QoS states defined in QoS_{C-Th}

A. Raw Data Preprocessing

Before the F-QoS metric can be computed, the inter-packet intervals (IPIs) should be calculated and a rolling window is defined to set the span of time that is to be considered at each point in the time series.

The raw time series of the messages for a node is defined as the series of packet-reception timestamps (t_i):

$$TS = [t_0, t_1, t_2, ..., t_{n-1}, t_n] \text{ for } n \text{ total timestamps} \tag{1}$$

The IPIs, or, time deltas (dt_i) between each message are calculated with the backwards difference of the timestamps:

$$\begin{aligned} dTS &= [NaN, dt_1, dt_2, ..., dt_{n-1}, dt_n] \\ \text{where: } dt_i &= t_i - t_{i-1} \end{aligned} \tag{2}$$

A threshold, X^* seconds, is applied to message time deltas to classify the state of the network as online or offline. Offline periods are defined as gaps between message transmissions that are beyond the X* threshold. The offline label is used to calculate a network uptime metric and to exclude these periods from F-QoS classification :

$$X_n = \begin{cases} 0 \text{ (Offline) if } dt_n > X^* \\ 1 \text{ (Online) otherwise} \end{cases} \tag{3}$$

A rolling window of dt_W seconds, aligned to the timestamps, is defined to produce a series of n windows, W. Each window defines a subset of the original time series that is right-aligned to the individual measurements :

$$\begin{aligned} W &= [W_0, W_1, W_2, W_3, ...W_{n-1}, W_n] \\ \text{where } W_j &= \{t \in TS \mid (t_j - dt_w) < t \leq t_j\} \end{aligned} \tag{4}$$

B. Functional QoS (F-QoS) Formulation

Firstly, the Pth percentile of the message delay distribution is calculated for each window $W_j(dTS)$:

$$Q_{P,Wj} = percentile(P) \text{ for } W(dTS) \tag{5}$$

F-QoS is then classified by applying the QoS_{C-Th} thresholds to the calculated percentile:

$$QoS_{C,Wj} = \begin{cases} 0 & \text{if } Q_{P,Wj} > Q_1 \\ 1 & \text{if } Q_{P,Wj} \leq Q_1 \\ 2 & \text{if } Q_{P,Wj} \leq Q_2 \\ ... & ... \\ (C-1) & \text{if } Q_{P,Wj} \leq Q_{(C-1)} \\ C & \text{if } Q_{P,Wj} \leq Q_C \end{cases} \tag{6}$$

For example, by defining the parameters for P and QoS_{C-Th} as:

$$P = 97\% \text{ and } QoS_{C,Th} = \begin{cases} Q_1 = 60 \\ Q_2 = 30 \\ Q_3 = 10 \end{cases} \tag{7}$$

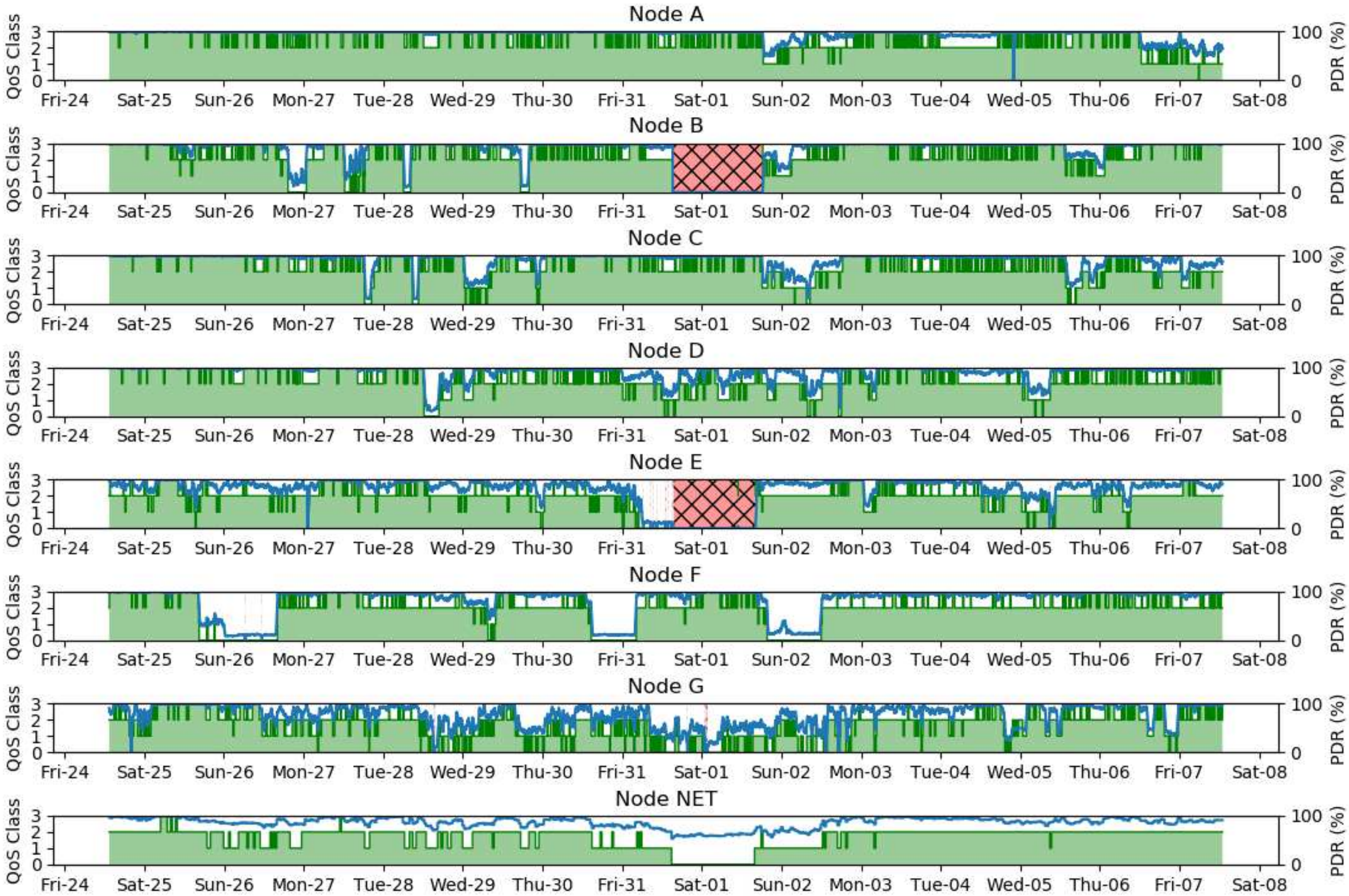

Fig. 3. QoS Classification for each node over a 14 day period. QoS is shown as green shaded areas with offline periods highlighted in hatched red. PDR(%) is overlayed in blue. Offline periods for B,E on Sat-01 are due to power-down maintenance. Node NET is the mean performance for the entire network

Node	Q_0*(%)*	Q_1*(%)*	Q_2*(%)*	Q_3*(%)*	$Q_{2,3}$*(%)*	*PDR(%)*	*Distance(m)*
A	0.06	7.7	33.72	58.52	92.24	94.79	51
B	4.52	4.68	38.69	52.11	90.8	92.61	56
C	3.2	9.32	34.59	52.89	87.48	91.61	26
D	2.3	11.17	47.6	38.93	86.53	91.3	48
E	4.78	10.55	70.75	13.92	84.67	85.65	65
F	16.3	1.19	56.67	25.84	82.51	82.61	26
G	12.79	26.23	46.85	14.13	60.98	77.44	44
NET	7.45	22.2	69.44	0.91	70.35	87.83	-

TABLE III

SUMMARY OF NODE PERFORMANCE AT EACH QOS LEVEL, PDR(%) AND LINK DISTANCE
MAXIMUM PACKET INTERVAL (SECONDS) : $Q_0 = (> 60s), Q_1 = 60s, Q_2 = 30s, Q_3 = 10s$

Using the values from (7), data with a classification of QoS Level 2 will have a valid raw measurement at least every 30s, across 97% of the time period.

C. Packet Delivery Rate (PDR)

The PDR gives the percentage of successfully delivered packets and can be calculated due to the fixed sending rate of the network (neglecting offline periods).

$$PDR(\%) = 100 \times \frac{n \text{ (No. received messages)}}{n^* \text{ (No. expected messages)}} \qquad (8)$$

V. RESULTS

To analyse the system, a rolling window of 30 minutes was specified, dt_W=1800s, with a percentile boundary P=97% and $QoS_{C-Th} = \{60s, 30s, 10s\}$ corresponding to QoS Levels of 1, 2 and 3 respectively. The offline threshold was set to 3 minutes, X^*=180s. Overall network (NET) QoS is classified with the mean $W_j(dTS)$ of each node's Percentile Time, and the overall PDR is calculated using the sum of total expected and received messages.

There is a significant gap between standard and implementation in the currently available LoRa devices [16]. This can be observed in the literature when considering the wide variety of network configurations used by researchers and industry. The periods of time with a PDR of approximately 10% (see Node F: Sun-26, Fri-31, Sun-02 in Figure 3) are caused by misconfiguration in the LoRa network stack causing the node to become trapped in a join-rejoin loop, underscoring the pitfalls inherent in a fractured ecosystem.

LoRa is a strong technology, however the set-up and installation cannot yet be considered plug-and-play. There are also considerations with certification and regulatory approval - given that the radios operate in the ISM band, it is possible to breach radio regulations if firmware has not been developed with sufficient care. An option to avoid this is to integrate a pre-certified module as a radio-only device that responds to AT commands, however this necessitates the inclusion of another microcontroller within the node to act as host.

Table III gives a summary of each node's performance in terms of F-QoS and PDR, also providing the distance from the base station. Given a goal of 30s resample rate (shown as $Q_{2,3}$, the sum of Q_2 and Q_3) the performance of the nodes ranges from 61% to 92.24%, with the aggregate network providing suitable data 70% of the time. The mean of the overall network performance (calculated using the mean percentile time of all nodes, and summation of the PDR) is given on the **NET** line at the bottom of the table.

The PDR has a strong relationship to the Q_3 ratio but is less indicative of performance when considering the lower resampling rate targets - emphasising the utility of the F-QoS performance measure in this use case, as compared to conventional networking metrics.

There is only a weak relationship between node-to-base distance and performance, most likely caused by the dense obstructions on each link. Considering this as a typical scenario for low-burden industrial investigation it reinforces the idea that it is difficult to predict the real-world performance of a radio system from floorplans.

VI. Conclusion

Classical performance metrics may under-represent the functionality of WSNs (which tend to be lossy) as the delivered data will often undergo further processing and resampling. F-QoS specifically defines the usefulness of time series data produced by a WSN and can be used as a tool in selection of time periods for further processing, or to assess the online performance of a WSN.

F-QoS could be used to inform LoRa's ADR (Adaptive Data Rate) mechanism, which does not yet have a definitive implementation. The metric could also be used as part of a network tuning mechanism to automatically arrive at a suitable end-use resampling rate. In the case of a manual radio survey the performance reported by F-QoS could be used to identify areas which require additional installation effort to reach a set goal in terms of sample rate and data completeness (defined allowable proportion of missing data/failed transmissions).

With the exception of a single node, >80% of the data provided by the experimental LoRa WSN was suitable for resampling on a 30s period. Under the conditions of a challenging environment and a low disruption installation, LoRa has shown itself to be suitable for data acquisition purposes. For 'set-and-forget' installation, the authors' recommendation is that radio transmissions are to be at least 3 times the rate of the desired final sampling rate.

VII. Future Work

The F-QoS metric takes a probabilistic view of network performance, and considers the delivered information in terms of completeness and reliability over various time horizons. Currently this is calculated based on a known and fixed frequency sampling period, a useful extension would be to also cater to event-based networks. A similar approach could be used, by building an expectation model of network transmissions and comparing this against the actual logged signals.

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