Poster: On the Feasibility of Wireless Sensor Networks for Edge Infrastructure Monitoring in Wind Turbines

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Abstract

Wind turbines provide the opportunity to build edge data centers where green energy is harvested since their towers are often empty. To secure such remote infrastructures, wireless sensor networks can be used, but their reliability remains uncertain in such an unpredictable environment. In this poster, we present measurement results of an IPv6 deployment on top of a Bluetooth Low Energy network in a wind turbine. We focus on two aspects: (*i*) the electromagnetic interference in the 2.4 GHz band, and (*ii*) the network reliability. We find that a high delivery success rate (99%) can be achieved on the network layer, even under strong interference, making wireless-based monitoring a feasible option.

CCS Concepts

• **Networks** → **Network monitoring**; **Network performance analysis**; **Network measurement**.

Keywords

Wireless sensor networks (WSN), Remote monitoring, Bluetooth Low Energy (BLE), Performance

1 Introduction

The demand for data center services is ever increasing, and with it the energy required to operate the underlying infrastructure. Recent work explores the potential of data centers located inside wind turbines [7]. Wind turbines provide an opportunity for edge data centers for three reasons. First, they enable the generated energy to be used on-site, bypassing the electrical grid. Second, they provide space. Third, they are located off-site in rural areas, which supports edge deployments.

Since wind turbines are deployed in remote locations, monitoring is crucial. Wireless Sensor Networks (WSNs) are a promising solution [3], but the unique environment inside a wind turbine (high-voltage cables, vibrations, metal, *etc.*) challenges their performance. This poster presents a first evaluation of a Bluetooth Low Energy (BLE)-based WSN inside a wind turbine. BLE multi-hop networks have been found to provide good reliability in office buildings [5], but seen only limited evaluation in industrial environments. In wind turbines, on the other hand, WSNs based on IEEE 802.15.4, Ultra-wideband (UWB) or long-range BLE have been proposed for structural health monitoring [2, 4, 6, 8], but existing work largely focuses on the wind turbine blades, nacelle, or hub, rather than the tower, and only includes short (< 1 hour) measurements. Our work contributes both complex baseband sampling of the environment with a Software Defined Radio (SDR) and active measurements of a BLE network, over the span of hours and days.

2 Setup and Preliminary Results

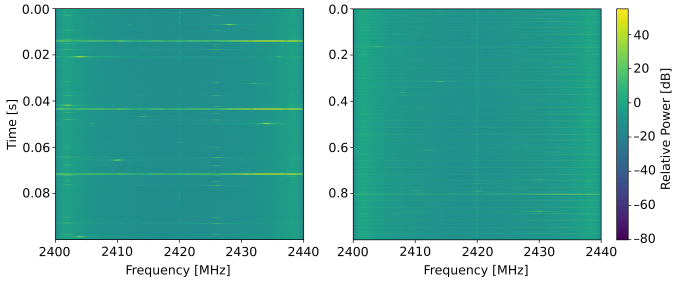
Our study is based on a real-world deployment in a wind turbine operated in Germany. We analyze two aspects. First, we assess the impact of the environment in the wind turbine on radio performance by sampling the power in the 2.4 GHz band. Second, we evaluate the performance of IPv6 traffic over BLE over two days.

Measurement setup. We deploy nine Adafruit Feather nRF52840 Sense boards at the bottom of the wind turbine. They are arranged in a 10 m diameter semicircle along the wall, next to high-voltage cables and several servers. All nodes run RIOT [1]. We use an AirBridgePro [9] gateway with a BladeRF xA4 SDR for raw IQ sampling. The nodes form a two-hop network with maximum three BLE connections per node. For remote access and addressing, we implement IPv6 support and the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) (RFC 6550). The RPL root serves as border router and sink node. For comparison, we deploy the same hard- and software in our office.

Interference in wind turbine towers. Figure 1 shows the 40 MHz spectrum (20 BLE channels) for 100 ms and 1 s. The spectrogram reveals a periodic interference occurring every 29 ms, with energy concentration around 2435 MHz and a duration of ≈0.5 ms. Additionally, there is occasional, longer interference lasting 2-3 ms (see Figure 1(b) at 0.8 s). A 10-s measurement shows that this stronger interference recurs every few seconds, but at irregular intervals.

Furthermore, we aggregate average and maximum power values over 10 ms windows for BLE data channels 8-11 and advertisement channel 38 over a duration of 10 hours. Figure 2 shows the temporal distribution of the maximum values for channel 8. Our BLE network traffic is visible around 30 dB. During the first hour, interference is notable that yields 40 dB. This may be caused by other devices in the wind turbine that turn on or off depending on the operational state of the turbine. We found similar patterns for other BLE channels.

Network performance. Each BLE node sends an ICMPv6 Echo request with a 1024 B payload to the root node (ID 0) every second. The experiment runs in the wind turbine for 48 hours and in an office environment for 12 hours. In both environments, the RPL



(a) Duration: 100 ms **(b) Duration: 1 s**

Figure 1: Spectrogram of the 2.4-2.44 GHz band.

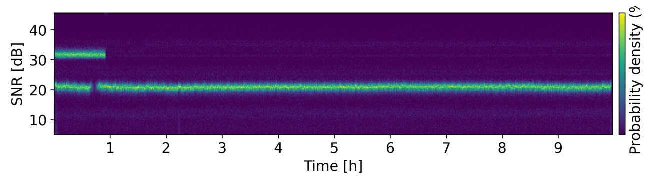


Figure 2: Distribution of the maximum sampled power over 10 ms in 1-minute bins on BLE data channel 8.

routing tree is balanced and stable, with only few nodes changing their RPL parent (Figure 3(a)). We observe occasional BLE disconnections and reconnections, as well as a noticeable drop in success rate for individual nodes (office node 6, wind turbine node 4) after they connect to a new parent. Most likely, this is due to our use of Objective Function Zero in RPL, which does not consider reliability metrics in the parent selection process. However, most nodes achieve very high reliability in both environments (Figure 3(b)).

We compare the BLE link-layer retransmission rate (Figure 4(a)) and the total round trip time (RTT) (Figure 4(b)) for office and wind turbine nodes with identical rank. The two deployments exhibit broadly similar performance, with comparable distribution shapes. Minor RTT variations can be attributed to BLE connection interval timings. A fraction of packets exhibit elevated retransmission counts in the wind turbine scenario, likely due to transient interference events. For the whole network, no strong statistical differences are observed in the retransmission rates (Office: mean 0.38 ± 0.89%, median 0.00%; wind turbine: mean 0.56 ± 1.09%, median 0.00%) and RTTs (Office: mean 530.50 ± 281.82ms, median 480.85 ms; wind turbine: mean 517.99 ± 279.00ms, median 470.76 ms).

3 Conclusion

Our work presents an evaluation of a BLE multi-hop network inside a wind turbine tower. While there is interference in the 2.4 GHz band, our results show minimal packet loss. The findings indicate that low-power wireless communication in the studied environment is generally feasible. In future work, we aim to (*i*) extend our measurements to capture rare environmental and industrial transient events, (*ii*) include a second deployment with denser infrastructure in the wind turbine, and (*iii*) synchronize our SDR and BLE communication measurements to correlate the findings.

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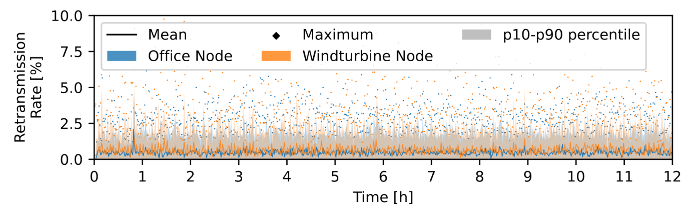
Deployment	Parent changes per node ID (#)							
	1	2	3	4	5	6	7	8
Office (12 h)	0	0	0	0	0	0	1	0
wind turbine (first 12 h)	0	0	0	0	0	0	0	0
wind turbine (48 h)	0	0	0	3	0	5	0	1

(a) Changes of the RPL *preferred parent*.

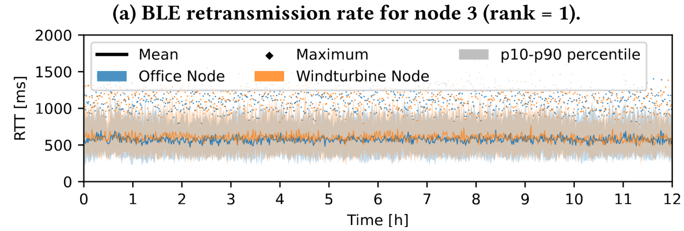
Deployment	ICMPv6 Echo success rate per node ID (%)							
	1	2	3	4	5	6	7	8
Office (12 h)	100	100	99.94	99.56	99.99	50.86	100	99.67
wind turbine (first 12 h)	100	99.99	100	99.95	99.06	99.90	99.87	99.99
wind turbine (48 h)	99.99	99.98	99.96	88.51	98.50	95.35	99.87	99.87

(b) Packet delivery rates.

Figure 3: Comparison of the different deployments.



(a) BLE retransmission rate for node 3 (rank = 1).



(b) Round-trip time for node 7 (rank = 2).

Figure 4: Comparison of office and wind turbine nodes using a sampling interval of 1 min.

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