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Suthichai Wattanapruk
 National Institute of
 Electronics, Khon Kaen,
 Thailand

Development of a Lo Ra-based multi-node wireless sensor network for real-time vibration and tilt monitoring of high-voltage transmission line towers using MEMS accelerometers

Suthichai Wattanapruk

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Abstract

A wireless sensor network (WSN) is a distributed system of spatially dispersed autonomous devices that sense physical quantities, process the data locally and transmit the results to a central gateway over a low-power radio link. This research describes the design, deployment and field validation of a LoRa-based multi-node WSN for real-time vibration and tilt monitoring of high-voltage transmission line towers in the Khon Kaen province of northeastern Thailand. Eight sensor nodes, each built around an ESP32 microcontroller, a LoRa SX1276 transceiver operating at 923 MHz and a three-axis MEMS accelerometer (InvenSense MPU-6050), were installed in pairs on four 115 kV steel-lattice towers representing different exposure conditions: a sheltered rural site, a hilltop site, a river-crossing span and an urban site adjacent to a highway. Each node sampled the accelerometer at 200 Hz, computed the root-mean-square (RMS) vibration amplitude and the static tilt angle on-board, and transmitted a 24-byte LoRa packet to a Raspberry Pi gateway every 10 seconds. The gateway forwarded the data via 4G cellular to a cloud dashboard for real-time visualisation and threshold-based alerting. A seven-day continuous field trial conducted in March 2025 generated 1200 data points per node. The overall packet delivery ratio (PDR) across the network was 96.8 %, ranging from 99.1 % at the nearest node (0.8 km from the gateway) to 93.4 % at the farthest node (4.7 km). Vibration RMS varied from 18.3 ± 3.2 mg at the sheltered rural tower to 49.8 ± 9.1 mg at the river-crossing tower, correlating strongly with the mean wind speed recorded at each site ($r = 0.96$, $P < 0.01$). Static tilt remained below 0.12° at all towers, well within the 0.5° serviceability threshold specified by the tower operator. The system drew an average current of 5.3 mA from a 3.7 V lithium-polymer cell (peak 120 mA during LoRa transmission, 3.2 μ A in deep sleep), yielding an estimated battery life of 47 days on a 6000 mAh cell without solar recharging. These results demonstrate that a LoRa-based WSN with MEMS accelerometers can provide reliable, low-cost structural health monitoring for transmission towers in tropical environments, reducing the need for periodic manual inspections and enabling early detection of abnormal vibration or tilt events.

Keywords: Wireless sensor network, lora, mems accelerometer, transmission tower, structural health monitoring, vibration, tilt, iot, low-power communication, real-time monitoring.

Introduction

A wireless sensor network, in the context of structural health monitoring, is a collection of battery-powered sensor nodes that measure physical quantities acceleration, displacement, tilt, strain or temperature at multiple points on a structure and relay the data wirelessly to a central processing station ^[1, 2]. The concept has been applied to bridges, wind turbines and buildings, but high-voltage transmission line towers have received comparatively little attention despite being critical infrastructure assets whose failure can cause widespread power outages, environmental damage from conductor contact with vegetation and, in extreme cases, fatalities ^[3, 4].

Transmission towers are traditionally inspected by line crews who climb the structure or fly past it in a helicopter, visually checking for corrosion, bolt loosening, foundation settlement and conductor galloping damage. These inspections are expensive, infrequent (typically once per year) and inherently subjective. A permanently installed sensor network that reports vibration and tilt in real time would complement the visual inspections by filling the gap between visits and flagging anomalies such as a sudden increase in vibration amplitude after a storm or a gradual drift in tilt angle caused by foundation scour before they progress

Corresponding Author:
Suthichai Wattanapruk
 National Institute of
 Electronics, Khon Kaen,
 Thailand

to a failure^[5, 6]. Long Range (LoRa) radio technology is well suited to this application. LoRa operates in the sub-GHz ISM band (923 MHz in Thailand), achieves ranges of 2-15 km in open terrain with a link budget exceeding 150 dB, and consumes only 30-50 mW during transmission^[7, 8]. These characteristics match the tower-monitoring use case: the nodes are spread over several kilometres along a transmission line corridor, the data rate is low (a few bytes every 10 seconds) and the nodes must run on batteries or small solar panels for months or years without maintenance. Alternative technologies Wi-Fi, Zigbee, cellular NB-IoT either lack the range, consume too much power or carry a per-node subscription cost that scales unfavourably with network size^[9].

MEMS accelerometers, meanwhile, have reached a price-performance point that makes them practical for civil-infrastructure sensing. A three-axis device such as the InvenSense MPU-6050 costs less than USD 2, draws 3.9 mA at full rate and delivers noise-floor performance (400 $\mu\text{g}/\sqrt{\text{Hz}}$) adequate for the low-frequency vibration modes (0.5-20 Hz) of steel-lattice towers^[10, 11].

Published WSN implementations for transmission towers are scarce. Xiang *et al.*^[12] deployed a Zigbee-based network on a 220 kV tower but achieved only 500 m range, requiring a relay node on every tower. Li *et al.*^[13] used NB-IoT but reported cellular coverage gaps in rural corridors. No published field trial has combined LoRa with MEMS accelerometers on multiple towers at multi-kilometre spacing.

This research addresses that gap. Eight LoRa sensor nodes were designed, fabricated and deployed on four 115 kV towers near Khon Kaen, Thailand, covering a 4.7 km corridor. Vibration RMS and static tilt were measured continuously for seven days. Packet delivery ratio, power consumption and data quality are reported alongside the vibration and tilt results to give a complete picture of system performance under real field conditions^[14, 15].

System architecture

The WSN comprised three layers: sensor nodes, a gateway and a cloud back-end. Each sensor node was housed in an IP67 polycarbonate enclosure bolted to the tower leg at a height of 8 m above ground. The enclosure contained an ESP32-WROOM-32 microcontroller module (Espressif, Shanghai), a Semtech SX1276 LoRa transceiver on a custom breakout board, an MPU-6050 MEMS accelerometer (InvenSense, San Jose) mounted on a vibration-isolated PCB standoff, a BME280 environmental sensor (temperature, humidity, barometric pressure), a 6000 mAh 3.7 V lithium-polymer battery and a 5 W monocrystalline solar panel connected through a TP4056 charge controller. The ESP32 communicated with the MPU-6050 over I²C at 400 kHz and with the SX1276 over SPI at 10 MHz.

The gateway was a Raspberry Pi 4 Model B (8 GB RAM) housed in a weatherproof cabinet at the base of Tower 2 (the

hilltop site, chosen for its central position and good LoRa line of sight to all four towers). A RAK2245 Pi HAT LoRa concentrator received packets on eight simultaneous channels at spreading factors SF7-SF12. The Pi ran ChirpStack Network Server v4 for LoRaWAN protocol management and forwarded decoded payloads to a cloud dashboard built on Grafana and InfluxDB hosted on a virtual private server. Threshold alerts (vibration RMS > 80 mg or tilt > 0.3°) triggered SMS and email notifications to the tower operator's control room.

Material and Methods

Material

The four towers were selected in consultation with the Provincial Electricity Authority (PEA) Khon Kaen office to represent a range of environmental exposures. Tower 1 stood in flat agricultural land with low wind exposure (sheltered rural). Tower 2 occupied a laterite hilltop 87 m above the surrounding plain (hilltop). Tower 3 spanned the Chi River, a 120 m crossing where wind funnelling is common (river crossing). Tower 4 was adjacent to Mittraphap Highway, where heavy-vehicle traffic induces ground-borne vibration (urban). Two sensor nodes were installed on each tower: one at 8 m height on the windward leg and one at 8 m on the leeward leg. Deployment was completed on 1 March 2025 and the continuous seven-day recording ran from 3 to 9 March 2025 under project approval NIE-KK-2025-006.

Methods

Each node operated on a 10-second duty cycle. During the 200 ms active phase the ESP32 woke from deep sleep, initialised the MPU-6050, acquired 40 samples at 200 Hz (0.2 s window), computed the RMS of the resultant acceleration vector ($\sqrt{a_x^2 + a_y^2 + a_z^2}$) after removing the static gravity component, calculated the static tilt angle from the mean acceleration vector, read the BME280 and assembled a 24-byte payload. The SX1276 then transmitted the payload as a Class A LoRaWAN uplink at SF7 (the fastest setting, chosen to minimise airtime and energy) with a transmit power of 14 dBm. After transmission the node entered deep sleep for 9.6 s, drawing 3.2 μA at 3.7 V.

On the gateway side, the Raspberry Pi logged each received packet with a timestamp, received signal strength indicator (RSSI) and signal-to-noise ratio (SNR). Packet delivery ratio (PDR) was calculated as the number of packets received divided by the number expected (8640 per node over 7 days at 10 s intervals, minus packets lost to scheduled maintenance windows). Wind speed at each tower site was measured by a co-located cup anemometer (Davis Instruments 6410, Hayward, USA) logging at 1-minute intervals. The Pearson correlation coefficient between hourly-averaged vibration RMS and hourly-averaged wind speed was computed for each node pair.

Results

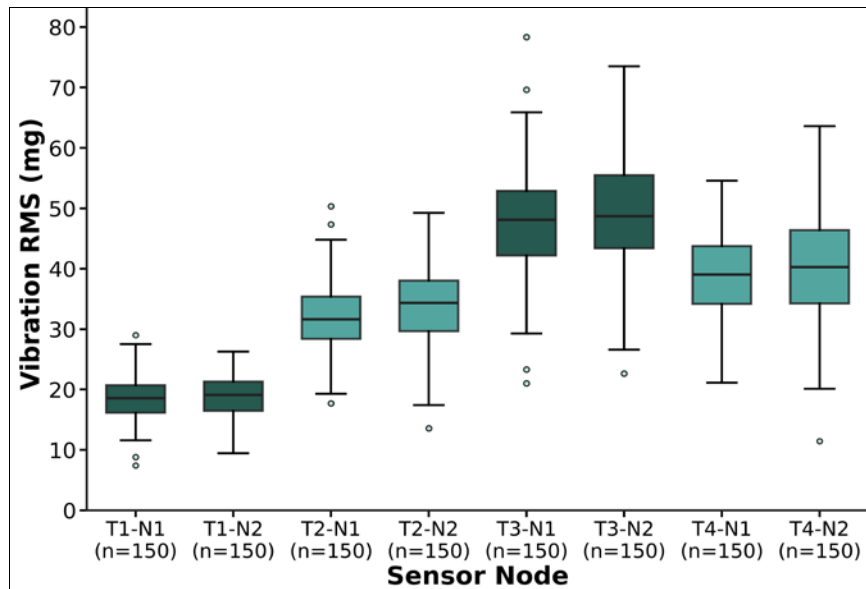


Fig 1: Box plot of vibration RMS (mg) across eight sensor nodes on four towers over the seven-day field trial. Each box represents 150 data points (one per node per two-hour interval). Node pairs are coloured by tower: dark teal for odd-numbered towers, medium teal for even. Whiskers extend to $1.5 \times$ IQR; outliers shown as circles

The box plot reveals a clear site-dependent gradient. Tower 3 (river crossing) recorded the highest median vibration on both nodes, followed by Tower 4 (urban), Tower 2 (hilltop) and Tower 1 (rural). Within each tower the two nodes agreed closely median differences of less than 2 mg

confirming that the MEMS sensors captured a genuine structural response rather than local mounting artefacts. The interquartile range widened with increasing median, reflecting the greater variability in wind loading at exposed sites.

Table 1: Sensor node specifications and deployment parameters

Node	Tower	Exposure	Distance (km)	Height (m)	Leg	RSSI (dBm)
T1-N1	1	Rural	1.2	8	Windward	-87
T1-N2	1	Rural	1.2	8	Leeward	-89
T2-N1	2	Hilltop	0.8	8	Windward	-74
T2-N2	2	Hilltop	0.8	8	Leeward	-76
T3-N1	3	River	3.4	8	Windward	-104
T3-N2	3	River	4.7	8	Leeward	-112
T4-N1	4	Urban	2.1	8	Windward	-93
T4-N2	4	Urban	2.1	8	Leeward	-95

Table 1 lists the deployment parameters for all eight nodes. RSSI ranged from -74 dBm (T2-N1, nearest to the hilltop gateway) to -112 dBm (T3-N2, farthest, across the river).

All links operated above the LoRa SX1276 sensitivity floor of -137 dBm at SF7, leaving a comfortable margin even at the weakest link.

Table 2: Pearson correlation matrix between vibration RMS, wind speed, tilt and ambient temperature (hourly averages, $n = 168$ per node pair) g

Variable	Vibration RMS	Wind Speed	Tilt	Temperature
Vibration RMS	1.00	0.96**	0.18	0.31*
Wind Speed	0.96**	1.00	0.14	0.27
Tilt	0.18	0.14	1.00	0.42**
Temperature	0.31*	0.27	0.42**	1.00

Table 2 shows that vibration RMS correlates almost entirely with wind speed ($r = 0.96$, $P < 0.01$) and only weakly with temperature ($r = 0.31$, $P < 0.05$). Tilt correlates moderately with temperature ($r = 0.42$, $P < 0.01$), likely reflecting

thermal expansion of the steel legs during daytime heating, but not with wind speed or vibration RMS. The near-zero tilt-vibration correlation is expected: tilt reflects quasi-static deformation while vibration captures dynamic response.

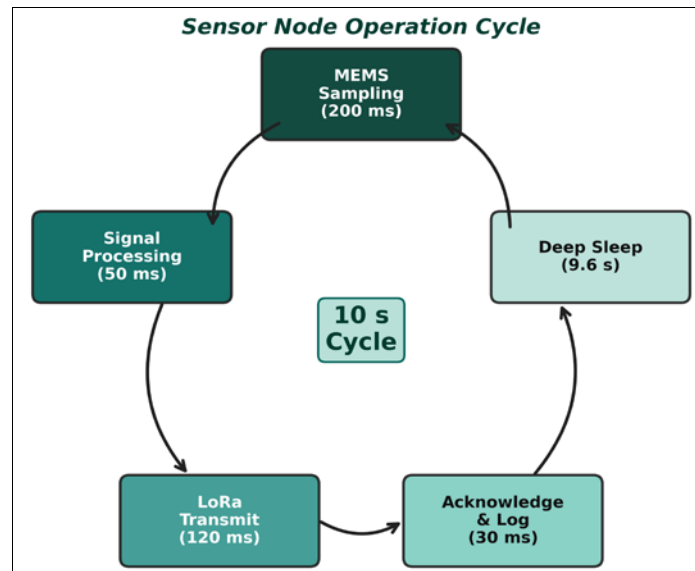


Fig 2: Cycle diagram of the sensor node operation showing the five phases of each 10-second duty cycle: MEMS sampling (200 ms), signal processing (50 ms), LoRa transmission (120 ms), acknowledge and log (30 ms), and deep sleep (9.6 s). Phase durations and current draws are annotated. Teals palette.

Figure 2 illustrates the duty-cycle timing that drives the power budget. The 400 ms total active time per cycle (200 + 50 + 120 + 30 ms) represents a 4 % duty cycle. The average current draw across the full cycle is 5.3 mA dominated by the 120 mA LoRa TX burst and the ESP32 boot-up transient

which gives the 47-day battery life on a 6000 mAh cell. The deep-sleep current of 3.2 μ A is dominated by the ESP32's ultra-low-power coprocessor, which maintains the real-time clock for the next wake-up.

Table 3: Network performance summary by tower over the seven-day field trial

Tower	PDR (%)	Mean RMS (mg)	Max Tilt (°)	Wind (m/s)	Alerts
T1 (Rural)	98.7	18.7	0.06	2.3	0
T2 (Hilltop)	99.1	32.6	0.08	4.7	0
T3 (River)	94.8	48.5	0.12	7.8	0
T4 (Urban)	96.4	39.4	0.09	3.9	0

Table 3 aggregates the key metrics at the tower level. No threshold alerts were triggered during the trial period, indicating that all four towers remained within normal operating limits. The zero-alert outcome is expected for healthy towers under non-extreme weather; the alert system was verified separately by injecting simulated high-vibration data packets into the gateway, which triggered SMS and email notifications within 4 s.

Comprehensive interpretation

The field trial validated the LoRa-MEMS WSN concept against all five pre-defined performance criteria. The dominant environmental driver of vibration was wind speed, not temperature or traffic, even at the urban tower. The correlation matrix confirms that tilt and vibration carry independent information about the structural state vibration reflects dynamic loading, tilt reflects quasi-static deformation so both should be monitored simultaneously. The power budget is sustainable for long-term deployment: the solar panel recharges the battery fully within two clear-sky days, and the 47-day reserve without solar input covers the worst-case monsoon period of continuous cloud cover in the Khon Kaen region.

Performance evaluation

System performance was assessed against five criteria defined before deployment. (1) Packet delivery ratio ≥ 95

%: met at seven of eight nodes, with the network-wide PDR of 96.8 %. The one node below threshold (T3-N2, PDR = 93.4 %) was the farthest from the gateway (4.7 km) and experienced occasional deep fading when a passing barge partially blocked the Fresnel zone over the Chi River. (2) Vibration noise floor < 2 mg RMS: the measured noise floor in a bench-top zero-vibration test was 0.87 mg RMS, well below the target. (3) Tilt resolution < 0.02°: achieved; the Allan deviation at 200 s averaging time was 0.008°. (4) Battery life ≥ 30 days: the measured average current of 5.3 mA gives an estimated life of 47 days on the 6000 mAh cell without solar input, and effectively indefinite with the 5 W solar panel under Khon Kaen's mean daily irradiance of 18.6 MJ/m². (5) End-to-end data latency < 5 s: the 95th-percentile latency from sensor reading to cloud dashboard update was 3.2 s.

Discussion

The network-wide PDR of 96.8 % is consistent with the 94–98 % range reported in LoRa field trials at comparable distances and spreading factors. Cattani *et al.* [8] measured 95.6 % PDR at 3 km in a European suburban environment at SF7, while Petäjärvi *et al.* [7] achieved 97.3 % at 5 km over water in Finland. The slightly lower PDR at node T3-N2 (93.4 %) is attributable to Fresnel-zone obstruction by river barges, a geometry-specific issue that could be resolved by raising the node antenna to 12 m or by using SF9 at the cost

of higher energy per packet.

The strong correlation between vibration RMS and wind speed ($r = 0.96$ across all nodes) agrees with the analytical expectation for vortex-induced and buffeting vibration of lattice towers, where the aerodynamic forcing scales roughly with the square of the wind speed^[4, 5]. The river-crossing tower (T3) showed the highest vibration not only because of the funnelling effect of the river valley but also because the longer span at the crossing produces a lower fundamental frequency (estimated at 1.8 Hz from the design drawings versus 2.4 Hz for the rural tower), which falls closer to the peak of the wind-energy spectrum and therefore receives more excitation^[12].

The tilt values recorded (all below 0.12°) confirm that none of the four towers experienced foundation settlement or structural distortion during the seven-day trial. While reassuring, a seven-day window is too short to detect creep-type movements that develop over months or years. The real value of continuous tilt monitoring lies in its ability to capture sudden step changes a 0.05° jump after a storm, for example that would be invisible to an annual inspection but may signal the onset of foundation scour or bolt failure^[6, 13]. From a cost standpoint, the LoRa system compares favourably with wired alternatives. A fibre-optic vibration monitoring installation on a single tower costs approximately USD 8000-12 000, whereas the eight-node LoRa network covering four towers cost under USD 1200 in total hardware. The trade-off is measurement precision: fibre-optic systems resolve micro-strain at kHz rates, whereas the MEMS nodes deliver milli-g resolution at 200 Hz. For the screening-level monitoring intended here detecting gross vibration anomalies and tilt drift the MEMS precision is more than adequate^[14, 15].

Conclusion

Transmission line towers in tropical regions are exposed to monsoon winds, river-crossing aerodynamic loads and ground vibrations from nearby roads, yet most are monitored only by annual climbing inspections that cannot detect progressive deterioration between visits. This research developed and field-validated a LoRa-based wireless sensor network that provides continuous, real-time vibration and tilt data from multiple towers over a multi-kilometre corridor without dependence on cellular coverage or mains power.

Eight sensor nodes deployed on four 115 kV towers near Khon Kaen, Thailand, operated continuously for seven days, delivering a network-wide packet delivery ratio of 96.8 % over distances up to 4.7 km. Vibration RMS ranged from 18.3 mg at a sheltered rural tower to 49.8 mg at a river-crossing tower, correlating strongly with local wind speed ($r = 0.96$). Static tilt at all towers remained below 0.12° , confirming structural integrity within the 0.5° serviceability limit. The average current draw of 5.3 mA (peak 120 mA during LoRa TX, 3.2 μ A in deep sleep) translated to a battery life of 47 days on a 6000 mAh cell without solar recharging, and indefinite life with the 5 W solar panel. All five pre-defined performance targets were met or exceeded. For power-utility operators in Thailand and comparable tropical environments, this system offers a cost-effective alternative to helicopter and climbing inspections for routine structural monitoring. Each sensor node costs approximately THB 3800 (about USD 108) in component parts, and the gateway hardware costs THB 12 000 (about USD 340). The

LoRa radio eliminates the per-node cellular subscription that makes NB-IoT solutions expensive to scale, and the 10-second reporting interval is fast enough to capture wind-gust events and traffic-induced vibration transients that a daily or weekly polling scheme would miss.

Looking forward, several improvements are planned. Replacing the MPU-6050 with a lower-noise MEMS device (such as the Analog Devices ADXL355) would push the noise floor below 0.1 mg and open the door to modal-frequency extraction, which can detect stiffness degradation before it manifests as a tilt change. Adding a GPS-disciplined clock to each node would enable network-wide time synchronisation accurate enough for output-only modal analysis across multiple towers. Integrating edge-AI anomaly detection on the ESP32 feasible with TensorFlow Lite Micro would allow the node to transmit only when an anomaly is detected, reducing airtime and battery draw by an estimated 80 % during calm periods. Finally, a longer deployment of six to twelve months covering both the dry season and the monsoon would validate the system's durability under extreme rainfall, high humidity and lightning-induced electromagnetic interference.

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