Wireless Sensing for Structural Health Monitoring of Bridges by Unmanned Aerial Vehicle (UAV) via BLE Communication

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***Abstract*— The Internet of Things (IoT) has significantly advanced the application of Wireless Sensor Networks (WSNs) in Structural Health Monitoring (SHM), particularly for civil engineering infrastructure. While unmanned aerial vehicles (UAVs) are commonly employed for data collection, this paper proposes a novel approach using Bluetooth Low Energy (BLE) for synchronization and data gathering in SHM systems. Unlike traditional methods that may suffer from compromised network security and increased energy demands, the BLE-based system ensures that individual sensor nodes operate autonomously, providing inherent security benefits and improved battery longevity. Each sensor node acts independently, minimizing the risk to the overall network if a single node is compromised. We present a synchronization scheme that leverages BLE's low-power consumption to enhance the SHM of bridges, supported by a prototype developed using a PASCO bridge kit with wireless load cells and accelerometers. The proposed BLE protocol, to the best of the authors' knowledge, represents an unexplored avenue in SHM, promising increased safety and efficiency in sensor networks.**

Keywords—Wireless Sensor Network (WSN), Internet of Things (IoT), reliability, unmanned aerial vehicle (UAV), drone, Structural Health Monitoring (SHM) Bluetooth Low Energy (BLE)

I. Introduction

The proliferation of Wireless Sensor Networks (WSNs) across diverse industries has led to innovative applications, from consumer electronics to Structural Health Monitoring (SHM) systems for critical infrastructure. In the domain of SHM, particularly bridge monitoring, this research introduces a pioneering synchronization and data collection methodology using Bluetooth Low Energy (BLE). As the trend in SHM moves toward wireless solutions, the advantages become evident: reduced costs, enhanced scalability, and more efficient deployment. Unlike previous applications that have not yet explored the potential of BLE in SHM, this study proposes the use of BLE to implement precise timing mechanisms, akin to a PC motherboard's clock, within each sensor node. This strategy allows for synchronized data collection cycles that optimize energy usage by avoiding constant communication and the traditional 'hopping' associated with networks like IEEE 802.11.

Figure 1 depicts a standard WSN topology reliant on IEEE 802.11, where sensor nodes communicate through multiple hops to a central base station, often at the expense of energy efficiency and network security. In contrast, the proposed BLE-based model enables each sensor node to independently collect and transmit data, significantly reducing energy consumption and enhancing system redundancy. Additionally, by incorporating drones as mobile collectors, we reduce the need for complex node-to-node communication, improving data collection efficiency and security. This novel approach not only streamlines SHM for bridges but also introduces a method that has not been extensively researched, marking a significant contribution to the field, and paving the way for future advancements in wireless sensor technology.

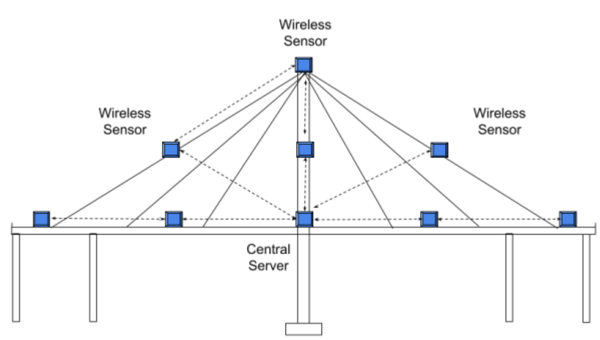

Fig. 1 Traditional WSN for Bridge Contour

II. SYNCHRONIZATION ISSUES

A. *Scope of Problem Space / System Model*

The scope of the research targets the intricacies of achieving precise time synchronization within a Bluetooth Low Energy (BLE) sensor network for bridge structural health monitoring (SHM). The system model leverages a network of BLE sensors, each equipped with their own internal clocks. These sensors are designed to operate predominantly in a low-power state, waking periodically to collect and timestamp data regarding the bridge's integrity before returning to sleep mode. The crux of synchronization is handled by a drone which acts as a roving time server. Equipped with a NTP clock, the drone periodically interfaces with the sensors to deliver BLE packets that update and resynchronize their internal clocks. This research will delve deeper on where this occurs in the BLE communication process. This approach is essential to maintain the accuracy of the sensors' timekeeping, as clock drift is a natural occurrence over time and can lead to significant desynchronization if left unaddressed. The scope of the research addresses the challenge of achieving synchronized data collection and feasibility in a Bluetooth Low Energy sensor network for bridge structural health monitoring (SHM). This system leverages modular sensors with individual clocks, in conjunction with periodic resynchronization facilitated by a drone equipped with NTP synchronized time via its docking station.

B. *Specific Problem to foreshadow our approach*

The existing landscape of bridge SHM has traditionally grappled with challenges stemming from the limited battery life of wireless sensor networks and the logistic complexities of consistent data synchronization among the independent sensors. This feasible approach emphasizes the BLE method for synchronization. The drone, central to our methodology, ensures that the sensors' clocks are updated with minimal energy expenditure and without the need for constant communication. It is imperative that synchronization is maintained even in the absence of the drone to ensure the integrity of data collection. When the drone is on-site, it acts as a mobile data harvester, collecting the timestamped data from the sensors. This setup presents unique challenges in protocol design to guarantee seamless interaction between the drone and sensors, alongside the implementation of security measures to safeguard the communication process.

The proposed system not only aims to mitigate the synchronization drift over time but also strives to address the operational constraints by ensuring the sensors can reliably timestamp data in the drone's absence. This necessitates a balance between synchronization accuracy, energy efficiency, and security, which will be explored in our research.

III. STATE OF THE ART

The proposed research integrates two key innovations. Firstly, harnessing WSN to SHM allowing for a more economic-friendly, safe, and robust approach in comparison to a wired sensor network [5]. Secondly, a drone implementation that collects synchronized sensor data in a fashion shown in figure 2 so that after the sensors have collected their data, they are in a sleeping state.

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In figure 2 the pathing, P stands for position of the drone and S for the individual sensors in the network. This design will mitigate the need for complex sensor-to-sensor communication networks. An interesting aspect to take from this diagram is the drone can move while collecting data. The drone does not need to stop for data gathering, and they do not consider the minimum time it must stay inside the sensor nodes' radio range [1]. This approach aligns with the current emphasis on energy efficiency and automation.

In this diagram, the fundamental communication pathways between the drone and sensors, as well as between the drone and the home server for data aggregation, are depicted. A low Energy Bluetooth protocol is a suitable protocol for the network. It is more efficient than ZigBee in terms of energy consumption and the ratio of transmission energy per transmitted bit. [11] Another candidate for the communication was Long Range (LoRa), which is an LPWAN communication technique that allows for the long-distance, low-power transfer of data between devices like sensors. As a result, it may offer. isolated places with little to no wireless coverage and a trustworthy wireless communications link. [8]

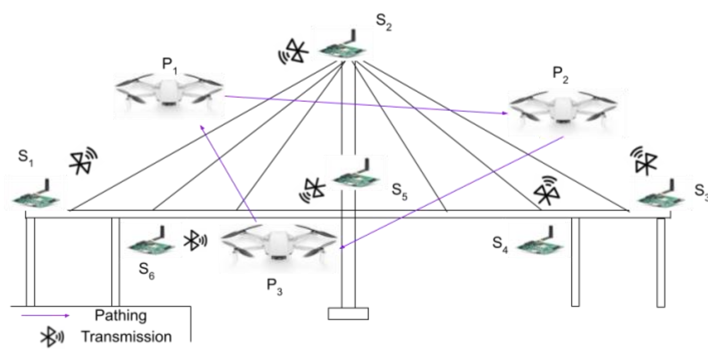

Fig. 2 Single Drone Pathing and Transmission

IV. BLE APPLICATION OVERVIEW

A. *BLE Protocol Stack Utilization for Synchronized Data Collection:*

The BLE protocol stack offers a lightweight and efficient communication standard, ideal for IoT applications such as in this case a UAV-assisted data collection[6]. Through its layers and profiles, the BLE stack ensures synchronized data transmission between the drone and sensors.

Using BLE's inherent capabilities, each sensor equipped with BLE can be accurately discovered and connected to the drone's control system. The connection establishment, as depicted in the BLE Connection Establishment Procedure diagram, proceeds through the advertising and scanning phases, leading to a connection request and subsequent connection. This sequence enables the drone to interact with the sensors in a coordinated manner, ensuring that the data collected is synchronized across all nodes.

B. BLE's Role in Time-Sensitive Data Handling:

BLE's Generic Attribute Profile (GATT) facilitates a structured framework for data exchange that is crucial for time-sensitive applications. By defining the characteristics and services, GATT ensures the orderly and synchronous collection of data. In terms of application to drone-assisted data collection: In drone operations, GATT services can be defined to manage the time-critical aspects of data collection. For instance, the GATT server on the sensor node can provide time stamps along with the data, which the drone's GATT client can utilize to maintain a coherent data set, synchronized in time, regardless of the individual data packet transmission times.

C. Energy Efficiency and Low Latency in BLE Communication:

BLE is designed for low energy consumption with fast connection times, which is essential for preserving battery life in both drones and sensor nodes[11]. The rapid connection and disconnection capabilities of BLE reduce latency and contribute to a more synchronous data collection process. In terms of application to drone-assisted data collection, the energy efficiency of BLE allows for prolonged field operations without the need for frequent recharging. [12]Furthermore, the low latency in establishing connections and transmitting data ensures that the drone can quickly collect data from multiple sensors, reducing the time skew that might occur in less efficient communication protocols.

V. Approach

A. Discovery Phase: Drone to Sensor Discovery

In a drone assisted SHM system, the discovery phase is crucial for the initial detection of sensors installed on structures. Looking at figure 3, the drone acts as a mobile scanner (Host A), flying within range of the sensors (Host B) embedded in the infrastructure. During this phase: The Scanner (Drone) listens for BLE advertisement packets transmitted by the sensors. It uses these packets to detect the presence and identity of sensors without previously knowing their exact locations. The Advertiser (Sensors) sends out advertisement packets (ADV_IND) that contain the sensor's unique identifier and possibly some initial data about the structure's condition. This could include information like the sensor's type, location on the structure, and a timestamp. ADV_IND: This advertisement packet is the first step in establishing communication. It is a general broadcast that can be picked up by any scanning device within range. For the drone, each ADV_IND packet helps it to identify and catalog all the available sensors in the area. These packets are crucial because they do not require a sensor to be connected to a network, allowing for a quick discovery even in vast or complex structures.

B. Connecting Phase: Synchronization and Connection Establushment

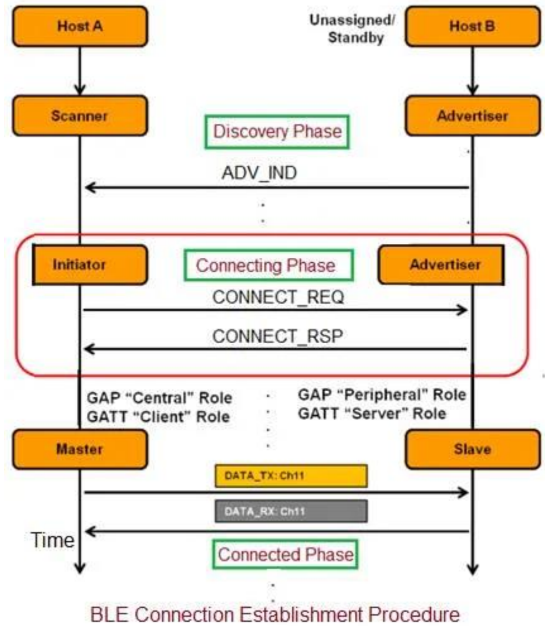

Fig. 3 Drone to Sensor Communication Protocol

Once the drone has discovered the sensors, the connecting phase begins: The Initiator (Drone) sends a connection request (CONNECT_REQ) to a specific sensor it wishes to synchronize with or retrieve data from. The Advertiser (Sensor) receives the connection request and, if it's ready to communicate, sends a connection response (CONNECT_RSP) to the drone. This establishes a connection between the two devices. During this phase, time synchronization occurs. The precise timing information can be exchanged to ensure that the sensor data is accurately timestamped, which is vital for later analysis in SHM. The sensor stops sending ADV_IND packets since it's now engaged in a direct connection with the drone.

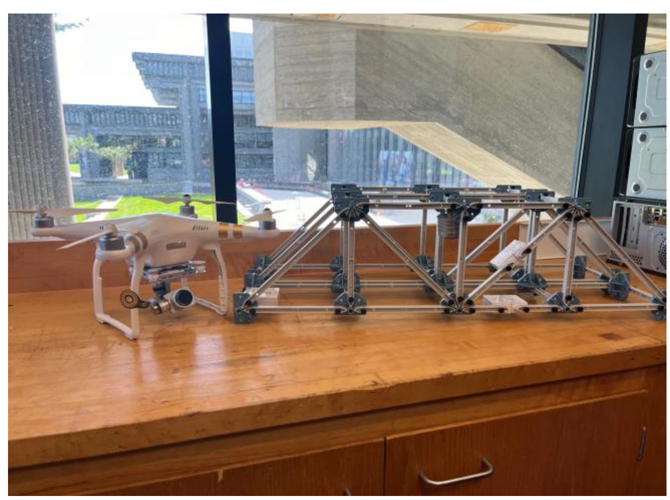

Fig. 4 Model Drone with Sensor Bridge at UmassD

C. Roles and Data Communication: Drone WSN with SHM

With the connection established, the drone and sensor assume their respective roles. The GAP "Central" Role / GATT "Client" Role (Drone as Master): The drone now controls the timing and frequency of data requests. It can synchronize multiple sensors, retrieve data from them, and command them to perform specific monitoring tasks. The GAP "Peripheral" Role / GATT "Server" Role (Sensor as Slave): Each sensor responds to the drone's requests. It collects structural health data and sends it back to the drone. This data includes measurements like vibration and strain, important metrics for SHM. The DATA_TX_CH1 and DATA_RX_CH1 channels facilitate the actual transfer of SHM data from the sensors to the drone. The drone may use this data to make real-time decisions or store it for later analysis as shown in Figure with the sensor data timestamped to a .txt file.

Sensor 1:	Sensor 2
2023-11-09 13:53:32 – Force: -1.13	2023-11-09 13:53:30 – Force: 2.01
2023-11-09 13:53:32 – Force: -1.12	2023-11-09 13:53:30 – Force: 2.01
2023-11-09 13:53:32 – Force: -1.14	2023-11-09 13:53:30 – Force: 2.01
2023-11-09 13:53:32 – Force: -1.13	2023-11-09 13:53:30 – Force: 2.01
2023-11-09 13:53:32 – Force: -1.13	2023-11-09 13:53:30 – Force: 2.0
2023-11-09 13:53:32 – Force: -1.12	2023-11-09 13:53:30 – Force: 1.97
2023-11-09 13:53:33 – Force: -1.14	2023-11-09 13:53:30 – Force: 1.99
2023-11-09 13:53:33 – Force: -1.12	2023-11-09 13:53:30 – Force: 1.99
2023-11-09 13:53:33 – Force: -1.11	2023-11-09 13:53:30 – Force: 1.98
2023-11-09 13:53:33 – Force: -1.12	2023-11-09 13:53:30 – Force: 2.0
2023-11-09 13:53:33 – Force: -1.1	2023-11-09 13:53:30 – Force: 2.0
2023-11-09 13:53:33 – Force: -1.11	2023-11-09 13:53:31 – Force: 1.99
2023-11-09 13:53:33 – Force: -1.11	2023-11-09 13:53:31 – Force: 2.0
2023-11-09 13:53:33 – Force: -1.11	2023-11-09 13:53:32 – Force: 1.99
2023-11-09 13:53:33 – Force: -1.11	2023-11-09 13:53:32 – Force: 2.0
2023-11-09 13:53:33 – Force: -1.11	2023-11-09 13:53:33 – Force: 2.01
2023-11-09 13:53:33 – Force: -1.13	2023-11-09 13:53:33 – Force: 2.0
2023-11-09 13:53:33 – Force: -1.13	
2023-11-09 13:53:33 – Force: -1.13	
2023-11-09 13:53:33 – Force: -1.12	

Fig. 5 Sensor Data transmitted between Sensor and Drone

VI. PROTOTYPING

This research presents a hybrid synchronization strategy, which leverages the individual timing capabilities of sensors and the precise time synchronization possible through BLE technology. In this framework, drones are not solely reliant on GPS for time information but utilize BLE to periodically update the sensor clocks, thus reducing the potential for time drift.

Each sensor in this network is equipped with an internal clock, akin to the timekeeping mechanisms found in computer motherboards. This allows sensors to independently record data timestamps, negating the necessity for constant inter-sensor communication. Our hybrid approach thus melds accuracy with independence, overcoming the limitations inherent to other methods. It facilitates dependable data acquisition without the need for continuous connectivity or centralized networking.

The efficacy of this methodology is exemplified in the scenario in the provided figures 4 & 5. Here, a drone, utilizing NTP from a docking station, capitalizes on BLE for efficient time synchronization. Sensors embedded within the bridge infrastructure, Pasco sensors, maintain individual timekeeping. This orchestration underscores the viability of the hybrid synchronization model.

Figure 5 illustrates the data acquisition from the Pasco wireless load from Figure 4, which operate using BLE within a decentralized sensor network. The data captured is meticulously timestamped, demonstrating the synchronization capability of the sensors as they communicate concurrently with the drone. This precise coordination is reflected in the simultaneous data points collected at a single moment, ensuring that the force measurements, expressed in Newtons, accurately represent the stress experienced by the bridge at that specific time. The in-depth source code of the project can be found using the GitHub link: https://github.com/bryceafonso11/PascoBLE.

VII. CONCLUSION AND FUTURE WORK

In addressing the challenges of synchronized data collection within a network-less sensor framework for bridge structural health monitoring (SHM), this study has introduced an innovative BLE-based solution. This method finds a balance between precision and autonomy, leveraging the advantages of BLE technology for individual sensor time synchronization without the need for a WLAN network. Tailored specifically for bridge monitoring, the integration of drone-assisted data acquisition and BLE connectivity offers a promising alternative to enhance the robustness and efficiency of our critical and often neglected SHM systems. The prototype constructed using a PASCO bridge kit and a set of wireless load cells/accelerometers that interfaced with a drone via BLE, yielded results that affirm the practicality and feasibility of using UAVs for wireless sensor data collection in bridge SHM. The employment of BLE for synchronization ensures precise data capture even in the absence of a centralized network infrastructure or the constraints of a continuous connection. This study represents a substantial step forward in the field of infrastructure preservation, offering cutting-edge solutions for continuous structural health monitoring that could greatly enhance the safety and longevity of critical constructions.

VIII. ACKNOWLEDGMENT

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