Energy Efficient Bike-Share Tracking System with BLE Beacons and LoRa Technology

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***Abstract*—Around the world, vast improvements in public transportation methods in urban environments have been made. However, in densely populated areas, the bicycle remains a very useful means of transportation. Its small size and minimal environmental impact are the critical factors that maintain its relevance. Moreover, the advancement of connected devices and sharing-based services have allowed private vendors to develop bike-sharing programs, giving millions access to bike transportation around the globe. These bike-sharing programs rely on the user to check out and return the bike to a designated bike-holding station. With the growth of Internet of Things (IoT) services and wirelessly connected devices, there is a major benefit in enabling vendors to track their bicycle assets. Satellite navigation has come a long way, however, it requires a large power overhead. This paper proposes an energy-efficient bicycle tracking system that utilizes bicycle powered Bluetooth Low Energy (BLE) beacons and Long Range (LoRa) type base-stations in order to track and maintain a real-time location-based inventory of all assets. The BLE beacons are used to track individual bicycle assets based on Received Signal Strength Indicator (RSSI) proximity and the LoRa base stations exploit longer range communication capabilities to transmit asset location information between each other, for added management capabilities. Preliminary proximity estimations using BLE beacons in an urban outdoor environment show promising results with proximity accuracy consistently under 2 meters.**

I. Introduction

There is an increased focus on environmental sustainability in all aspects of life. Especially with respect to transportation and technology as it pertains to carbon/ fuel emissions and overall energy consumption. A push towards better public transportation infrastructure limits the number of individual vehicles on the road but still often requires the consumption of fossil fuels, whether it be a train, subway car, or bus. New technological advancements have begun to bring electric cars to the average consumer, which cuts down drastically on carbon emissions. However, the batteries that are used to power any electric vehicle are still harmful to the environment. The research in [1] reports that in 2018, 28.2% of greenhouse gas (GHG) emissions were from the electricity sector, and that electric vehicles in 2017 cause a minimum of 67.12 gCO_2eq/km up to 149.21 gCO_2eq/km of GHG emissions. A 2018 study [2], finds that electric vehicles have a mean life cycle GHG emission of 316 gCO_2eq/km. Even with vast improvements, this has a significant negative impact on the environment, and falls short of current climate policies, such as *ClimPol* [3].

Besides walking, biking remains to be one of the best transportation alternatives that impose extremely little environmental impact. Bicycles may not be appropriate for particularly long travel distances but are extremely advantageous in urban environments. This advantage has been realized in the private sector, where public bike-sharing vendors capitalize on providing easily accessible bike transportation to environmentally conscientious people who live in dense populations.

These vendors, such as *Bike Share Toronto* [4], are required to keep track of and maintain their bicycle assets in order to remain operational. Hence, this paper proposes an energy-wise tracking system that utilizes the combination of Bluetooth Low Energy (BLE) beacon and Long Range (LoRa) technologies to provide real-time asset tracking and inventory management for bike-sharing providers.

BLE beacons are small, low power transmitting devices that were built for IoT applications. They transmit small packets over the 2.4GHz band. Each can be configured with their own universally unique identifier (UUID) and custom transmission power and transmission interval. BLE beacons are chosen over other alternatives such as RFID tags because BLE transmissions can be detected within a few meters proximity, up to approximately 50 meters depending on the line of sight (LOS). Beacons are also very cheap and can be scaled easily. LoRa is a low power wireless technology designed for longer range communication. It achieves ranges up to 10km by transmitting over the unlicensed 915MHz band (or 816MHz if you are in Europe) [5].

The proposed tracking system requires that each bicycle asset is assigned a BLE beacon device with a UUID, which is then capable of transmitting this information to a base station at any designated bike-sharing drop-off/pick-up location. The base station can identify nearby assets and estimate their respective proximity's using received signal strength indicators (RSSI). The base stations implement LoRa wireless technology and are capable of transmitting asset information between them as well as to a final server for off-site management.

Most BLE beacon devices operate using batteries, often coin cell. So, in pursuance of preserving the minimal environmental impact of bicycle transportation, a battery-less model is proposed. In order to realize a battery-less implementation, a small portion of the power produced from the bicycle user is extracted from the moving bicycle wheel using a simple dynamo-type dc motor. There is sufficient research proving that these devices can power many low-power devices, such as LED lights for added rider safety. The research in [6] reports that they provide a consistent power level of 3W at 6V, which is far greater than what BLE beacons require for operation.

The rest of the paper is organized as follows. Section II discusses the research pertaining to bicycle power, BLE and LoRa-based localization, and power requirements. Section III gives a detailed description of the proposed tracking system architecture. This includes a topology overview, required hardware, and wireless communication mechanisms. In Section IV, the proximity estimation path-loss model, power measurements, and proximity accuracy experiments are described. This is followed by preliminary results in Section V. Use cases and a feasibility assessment are discussed in Section VI. Finally, the conclusion is in Section VII.

II. Related Works

Bike-sharing is growing all over the world, and so, research that promotes further improvement grows along with it. There is a number of works and research with regards to bike-share models optimization, energy consumption, and smart management. In [7], the authors present a system that better identifies which electric bicycles have enough charge to accommodate the user's route by estimating energy expenditure along the desired course. They achieve this by utilizing a mobile platform backed by cloud services. The research presented in [8] proposes a two-level clustering algorithm to forecast the number of rents or returns to each station cluster in order to re-balance the distribution of bicycle assets at each station. The prediction model showed superiority over other common prediction models like K-Nearest Neighbors (KNN), validating the model with data from the bike-sharing system in New York City. The works of [9] produce similar work, in that they develop a model to better allocate bike fleets and maximize the time between re-allocations. They do this by presenting two mathematical programming models. In [10], a clustering algorithm based on common flow is proposed in order to better allocate bike resources at particular stations based on usage/route flow. Preliminary analysis shows some level of effectiveness in the model. Finally, a proposal for a microcontroller and BLE-based system for detecting bike theft and providing localization capabilities for a public bike-share system can be found in [11]. Here, a hub-type dynamo generator is proposed for energy harvesting. However, there are no tests indicating the location or power extraction feasibility, demonstrating that there is a need for further development.

Localization and proximity estimation using BLE beacons is a key aspect of the proposed system. Using RSSI values is a common technique in estimating distance/proximity. Many papers such as [12], [13], [14], [15], [16], and [17] provide a solid background in the performance of multiple BLE beacons. They implement RSSI techniques along with additional filtering in order to achieve better proximity estimation and localization for IoT applications.

While a lot of research has been conducted in predictive models and smart management systems, little research seems to present itself with regards to a simple means of bicycle asset tracking, especially with an emphasis on energy conservation and sustainability. With regards to this gap, this paper proposes a sustainable and battery-less localization model for bike-sharing asset tracking in urban environments. This is a continuation and expansion on previous work of ours, as seen in [16]. This paper proposes a specific application based on similar research and incorporates new wireless technologies, fusing BLE and LoRa wireless networking.

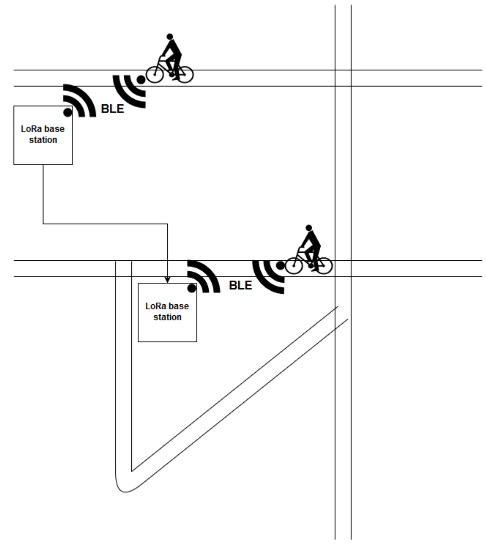

Fig. 1: System framework.

III. System Architecture

This section describes the communication technologies and hardware used in the proposed implementation of the bike-share tracking system. Specifically, the unique BLE beacons assigned to each bicycle, the power generation module and the LoRa transceiver base stations are described in terms of their function, power requirements, wireless technology standards, and cost.

A. System Framework

The overall system framework is shown in Fig. 1. Bicycle users may travel as they please, while a portion of their pedaling power is utilized to power the BLE beacons which broadcast their UUIDs. When approaching any LoRa base station, the UUID of the bicycle will be read and recorded by the base station in order to keep a real-time inventory of the system asset's location. Using RSSI techniques the base station has an approximate estimation of the proximity of the bike to the base station. Lastly, each base station may participate in node hopping, transmitting information between each other using LoRa, in order to pass critical asset information to the network for inventory and asset localization purposes.

B. Communication Infrastructure

1) BLE: Bluetooth Low Energy is a low-power subset of the Bluetooth wireless technology. It operates on the 2.4 GHz band, similar to Wi-Fi. BLE is capable of effectively transmitting to distances up to 50m. The main advantage of the BLE technology is the ultra-low power requirements and the ability to estimate proximity and position with an appropriate

Fig. 2: Gimbal Series 10 Beacon [19].

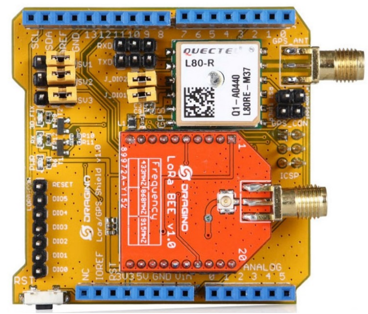

Fig. 3: Dragino Shield v1.3 [22].

level of accuracy. [16] reports BLE positioning accuracy of approximately 2m using RSSI techniques. In order to maintain inventory across base stations of a bike-share tracking system over a large region, an alternative technology also needs to be employed on top of the BLE positioning.

2) LoRa: LoRa (Long Range) is an unrestricted wireless technology that operates at various frequencies depending on your region. 868 MHz for Europe and 915 MHz for North America [5]. Regardless of region, the main advantage of using sub-gigahertz frequencies is the long transmission range. LoRa is capable of reaching distances of approximately 10 km [18]. This characteristic makes LoRa-type base stations ideal receivers for the proposed bike-share tracking system so that multiple stations in an urban region are able to communicate with each other. The disadvantage of LoRa is that determining the true location using RSSI techniques produces poor results when compared to alternatives like Bluetooth, hence the use of BLE beacons.

C. Hardware

1) Nodes - BLE Beacons: BLE beacons are small, low cost, transmitting devices. They cannot be used as a receiver and they employ simple transmission protocols, such as Google's *Eddystone* and Apple's *iBeacon* protocol. Fundamentally, both transmission protocols are formatted such that each beacon is assigned a UUID. These identifiers can be assigned to individual bicycle assets within a larger set. BLE beacons also have two critical configuration parameters, transmission power, and transmission interval. Both of these parameters have an effect on the attainable accuracy and the overall lifetime of the beacon, assuming it is powered with batteries. Research indicates that positioning accuracy increases with an increase in transmission power and transmission interval, while node lifetime has an inverse relationship with both parameters [13], [15]. The following experiments in this paper utilize the Gimbal series 10 beacon, shown in Fig. 2, chosen for its very low cost, $5 USD, and very small form factor (40mm x 28mm x 5.5mm) [19].

2) Base Stations/Access Points - LoRa Transceivers: LoRa transceivers are less common than BLE beacons and require more power, however, the long transmission distance makes them ideal for communication between bike storage stations in an urban region. It is also critical for the base station to be compatible with BLE reception in order to track which bicycle assets are stored at any given time. In this case, a Bluno Uno Bluetooth 4.0 microcontroller [20] and Dragino LoRa Shield [21] are chosen, shown in Fig. 3. Both modules have a small form factor and integrate with each other.

TABLE I: Bicycle Power Generator Comparison

	Alternator	Dynamo-Bottle	Dynamo-Hub
Advantages	Very high output power	Simple installation Attach to any Bicycle Low cost >300g [23]	No slippage Better power output than bottle type
Disadvantages	Large/Heavy >4kg [24] Large resistance/load	Tire wear Slip if wet	Heavier and more expensive than bottle-type >800g [25] Non-universal installation

3) Power Generation: The energy-wise characteristic of the proposed tracking system is that the beacons are battery-less and rely solely on green energy generated from the bicycle in use. There are a number of options that convert the rotational energy of a bicycle's tire into electrical energy. The two main categories are dynamo type motors, which use commutator plates, and alternators. [6] does an in-depth analysis of the power generation capabilities of such devices. The authors report a power generation of up to 300W with the use of an alternator, assuming a high level of physical fitness. However, alternators are large, heavy, and vastly increase the load on the bicycle operator. The dynamo type devices still generate approximately 3W at 6V, have little to no noticeable impact on user effort, and are much more compact and lighter in weight. There are two sub-categories of such devices. There are bottle-type dynamo generators that use the friction of the tire to spin the armature of the dc motor, and hub-based motors which have the dc motor built into the hub of the wheel, thus generating energy directly from the rotation of the wheel. The advantages and disadvantages of all designs are further detailed in Table I.

IV. Experimental Procedure & Methodology

In order to validate the functionality and support feasibility of the proposed system, preliminary power and proximity accuracy measurements had to be taken. Here, the power requirements of BLE beacons and LoRa transceivers are measured. Furthermore, the estimated proximity using RSSI techniques and BLE beacons are conducted.

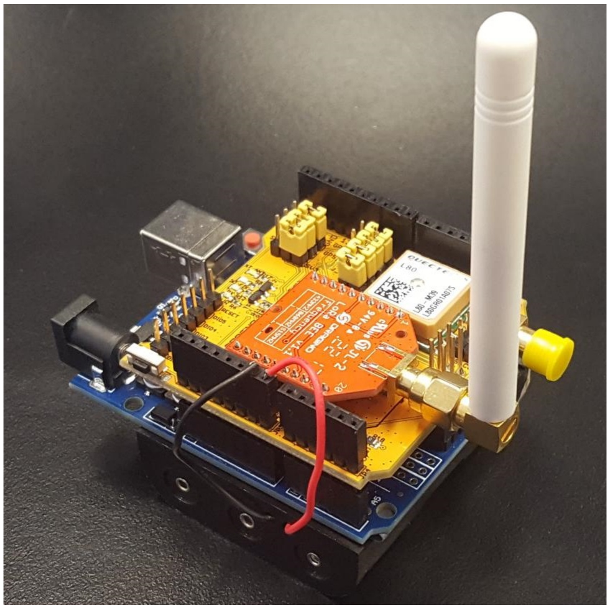

Fig. 4: Dragino shield and Arduino node.

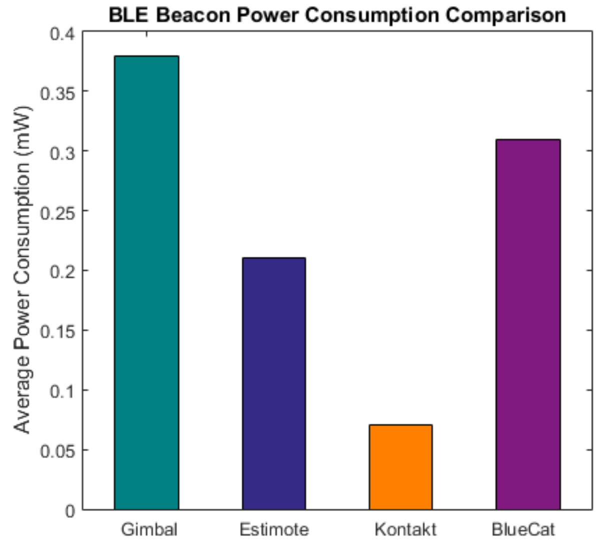

Fig. 5: BLE beacon power consumption.

A. Measuring Power Consumption

In order to verify that the dynamo motors can consistently power the BLE beacons, a Monsoon power monitor [26] was used to measure the power consumption of four BLE beacon devices available on today's market. Specifically, a Gimbal series 10 [19], Kontakt [27], Estimote [28], and BlueCat beacon [29]. Each was configured with a transmission power of -12 dBm and a transmission interval of 3 seconds. -12 dBm was chosen due to the fact that the beacons only need to transmit short distances (i.e. only need to be seen when close to a base station). The power consumption was monitored for 3 minutes, and the average value recorded.

The Dragino LoRa shield acts as a transmitter and receiver and has to transmit over greater distances. The Dragino shield was set up along with the Arduino (see Fig. 4) and set to have a transmission power of 20 dBm and a transmission interval of every 3 seconds, similar to the BLE beacons. It should be noted that the LoRa base stations are assumed to have a wired power source and do not require any batteries to operate.

B. Proximity Estimation

Proximity estimation can be achieved using RSSI values obtained from the transmitting BLE nodes. First, a path-loss model must be created that models the environment in which the beacons are deployed. A path-loss model delineates the non-linear and non-parametric nature of RSSI signals in a dynamic environment. It is required in order to model the noise and signal propagation loss experienced in each environment. The path-loss model and subsequent distance estimations are carried out in an outdoor parking lot at the University of Guelph in order to simulate an outdoor environment in which a bicycle station may be located. In this experiment, the proposed Gimbal beacons are used. The beacon retains the same configurations set for the power experiments. All RSSI data is collected using a Google Nexus 5 smartphone running Android 6.0.1.

The path-loss model is built by constructing a set of RSSI measurements at 20 distinct distances $d = 0.2, 0.4, 0.6, 0.8, 1.0, ..., 2.0m$ and follows equation (1), similar to [17]

$$RSSI = -10nlog_{10}(x) + C \quad (1)$$

Where n is the signal propagation loss factor specific to the wireless medium, x is the distance between the beacon node and the receiver, and C is a constant that accounts for system noise.

V. Preliminary Results

A. Power Consumption Results

Figure 5 depicts the power consumption of four popular beacon devices. All beacons have an average power consumption under 0.4mW, which is 7500 times less than what the bicycle dynamo motors are capable of producing. This leaves ample room for mechanical and electrical energy losses within the system and allows the beacons to operate under low rider effort. The Gimbal beacon has the highest power consumption of 0.38mW, which is likely a result of simple circuit design and leakage that is associated with the very low cost. Next was the BlueCat at 0.31mW, the Estimote at 0.21mW, and the Kontakt beacon at 0.07mW. All beacon devices vary in circuit design, power source, and additional sensing capabilities. Hence the variation in power consumption.

The Dragino LoRa shield/Arduino combination required significantly more power than the BLE beacons at 92.37mW. It should also be noted that this still falls under the threshold for available power produced by the dynamo generator.

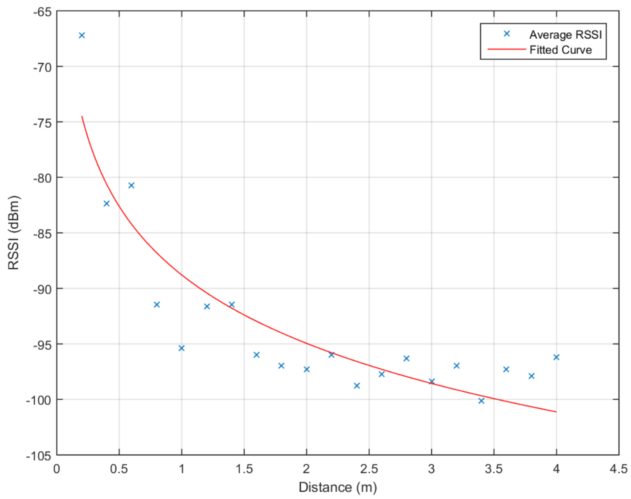

Fig. 6: Path-loss model-best curve fit.

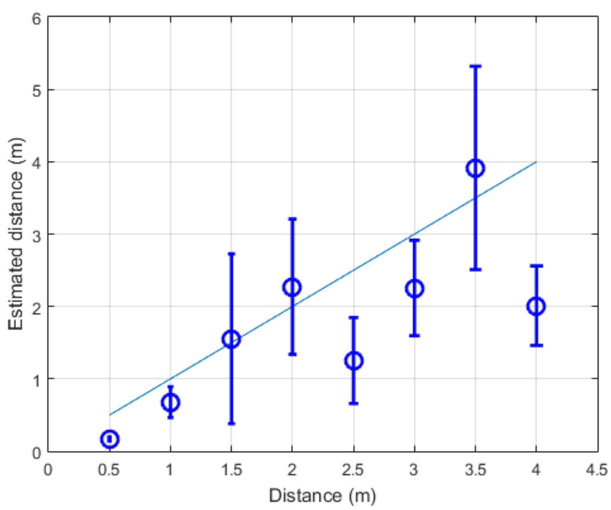

Fig. 7: Proximity estimations.

B. *Proximity Estimation Results*

Figure 6 depicts the RSSI values at each distance and the best curve fit line that models the environment. The best curve fit line applies the function defined by equation 1 to the RSSI data set collected for that particular environment. It finds the optimal n and C values to best fit this function to the data-set. Here, the propagation path-loss factor n was found to be 2.049, and the system noise C to be -88.78 dBm. With this information the distance estimation experiments could be conducted, the results of which are depicted in Fig. 7. The solid line depicts the expected distance, while each proximity measurement and its deviation are shown with circles and error bars. The best accuracy is achieved when the BLE transmitter is within a 2m proximity of the receiving node. In this particular experiment, the error consistently lies within 2m at any point for all measurements in the data-set, which falls directly in line with the results found in similar literature, like [16].

VI. Discussion & Analysis

A. *Power Consumption Implications*

The power consumption results indicate that BLE beacons are perfectly suited for an energy-wise application that does not need to rely on battery power and can instead be powered by alternative methods. In particular, bicycle power generation is a feasible solution. It should also be noted that due to the extremely low power requirements of BLE beacons and the available power generation of simple dynamo generators, other devices can be powered simultaneously, such as LED lights for rider safety.

The Gimbal series 10 beacon, although the highest power consumer, is likely the best option of the four beacons due to its low cost, making it cost effective for large scale applications.

It was also confirmed that the Dragino LoRa transceivers require less than the available power generation of the dynamo motor. However, the Dragino shields are larger in size and thus, harder to conceal. Furthermore, they are more expensive than Gimbal BLE beacons. In addition, more complex weather-proofing measures would also need to be implemented in order to ensure long term operation of the device in varying conditions. Lastly, LoRa transceivers are known to produce proximity estimation with greater error than BLE at close proximities [17].

B. *Proximity Estimation Accuracy*

The proximity accuracy of the BLE beacons was consistently estimated to be within 2m of the true value. This is sufficient for the application context of this system, where the base stations only need an approximate location of each unique bicycle asset in order to maintain a robust real-time inventory. Further steps could be taken to improve the proximity accuracy, such as implementing a particle filter to better eliminate outliers produce better estimation performance.

VII. Conclusion

This paper introduced an intuitive energy-efficient tracking system for bike-sharing applications that utilize BLE beacon and LoRa wireless technologies. The low cost of BLE beacons allows for large scale implementations with a constrained budget. Bicycle power generation is exploited in order to eliminate the need for batteries for the beacon devices. The beacons require only a very small fraction of the power that can be generated without adding unnecessary load to the bicycle user. This opens up space for additional sensing or device power opportunities. The proximity accuracy of each beacon was found to be in the order of 1-2 meters in the worst case and 1-5 centimeters in the best case. Alternative energy harvesting techniques, such as solar and wireless power transfer are potential extensions for future work. Additional data filtering techniques, such as a particle filter for improved proximity accuracy will also be highly considered for future work. Overall, the system proves to be feasible and operates with little environmental impact, even at large scale implementations.

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