An Asynchronous Dual Radio Opportunistic Beacon Network Protocol for Wildlife Monitoring System

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***Abstract*—In this paper, we introduce an asynchronous dual interface opportunistic beacon network for wildlife monitoring. Unlike conventional opportunistic networks which are based on multi-copy data replication techniques, our approach utilizes an optimized single-copy beacon data transmission to achieve high energy efficiency. Furthermore, the collected data is aggregated and relayed to the central system by leveraging a low power and long range radio to provide high connectivity coverage. This approach will allow ultra-low power IoT devices to be deployed for sustainable wildlife monitoring applications. We evaluate the proposed approach in an actual animal movement use-case scenario. The results indicate that the proposed approach outperforms the traditional opportunistic network protocols in-terms of energy consumption and packet delivery ratio.**

Keywords*—*Wildlife monitoring, LoRa, BLE, Beacon

I. Introduction

During the last few years, Internet of Things (IoT) has received increasing attention worldwide for its numerous applications. Consequently, number of IoT devices deployed are growing steadily. One of the applications of IoT is wildlife monitoring, in which the activities of wild animals are monitored by employing heterogeneous sensors (e.g. gyroscope, accelerometer, etc) either on collars or buried underground [1, 2]. Wildlife monitoring systems (WMS) need to monitor the animal herd physiological activities in real-time as well as to provide network services such as localization, proximity detection, data pre-processing, and cluster nodes management. This requires (i) high energy efficiency, since the sensors used in a WMS will operate with a limited source of energy, (ii) good reliability to avoid false alarms, and (iii) low latency for a responsive WMS.

Based on movement behavior of wild animals and target application requirements, conventional mobility adaptive opportunistic networks e.g Epidemic or PRoPHET [3, 4] are not suitable for WMS applications, this is mainly due to their multi-copy replication approach that leads to high resource consumption in-terms of such as energy and data storage space. Moreover, the movement behavior of wild animals often show a sparse and con-species (clustered) movement behavior. This behavior results in frequent change in the network topology, which gives rise to challenges in peer-to-peer network connectivity and energy management [5]. Eventhough mobility is considered as the fundamental facilitator for information dissemination in opportunistic networks, recent works have revealed that current opportunistic protocols perform worse than expected for sparsely mobile networks with non-deterministic movement [3, 4]. For instance, Epidemic [3], and PRoPHET [6], offer a high data delivery ratio at the expense of high network overhead and latency [4]. Spray and Wait (SnW) [3] on the other hand results in low latency but has high network overhead [4].

Several projects exist that use opportunistic networks for wildlife monitoring, for instance, ZebraNet [7], Rat Watch [8]. These projects, however, implement opportunistic networks by leveraging an Epidemic flooding, which is prone to low delivery ratio and high latency [3]. Moreover, they lack the low power data aggregation backbone network to relay data to a central system. Instead, they often utilize offline data gathering or cellular and satellite based systems [9]. However, the inherently high energy cost and intolerable communication latency make these approaches less attractive.

In this paper we present an asynchronous dual radio opportunistic beacon network for wildlife monitoring. Our proposed opportunistic beacon network leverages a high data rate BLE radio in a low power long range LoRaWAN network [5]. Utilizing LoRaWAN for long range data relaying introduces a *1% duty-cycle* communication restriction, which impacts the real-time latency requirement. We, therefore, address this challenge by utilizing dual interface, to provide a wider control over the trade-offs in energy versus latency, and by not sending all raw data to the LoRaWAN server. Instead, data pre-processing within the animal herds or groups is applied before relaying the data to the central server. This is mainly because data processing is computationally cheaper than data transmission. This ultimately reduces the implementation complexity of the solution [5]. Unlike existing opportunistic protocols that uses a multi-copy data replication scheme, our protocol utilizes a single copy replication scheme with data aggregation and pruning at the receiving nodes. This will have a higher impact on the network performance e.g. energy, latency, and reliability measures as it will be demonstrated in the evaluation section.

The rest of the paper is organized as follows: Section II describes the existing opportunistic network protocols. Section III presents the proposed network protocol and design approaches for the wildlife monitoring system. Section V discuses the use case scenario and presents the large scale evaluation results. Finally, a concluding remark and future research challenges are described in Section VI.

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II. Related Work

In conventional opportunistic networks (e.g Epidemic or ProPHET [3]), deciding where data should be sent to is often straight forward; i.e. the data is forwarded to the next neighbor along the path to the sink usually through the shortest path. Moreover, the gathered data is transferred to a sink using either fixed or mobile intermediate nodes used as relays. Traditional opportunistic protocols will perform poorly in WMS scenarios where the network is sporadically connected due to animal mobility pattern [7]. Currently, several research works have improved data collection based on opportunistic sensing with mobile network infrastructure support [6]. However, unless standard mobility model is considered, they often result in low delivery ratio and high latency [7, 8]. Thus, an efficient data dissemination protocol is needed for a newly surfacing wildlife monitoring applicaions with mobile sensor nodes.

A similarity among opportunistic protocols is that, they are based on store-carry-forward (SCF) data replication technique, however, they differ in their approach to optimize and restrict the degree of replication. For instance, Direct Delivery (DD) algorithm enables a node to directly exchange a data to the destination in range [4]. After the communication is finished the sender node erases the replicated message to avoid local buffer queue overflow. Hence, the direct delivery scheme is based on single replication routine which often results in low delivery ratio.

Epidemic protocols spread data through out the network similar to microorganism infection [3]. When end-devices are in contact, they exclusively replicate multiple copies of data to the near by receiver nodes. These processes will be repeated through the network when nodes are in their range of communication, and ultimately data will reach the intended sink node. These epidemic approaches result in a high data reliability, however, they will drastically deplete sensor node resources, e.g. energy and data storage space [4].

To solve the problem in Epidemic protocol, Balasubramanian et al. [10] treated routing as a resource allocation problem and proposed RAPID protocol. The authors used an in-band control channel to exchange various metadata including expected contact time with other nodes, list of data delivered, and average size of past transfer events. RAPID essentially defines a per-data utility function, in which the data is replicated in such a way that it locally optimizes the marginal utility.

Similarly, ProPHET [6] was introduced to estimate data delivery probability for every contact with a destined node before sending a data. Moreover, Spyropoulos et. al [6, 11] introduced the Spray and Wait (SnW) protocol, by limiting and optimizing the number of data replication for every data forwarding. ProPHET and SnW have been found to reduce the energy consumption and increase the data delivery ratio considerable compared to Epidemic like protocols.

III. Protocol Design

In this section, we introduce an asynchronous opportunistic beacon network protocol for wildlife monitoring system. In order to carry out fine-grained monitoring applications, our proposed opportunistic beacon network protocol introduces a versatile and lightweight connectivity scheme, called opportunistic beacons, that expedites rapid and energy-efficient information sharing between mobile sensor devices without requiring connection establishment and complex configurations.

A. Opportunistic Beacon Communication Scheme

In the proposed protocol, there are three network device types: (i) Animal Scanner (AS), (ii) Animal Broadcaster (AB), and (iii) LoRaWAN Gateway (LG). AB is a BLE beacon broadcasting node, while AS is a BLE scanner node, which listens for BLE beacons in the surrounding. AS node has a dual radio i.e. BLE and LoRa. It uses the BLE interface to scan for BLE beacons from AB nodes, and the LoRa interface to send the aggregated received BLE data to LG. LG is LoRaWAN gateway node which receives a LoRa packets from AS node. The AB-to-AS opportunistic beacon communication includes three main schemes: (i) periodic beacon advertising by AB nodes, (ii) periodic beacon scanning by AS nodes, and (iii) beacon data pruning and aggregation by AS node. The overview of the proposed beacon protocol scheme is shown in Figure 1. In what follows we elaborate on each of these three schemes.

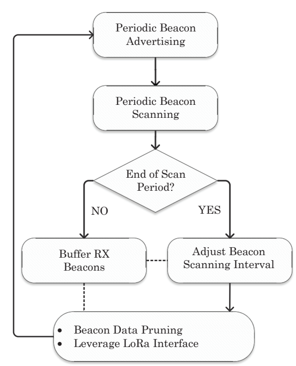

Fig. 1: AB-to-AS opportunistic beacon communication scheme.

1) Periodic beacon advertising: Beacon discovery is initiated by *AB* nodes periodically sending beacon data to AS nodes and *AS* nodes scanning for nearby beacons by listening for AB's data in advertising channel. AB nodes use periodic asynchronous BLE mode to broadcast data to an AS scanners within range. This sequence of events is called an advertising event. Advertising activities could occur at regular intervals called broadcast interval. AB-AS BLE beacon communication is a *many-to-many (m-to-m)* transfer [12].

2) Periodic beacon scanning: As AS nodes commence their scanning operation, they listen and buffer the number of beacons they have received during their current and previous scanning window. Scanning activities occur at regular intervals. At the end of every scan window, AS nodes adapt the duration of the scanning interval according to the number of beacons received in the current and previous scanning. AS nodes switch to LoRa interface to relay beacons to LG node. This enables the AS node to considerably decrease the energy consumption.

3) Beacon data pruning and leveraging LoRa radio: AS nodes have a dual radio, i.e. they utilize BLE as a short-range asynchronous interface and LoRa as an LPWAN solution, while AB nodes only have a BLE bearer. The AS end-devices use short range BLE to receive beacons from AB, and long range LoRa radio to send aggregated data to LoRaWAN Gateway (LG). While obeying the 1% duty-cycle of limitation of LoRa radio. Readers are referred to [12, 13] for more details on LoRa and BLE technology. After finishing sending LoRa packets, AS node switches back to listening the incoming BLE beacon data from AB nodes.

B. Operation of AB and AS Nodes

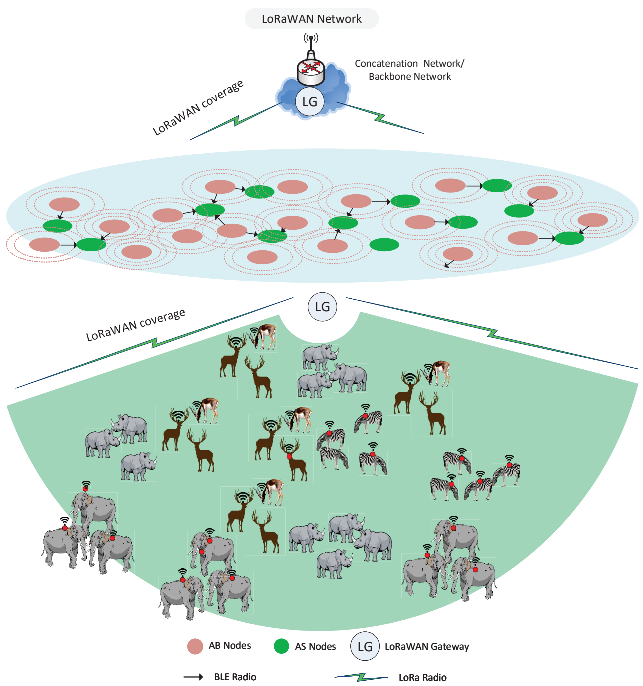

Fig. 2: A hybrid radio opportunistic beacon network. Short range radio (BLE) is utilized for opportunistic beacon network mode (AS-AB) realization and LoRa radio is used to link to LoRaWAN Gateway (LG). Device types are: (i) AS- Animal Scanner, (ii) AB- Animal Broadcaster, and (iii) LG-LoRa Gateway.

The proposed opportunistic beacon network is shown in hierarchical layout in Figure 2. The bottom tier consists of a network of AS-AB devices. The detailed operation of AB and AS nodes are show in Figure 3a and Figure 3b respectively. As shown in Figure 3a, AB nodes start beacon advertising with a single copy beacon data by periodically (with T^{+}_{BC}) interrupting BLE radio from low power *BLE: Sleep Mode* to *BLE: TX Beacon Mode*. In case of opportunistic BLE beacons operation, AB and AS nodes are not *synchronized*; so these activities should *overlap* for beacon discovery to initiate.

Similarly, as illustrated in Figure 3b, AS nodes also commence periodic scanning operation by changing their BLE radio from *BLE: Low Power Mode* to *BLE: RX Scanning Mode*. An AS node starts the beacon scanning with predefined default $T^{+}_{sw} \geq T^{+}_{s,min}$ values, to allow the asynchronous AB beacon data to overlap with the listening window of AS

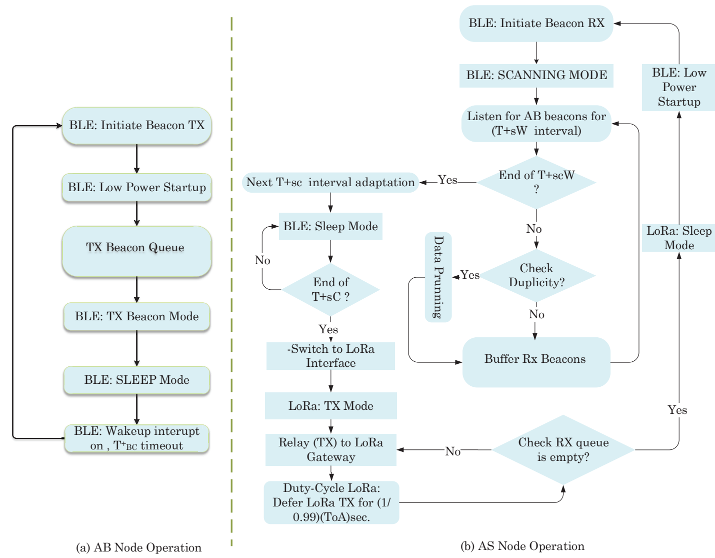

Fig. 3: AB and AS node operation flowchart.

node. To cope with the variable number of incoming AB beacons, AS node adjusts the scanning time interval based on the number of beacons received from AB nodes. An AS node listens and keeps track of the number of beacons it has received during its current and previous scan period (T^{+}_{sw}) with ($prevBeaconNum$ and $curBeaconNum$) variables. Each AS node compares its ($prevBeaconNum$) with $curBeaconNum$ to decide the duration of the next scanning interval (T^{+}_{sw}). This approach will contribute to lower energy consumption for AS nodes by adaptively controlling the scanning interval (T^{+}_{sw}). Algorithm 1 summarizes this procedure.

Algorithm 1 AS node operation: T^{+}_{sw} time adaptation to received beacons

$Input$: $T^{+}_{s,min}$, $curBeaconNum$, $prevBeaconNum$
$Output$: T^{+}_{sw}

procedure *AS Beacon Scan*
top:
  $T^{+}_{sw} \leftarrow T^{+}_{s,min}$ **repeat every** T^{+}_{sw}
  if $curBeaconNum \geq prevBeaconNum$ **then**
    $T^{+}_{sw} \leftarrow T^{+}_{s,min} + 0.625 \times curBeaconNum$
  if $curBeaconNum \leq prevBeaconNum$ **then**
    $T^{+}_{sw} \leftarrow T^{+}_{s,min}$
   continue
  $curBeaconNum \leftarrow 0$
  $prevBeaconNum \leftarrow 0$
  goto *top*

The $T^{+}_{s,min}$ is equal to the recommended minimum broadcast interval ($T^{+}_{BC} = 100$) in BLE protocol specification for beacon functionality [14]. When ($curBeaconNum \geq prevBeaconNum$), then AS node updates its next service to start with longer scanning window of ($T^{+}_{sW} = T^{+}_{s,min} + 0.625 \times curBeaconNum$), where, $[2.5 \leq T^{+}_{sW} \leq 10240]$ms and $T^{+}_{sW} \leq T^{+}_{sc}$ as per BLE specification [14]. The longer the

T^+_{sW} interval, the more beacon it can listen to in one period. In case of ($curBeaconNum \leq prevBeaconNum$), T^+_{sw} is by default $T^+_{sw} = T^+_{s,min}$ to start over the periodicity. In this way, AS node adapts its scanning time according to the dynamic number of beacons it receives.

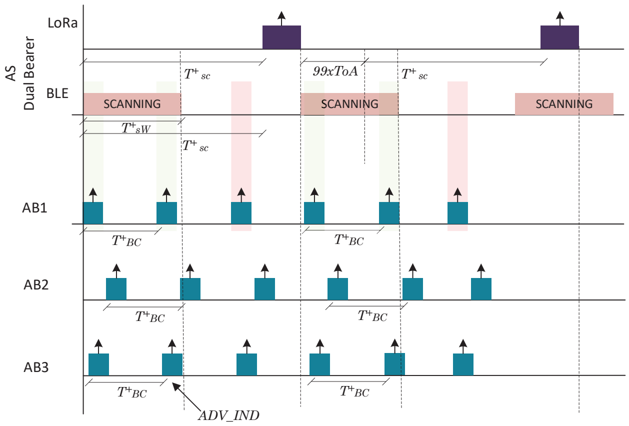

Fig. 4: Data transmission timing for AS node with dual interface (BLE and LoRa). The AS node concatenates AB beacon packets and relays it through LoRaWAN every T^+_{sc} cycle, while obeying the 1% duty-cycle restriction. BLE AB-to-AS Timing: T^+_{BC} -advertiser interval, T^+_{sc} -scanner interval, and T^+_{sW} -scanner window, where $T^+_{sW} \geq T^+_{BC}$.

Figure 4 shows the operation of AS nodes with the beacon timing required to establish a reliable opportunistic beacon network, where: T^+_{BC} - is advertising interval, T^+_{sc} - is scanning interval, and T^+_{sW} - is scanning window, where $T^+_{sW} \geq T^+_{BC}$ for the AS node to pickup the AB BLE beacons in the area. As guideline, choosing the right AB beacon timing parameters, (T^+_{BC}, T^+_{sc}, and T^+_{sW}), should be based on application requirements. Both fast or slow beacon modes have advantages and disadvantages. For instance, longer T^+_{BC} duration is slower beaconing and have a lower power consumption.

Consequently, has a lower probability for short discovery time by AS nodes. While shorter T^+_{BC} duration for fast beaconing results in a higher power consumption, it also has with higher probability of short discovery time by AS nodes. In a time-constrained applications as in WMS, when the AS needs to receive data in real-time, then T^+_{sW} should be $T^+_{sW} \gg T^+_{BC} + \beta$ to guarantee discovery. Moreover, to prevent advertising events from multiple beacons colliding, a small random time ($\beta = [0 - 10]ms$) is added between advertising events. Adhering to this beacon timing guide line will reduce beacon collision and increase the delivery ration. Table I summarizes the BLE beacon communication timings involved.

At the end of every scanning window (T^+_{sw}), AS node periodically relays processed AB beacon data to LoRaWAN network by utilizing its LoRa radio interface. While leveraging LoRa the AS node is restricted by the 1% LoRa transmission duty-cycle regulation [5]. This restriction and node mobility could contribute to high network latency. For example, for LoRa payload of $PL = 51$ bytes using LoRaWAN (SF = 7, CR = 1, DR = 5kbps), the time on air will be $ToA = 71.936$ms and AS node has to wait for sending for $T_{off} \approx 7.1936$s, which is practically long for real-time (fine-grained) monitoring of mobile network environment with frequently changing RSSI values [5].

TABLE I: BLE Beacon Timing

Notation	Meaning	Recommendation
T^+_{BC}	Adv. Interval	Int. multiple 0.625ms in $[20 \sim 10240]$ms
β	Upper delay bound	$[0 - 10]ms$
T^+_{sc}	Scan Interval	Integer multiple of 0.625 ms in $[2.5 \sim 10240]$ms
T^+_{sw}	Scan Window	Integer multiple of 0.625 ms in $[2.5 \sim 10240]$ms, $T^+_{sW} \leq T^+_{sc}$

To alleviate this issue, our proposed approach utilizes data merging and pruning at AS node to reduce latency. Therefore, AS nodes encode several BLE beacons into a single LoRa packet to be relayed to the LG node (see Figure 3b). At the end of every scanning interval, AS node turns off LoRa interface and again switches back to BLE interface to continue receiving the BLE beacons while complying to 1% duty-cycle regulation.

IV. Optimal Beacon Transmission Intervals

The AB node's beacon advertising interval (T^+_{BC}) value for AB nodes has an impact on application requirements of a given opportunistic beacon network protocol. Achieving high *average delivery ratio (D_e), low average latency (ℓ), and high average network life-time (N_l)* are the main requirements often considered [5]. Hence, in this section, we formulate these requirements as an optimization challenge and discuss its practicality.

Let $S_r \subset N$ denote a set of AB beacon generating nodes in a network with N number of AB nodes. L denotes the set of wireless (AB to AS) links. The link $L_i \subset L$ originating from node $i \in S_r$ is the link that connects AB node i to a AS node. Hence, the beacon network requirement optimization could be expressed as:

$$\begin{aligned} \underset{\ell \in L_i}{\text{Maximize}} \quad & D_e = \frac{1}{|S_r|}\sum_{i \in S_r} D_{e L_i} = \frac{1}{|S_r|}\sum_{i \in S_r} P_i \\ \text{Subject to} \quad & D_e \geq D_{emin}, \; i = 1, \ldots, N. \\ & \ell = \frac{1}{|S_r|}\sum_{i \in S_r} \ell_{L_i + L_{LoRa}} \leq \ell_{max} \\ & N_l = \frac{1}{|S_r|}\sum_{i \in S_r} N_{l_i} \geq N_{lmin} \end{aligned} \tag{1}$$

Where per AB-AS link, the delivery ratio $D_{e L_i}$ of link L_i is the expected beacons successfully delivered from AB node $i \in S_r$ to AS node along the L_i link. The *average delivery ratio (D_e)* is defined as the average of all links L_i (See Eq. 1). D_e is further simplified as the probability P_i that AB node i will successfully deliver to AS.

Similarly, we define the per-hop latency ℓ_{L_i} of link L_i as the time required for AB node i to deliver a beacon to AS nodes. In addition a significant latency overhead is introduced due to the 1% LoRaWAN duty-cycle regulation (L_{LoRa}), when at the end of every T_{sC}^{+}, AS nodes utilize LoRa interface to relay data to the LG node. L_{LoRa} is directly related to the time-on-air (ToA) of the defined LoRa packet payload (PL). Thus, as shown in Eq. 1, the total average end-to-end network *latency* (ℓ) is expressed as a total average of ℓ_{L_i} and $L_{LoRa} = T_{sC}^{+} + 99 \times ToA$. Furthermore, the *Network life-time* (N_l) is also defined as the average time before individual nodes (N_{l_i}) stops operating (see Eq. 1).

Therefore, to satisfy the given beacon network requirements, an upper bound could be introduced on the acceptable level of maximum latency, $\ell \leq \ell_{max}$, for a timely data delivery. Likewise, an applicable minimum average delivery ratio, $D_e \geq D_{emin}$, and minimum per node-life-time $N_{l_i} \geq N_{lmin}$ could be defined.

Since the performance of AB beacon advertising primarily depends on (T_{BC}^{+}), thus, AB nodes should be configured with an optimal T_{BC}^{+} beacon interval to satisfy the network requirements. To solve Eq. 1, we define a simple mathematical model to describe the AS device discovery latency, and characterize the collision probability and/or reliability according to the ideal implementation of BLE specification [14]. Note that the beacon collision probability depends on three main factors: (i) collisions between AB beacon packets, (ii) AB beacon timing parameter configurations and (iii) channel and interference conditions.

Thus, we model the probability of how likely it is that an AB device sends an AB beacon packet AS without a collision, given that T_{BC}^{+} is beacon interval and Γ is the duration of AB beacon data. The number of BLE devices involved in the analysis is $N+1$, i.e. a device is configured as a scanner (AS), whereas the other N devices are configured as advertisers (ABs). Hence, AB beacon data will overlap and create collision if it starts anywhere in Γ duration, inclusive before AB starts up until when it finishes advertising $[0, \Gamma]$, then it will be an overlap window of 2Γ or $[0, 2\Gamma]$ length, where there is a chance of collision.

$$P_i(\forall\ (N-1)) = (1 - 2\Gamma/3T_{BC}^{+})^{(N-1)} \qquad (2)$$

For N number of AB nodes in the network and assuming the best case scenario, (i.e. the transmitted AB beacons are all successfully received by the AS node), the probability that i^{th} node's beacon misses (no collision) all other (N-1) AB's beacons in the same channel is $P_i(\forall\ AB) = P(no\text{-}collision)^{(N-1)}$, as expressed in Eq. 2.

Thus, the average network reliability (R) for the beacon network, would be $D_e = \frac{1}{N}\big(\sum_{i \in N-1} P_i(\forall\ AB)\big)$. This generalization holds true even when multiple AS nodes exist in the same radio coverage area, since BLE beacon is based on broadcast communication mode where multiple AS and AB nodes share the same channel.

Similarly, the expected per-link i^{th} beacon discovery latency at AS node is given by:

$$\ell_{L_i} = [T_{BC}^{+} + \beta_{Bd_{max}} + P_i(\forall\ (N-1)) \times (\Gamma)] \times 10^3 [ms] \quad (3)$$

Thus, the average network latency (ℓ) for the beacon network, would be $\ell = \frac{1}{N}\big(\sum_{i \in N-1} \ell_{L_i + L_{LoRa}}\big)$.

In addition, given a battery capacity $Q_p[mAh]$, E is the average energy consumption, and supply voltage (v), the individual i^{th} AB node's life-time (N_{l_i}) is expressed as:

$$N_{l_i} = \left(\frac{Q_p \times V}{E_i \times T_{BC}^{+}}\right) \qquad (4)$$

Likewise, the average network node-life time would be $N_l = (\frac{1}{N})\big(\sum_{i=1}^{N} N_{l_i}\big)$, where $E = \Gamma_i \times P_{t_i}$, P_{t_i} is the transmission power, N is the number of end-nodes.

Hence, finding the optimal T_{BC}^{+}, is straight forward given the required expected delivery ratio (D_e), latency (ℓ), and network node-life time (N_l), by averaging Eq. 2, Eq. 3, and Eq. 4 for N AB nodes, respectively. This approach is demonstrated in the evaluation section.

V. Evaluation

In order to evaluate the proposed protocol for large scale scenario, a realistic simulation environment is setup. To investigate our protocol suitability for animal monitoring applications, we compare our approach with conventional opportunistic protocols, such as Epidemic, and ProPHET in-terms of network life-time (energy) and packet delivery ratio as described in our previous work [4].

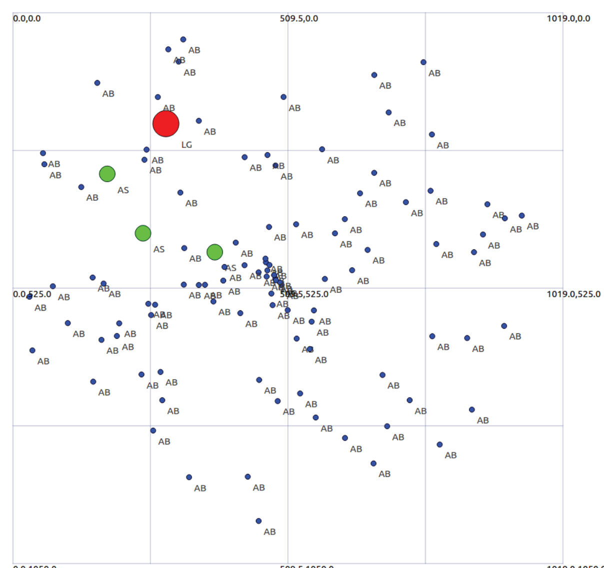

Fig. 5: Simulation Setup With Dual Interface NS3 Simulation Environment. Color labels; BLUE=AB, GREEN=AS, RED=LG nodes

A. Simulation Set-up

We evaluate the performance of the protocol in the NS3 simulation environment [15]. Figure 5 shows the simulation setup for NS3 deployments with 70 AB and 3 AS nodes moving in a defined trajectory in a grid area of 1000mx1000m, with one LoRaWAN gateway to receive data from the AS node. However, we also setup the simulation with a range of parameters as summarized in Table II.

AB nodes generate beacons with 31 bytes (i.e. max BLE payload). We configured N number of AB and N_{AS} of AS devices in NS3 simulator. To investigate the effect of T^+_{BC}, T^+_{sc}, and T^+_{sW} on the network performance metrics, we run several simulations, where AB nodes transmit beacon at varying T^+_{BC} and AS nodes perform scanning with particular T^+_{sc}, and T^+_{sW} settings.

For each T^+_{BC}, we use the values in steps of 100ms in range [100∼600] ms. To make sure that AS and AB timing overlap, we follow the BLE timing guide line, i.e. for T^+_{sc} values of setting 700ms, 800ms, 1000ms and T^+_{sW} values of setting $T^+_{sW} \gg T^+_{BC} + 10$, 600ms, 700ms. While, this setting is not optimal for power, it is useful to test the beacon packet collision and delivery.

TABLE II: Simulation Input Parameters

Mobility Model (M_1)	M^1_o: ZebarNet
Freq.	2.4GHz (BLE), 868MHz (LoRa)
Duty-cycle	1% (LoRa)
Coding Rate	4/5 (LoRa)
Bandwidth	125KHz (LoRa)
Spreading Factor (SF)	7-12 (LoRa)
Bandwidth	125KHz (LoRa)
Data Rate (DR)	BLE (1Mbps)
P_t	4dBm (BLE, LoRa)
AB Node Density (N)	N^0: 15, N^1: 50, N^2: 100, N^3: 150, N^4: 200, N^5: 250, N^6: 300, N^7: 350, N^8: 400
AS Node Density (N_{AS})	N^0_{AS}:1, N^1_{AS}: 3
Simulation Area (S_A)	500mx500m
Packet (PL)	31 bytes (Max for ADV)
T^+_{BC}	[100∼600]ms in 100ms steps
T^+_{sc}	700ms, 800ms, 1000ms
T^+_{sW}	600ms, 700ms
Simulation duration (hr)	15

We recorded the packet generation time at AB nodes, as well as the time when they are received at the LoRaWAN gateway. The simulation measurement is performed for a total of 15hr simulation time. In our simulation animals are assumed to be mobile, hence, we introduce a mobility model (M_1) for group (herd) of animal movement from the ZebarNet project, generated from real GPS data [7]. For Epidemic and ProPHET protocols the replication data is set to TTL=10s. Other parameters are set according to values in Table II.

B. Performance Metrics

Three metrics are used to evaluate the proposed network as outlined in Section IV:

- Average Delivery Ratio (D_e) is a measure of the ratio of number of beacon packets successfully received by a loRaWAN gateway (LG) to number of AB beacons sent. In NS3, we count the number of LoRa packets received at the LG node and the total number of AB beacons sent.
- End-to-End Latency (ℓ), since beacon network is one-hop communication a unidirectional average latency of a beacon defines the ratio of the time when the beacon is transmitted to the time when it is received at LG. Hence, the ℓ will be highly influenced by the Time-On-Air (ToA) of a LoRaWAN packets and 1% duty-cycle limitation imposed. NS3 records the time when a packet is received at the LG node and the time when it is sent to determine the ℓ.
- Network life-time (N_l), is a function of average energy consumption of all nodes, as defined in Equation 4.

C. Result and Discussion

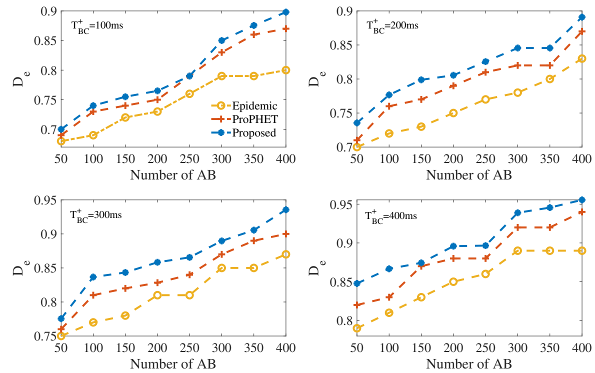

Fig. 6: Comparison of average delivery ratio (D_e) for proposed, Epidemic, and ProPHET opportunistic protocols in ZebarNet mobility scenario: with $T^+_{sc} = 700ms$, and $T^+_{sW} = 600ms$ for variable number of AB nodes.

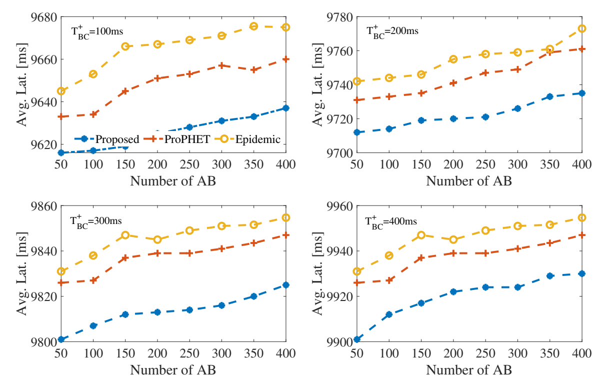

Fig. 7: Comparison of average latency (ℓ) for proposed, Epidemic, and ProPHET opportunistic protocol in ZebarNet mobility scenario: $T^+_{sc} = 700ms$, and $T^+_{sW} = 600ms$ for variable number of AB nodes.

Figure 6 shows that our approach performs better than Epidemic and ProPHET network in terms of average data delivery ratio (D_e). The main reason for this is that Epidemic and ProPHET have a multiple copy data delivery approach compared to our single copy approach. This will create a high collision at the receiver nodes. Hence, they have lower probability of data delivery than our proposed protocol. Moreover, Epidemic and ProPHET are often demand higher network resources such as buffer and battery, which are very scarce in the wildlife monitoring applications, this result in higher latency and high energy consumption (Fig. 7). As shown in Figure 8, the network life-time is very short for Epidemic, due to the same reason that it increases the communication overhead than the our simplified protocol [4].

Figure 8 shows the average network life time assuming all AB nodes in the beacon network are configured with same T^+_{BC} settings. The network life-time is independent of

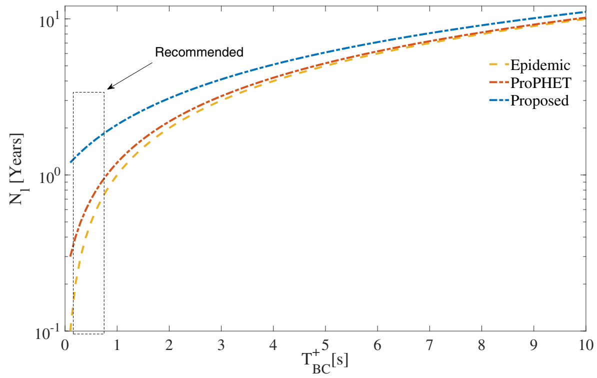

Fig. 8: Comparison of network life-time (N_l) for proposed, Epidemic, and ProPHET opportunistic networks with ZebarNet mobility scenario for $V = 1.225v$, $Q_p = 1150mAh$.

the number of AB nodes in the network, however, it highly depends on the value of advertising interval set (T^+_{BC}). For example, longer T^+_{BC} interval has slower advertising rate with a lower power consumption. Consequently, has a lower delivery ratio for short discovery time by AS nodes. One of important issue to realize is the trade-off between power consumption and latency. Generally, the less frequent advertisements, the longer the beacon network runs (Figure 8). For example, if the total number of AB nodes in the network is N=200, therefore, in order to ensure a network life-time of $N_l \geq 1$ years, average delivery ratio $D_e \geq 80\%$ and average discovery latency of $\ell \leq 9800ms$, thus, the common optimal T^+_{BC} for our proposed protocol would be in the range of $T^+_{BC} =\approx [200, 300]ms$ (as per Figure 6, 7 and 8). Hence, the optimal value of T^+_{BC} should be chosen depending on N and the required beacon network performance measures, to optimally reduce collision in beacon network.

VI. Conclusion

In this paper, we presented a simple asynchronous dual interface network architecture for animal monitoring. The key advantage of this architecture is that nodes achieve wider control on the trade-off between total energy consumption and latency. The evaluation results show that the proposed architecture outperforms the traditional opportunistic networks. On average, our protocol improved the data delivery radio and latency incured by up-to 60% and 75% respectively. In addition, the architecture improved the network life time by up-to 50% especially for the faster packet traffic rates in the network. Therefore, our protocol is more optimal to deploy than utilizing only conventional opportunistic network. Moreover, in the future, we plan to implement this architecture in the real world sensor devices, by building a prototype with dual radios.

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