

Energy Conservation in Animal Tracking

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Abstract—Wireless animal tracking represents the process of using battery operated wireless collars or tags to monitor and track animals in the wild. Given that it is particularly difficult to tag some species, communication protocols must be designed to be energy efficient, while still ensuring a high packet delivery ratio and low delay. In this paper, we present an energy efficient cross-layer protocol for an animal tracking application. The proposed protocol, MAC-LEAP, is a MIMO based energy adaptive protocol that reduces the energy consumption of the nodes by dynamically selecting their number of antennas for communication. We evaluate this protocol in an elephant tracking application in three different scenarios; when the nodes have limited energy, when the nodes have unlimited energy; and when the tags can be recharged via energy harvesting. Our results show that MAC-LEAP outperforms traditional protocols in terms of packet delivery ratio, and average packet delay and energy consumption.

I. INTRODUCTION

Animal tracking is a popular wireless networking research area that enables the monitoring and tracking of the behavior and some characteristics of the animals such as heart rate [1], location [2], body temperature [3], or activity [4]. This information is useful for scientific and conservation purposes. Among these characteristics, tracking the locations of the animals may provide safety for both humans and the animals.

In traditional animal tracking systems, the animals are tagged with a collar with a basic Very High Frequency (VHF) transmitter [5], while the researchers drive through an area carrying a receiver antenna in order to find the animals. As soon as an animal is found, they measure the required characteristics and store the information in a database. It is obvious that these systems cannot monitor the animal behavior in real time, and depend on the weather conditions since during snowy and rainy days, it may be harder for the humans to frequently come outside to capture and record the information. Moreover, it is very hard to track some species such as wild animals or the ones that avoid human contact. Wireless networks along with the Global Positioning System (GPS) and satellite tracking represent a viable solution to this problem.

To find the animal location, a wireless device is attached to the animal. The required information such as the location is acquired with the GPS, and can be transmitted either through satellite communication [6]–[8] or locally to a base station for further processing [2]. The satellite-based tracking systems are very expensive since they require the periodic transmission of data from the satellite transmitters mounted on the animals to the satellite database in order to collect regular updates [9]. Moreover, most of these applications use non-rechargeable

batteries that not only provide limited energy for the device but also require battery replacement once in a while.

In order to prevent the battery replacement issues and satellite expenses, other applications combine GPS and multi hop routing protocols for data delivery with solar power to recharge the batteries of the tracking collars. In [2] the authors proposed the ZebraNet system, which is designed for tracking zebras. Each zebra has a collar that is embedded with GPS to find the zebra location. The gathered data is transmitted by a peer-to-peer routing protocol to the base station (mounted in a car or a plane) on a daily/weekly basis. The authors in [9] and [10] proposed animal tracking applications for tracking turtles and reindeers. In [11], the authors proposed JumboNet, an elephant tracking application that is able to monitor and track wild elephants in real-time. All of the aforementioned applications use GPS for finding the animals' locations, and their devices are equipped with solar panels or kinetic energy harvesters for recharging the batteries [9], [11].

In many of the animal tracking applications, critical parameters such as energy efficiency and delay should be taken into account. In terms of delay constrained networks, the data should be transmitted in a real-time manner, and thus the routing algorithm should be efficient in order to deliver the data to the base station as soon as possible. The energy efficiency of the network is also very important. Although the aforementioned animal tracking applications use solar or kinetic energy harvesters to recharge the batteries, they still may have problems providing the energy when the animal is mostly in the shade or dark places or when the animal doesn't move.

Due to this shortcoming, in this paper we propose an energy efficient protocol for animal tracking applications. Multi-Antenna, Cross Layer, Energy Adaptive Protocol (MAC-LEAP) [12] is an energy efficient protocol for MIMO wireless networks that reduces the energy consumption of the wireless nodes by dynamically selecting their number of antennas for communication. Moreover, in order to reduce the latency for delivering the data to the base station as much as possible, a delay tolerant routing protocol is employed along with MAC-LEAP for speeding the data delivery process. We test the proposed protocol in the JumboNet application, and compare the performance of MAC-LEAP with the traditional JumboNet implementation under different settings.

The rest of the paper is organized as follows. Section II describes the MAC-LEAP protocol, its energy consumption model, and the employed delay tolerant routing protocol.

The proposed protocol is evaluated through simulations in Section III for various numbers of sinks and packet sizes. Finally the paper is concluded in Section IV.

II. MAC-LEAP: MULTI-ANTENNA, CROSS LAYER, ENERGY ADAPTIVE PROTOCOL

Multi-Antenna, Cross Layer, Energy Adaptive Protocol (MAC-LEAP) [12] is an energy efficient cross layer protocol designed for MIMO-based wireless networks that employs dynamic antenna selection to use the most energy efficient approach for data transmission. MAC-LEAP dynamically adjusts the number of transmitter and receiver antennas to use for the communication on a per-packet basis, based on the current remaining energy of the nodes, their distance, bit-error-rate (BER) requirements, and other physical layer parameters. Based on a standard CSMA/CA protocol, MAC-LEAP utilizes request-to-send (RTS) and clear-to-send (CTS) packets to provide collision avoidance. Information regarding the transmitter location and current energy, which is required for the dynamic antenna selection, is included in the RTS packet. The fields of the RTS and CTS packets in MAC-LEAP are shown in Fig. 1. Using this information, MAC-LEAP runs a dynamic antenna selection algorithm at the receiver to find the most energy efficient MIMO scheme that provides the highest link lifetime. The receiver piggybacks this information onto the CTS packet so that both nodes know what MIMO scheme to use for the subsequent data transmission.

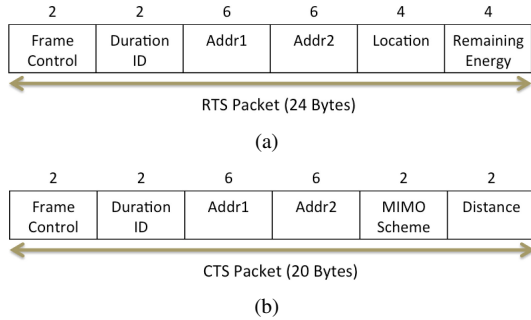


Figure 1. The fields and the size (in bytes) of (a) the RTS packet, and (b) the CTS packet in the MAC-LEAP protocol.

A. Energy Consumption Model

MAC-LEAP adopts the energy consumption model presented in [13]. Consider a single hop communication link with a transmitter node tx and a receiver node rx . Nodes are assumed to be within communication range for the time it takes to successfully transmit a packet, and time is slotted such that every time slot includes the fixed transmission time of a packet and the subsequent retransmissions due to unsuccessful delivery. The nodes are powered through a battery and, at a generic time slot t , the remaining energy of the transmitter and the receiver nodes are defined as B_{tx}^t and B_{rx}^t , respectively. The nodes are equipped with $M = 2$ antennas and have the possibility to operate using $M_{tx} \times M_{rx}$ MIMO, with $M_{tx}, M_{rx} \in \{1, 2\}$, depending on the number of antennas

selected at the transmitter and the receiver (i.e., 2×2 MIMO, 2×1 MISO, 1×2 SIMO and 1×1 SISO).

Moreover, we consider a Rayleigh fading channel, and we design our system based on the IEEE 802.11 protocol with a fixed data rate and BPSK modulation. By sending or receiving a packet, the node energy will be reduced depending on the energy consumed by that packet. In this perspective, the node number of antennas, the communication distance, the channel BER, the data rate, and the node current operation state (e.g., Idle, Reception, Transmission, or Sleep) are the most important factors that determine the energy consumption. In what follows, we describe the energy consumption model used in the physical layer of MAC-LEAP.

As mentioned previously, the nodes are battery powered with initial energy levels B_{tx}^0 and B_{rx}^0 at the transmitter and the receiver, respectively. By sending or receiving a packet at time t , the residual energy stored in the devices (i.e., B_{tx}^t and B_{rx}^t) decreases over time according to the energy consumption of the selected antenna mode. The receiver energy is consumed only using the receiver circuit block (P_C^{rx}) while at the transmitter side, it is consumed by both the transmitter circuit (P_C^{tx}) and the Power Amplifier (P_{PA}). We consider the circuit blocks of the receiver and the transmitter as discussed in [13].

At the receiver side, the total power consumption $P_{rx}(M_{rx})$ is equal to the circuit power consumption $P_C^{rx}(M_{rx})$, which is given by

$$P_C^{rx}(M_{rx}) = M_{rx}(P_{ADC} + P_{Mix} + P_{Fil}^{rx} + P_{Dem} + P_{IFA} + P_{LNA}) + P_{Syn}, \quad (1)$$

where P_{ADC} represents the power consumption of the Analog-to-Digital converter (ADC), P_{Mix} is the power consumption of the mixer, P_{Fil}^{rx} is the power consumption of the receiver filter circuit, P_{Dem} is the power consumption of the demodulator, P_{IFA} is the power consumption of the Intermediate Frequency Amplifier (IFA), P_{LNA} is the power consumption of the Low Noise Amplifier (LNA) and P_{Syn} is the power consumption of the frequency synthesizer. The power consumption at the transmitter side $P_{tx}(M_{tx}, M_{rx})$, instead, is given by

$$P_{tx}(M_{tx}, M_{rx}) = P_{PA}(M_{tx}, M_{rx}) + P_C^{tx}(M_{tx}), \quad (2)$$

where P_{PA} and P_C^{tx} are defined below. The power consumption of the transmitter circuit P_C^{tx} is expressed as

$$P_C^{tx}(M_{tx}) = M_{tx}(P_{DAC} + P_{Mix} + P_{Fil}^{tx} + P_{Mod}) + P_{Syn}, \quad (3)$$

where P_{DAC} is the power consumption of the Digital-to-Analog Converter (DAC), P_{Mod} is the power consumption of the modulator and P_{Fil}^{tx} represents the power consumption of the transmitter filter circuit. The power consumption of the power amplifier $P_{PA}(M_{tx}, M_{rx})$ depends on the transmission power P_{out} and the modulation scheme [14], and is expressed as

$$P_{PA}(M_{tx}, M_{rx}) = \left(1 + \frac{\xi}{\eta}\right) P_{out}(M_{tx}, M_{rx}), \quad (4)$$

where η is the drain efficiency of the power amplifier, while $\xi = 3 \frac{K-2\sqrt{K}+1}{K-1}$ represents the Peak-to-Average Ratio (PAR)

that depends on the constellation size K . We note that for the results presented in this paper, ξ is a constant value since we only consider a BPSK modulation scheme (i.e., $K = 2$). Moreover, the transmission power P_{out} can be calculated using the following formula [15]:

$$P_{\text{out}}(M_{tx}, M_{rx}) = \bar{E}_b(M_{tx}, M_{rx}) R_b \left(\frac{4\pi d}{\lambda} \right)^k \frac{M_l N_f}{G_{tx} G_{rx}}, \quad (5)$$

where R_b is the system bit rate, G_{tx} and G_{rx} are the transmitter and the receiver antenna gains, d is the transmission distance, λ is the carrier wavelength and k is the path loss exponent. Moreover, N_f is the receiver noise figure, which depends on the thermal noise Power Spectral Density (PSD) N_0 and on the PSD of the total effective noise at the receiver. M_l is the link margin, which shows the difference between the receiver sensitivity and the actual received power. $\bar{E}_b$ is the average energy per bit required to achieve a given BER p_b , in a BPSK $M_{tx} \times M_{rx}$ MIMO system. We obtain the BER of the channel as [16]:

$$p_b = \left(\frac{1}{2}(1 - \zeta) \right)^L \cdot \sum_{l=0}^{L-1} \binom{L-1+l}{l} \left(\frac{1}{2}(1 + \zeta) \right)^l, \quad (6)$$

where $L = M_{tx} M_{rx}$ and $\zeta = \sqrt{\frac{\rho/M_{tx}}{1+\rho/M_{tx}}}$.

Moreover, with the special case of 1×1 SISO communication with no diversity, we obtain the BER of a Rayleigh fading channel as

$$p_b = \frac{1}{2} \left(1 - \sqrt{\frac{\rho}{1+\rho}} \right). \quad (7)$$

Given the above, we can now define the total energy required at the transmitter or the receiver to send or receive a packet of size N bits as

$$E_{\text{pkt}}^X(M_{tx}, M_{rx}) = \frac{P_X(M_{tx}, M_{rx})}{R_b} N, \quad (8)$$

where $X \in \{tx, rx\}$. Given the per packet energy consumptions $E_{\text{pkt}}^{tx}(M_{tx}, M_{rx})$ and $E_{\text{pkt}}^{rx}(M_{tx}, M_{rx})$ and time slot t , the number of successful packets that can be processed by the nodes using a $M_{tx} \times M_{rx}$ MIMO scheme is

$$L_X^t(M_{tx}, M_{rx}) = \frac{B_X^t}{E_{\text{pkt}}^X(M_{tx}, M_{rx}) \frac{1}{1-p_{\text{pkt}}}}, \quad (9)$$

where $X \in \{tx, rx\}$ and $p_{\text{pkt}} = 1 - (1 - p_b)^N$ represents the packet error rate and accounts for packet retransmissions. Thus, the expected total number of packets that can be successfully received is given by

$$L^t(M_{tx}, M_{rx}) = \min\{L_{tx}^t(M_{tx}, M_{rx}), L_{rx}^t(M_{tx}, M_{rx})\}. \quad (10)$$

where $L_{rx}^t(M_{tx}, M_{rx})$ is the number of packets processed by the receiver and $L_{tx}^t(M_{tx}, M_{rx})$ is the number of packets processed by the transmitter. The total number of successfully received packets in the system is the minimum of the two values. Moreover, the receiver is responsible for calculating the number of packets based on the antenna selection policy for the communication and sending the selected MIMO scheme to the transmitter.

B. Online Policy: Dynamic Antenna Selection Algorithm

In a wireless network, the total remaining energy and, consequently, the total lifetime of the system, depends on the lifetimes of both the transmitter and the receiver. For instance, if the transmitter has enough energy but the receiver does not, or vice versa, by choosing a fixed communication scheme, the bottleneck node will eventually be depleted. The main goal of MAC-LEAP is to extend the lifetime of the system by varying the MIMO scheme over time.

As the name suggests, the *Online Policy* works online and chooses the best MIMO scheme to be used for the communication, at each transmission slot. In the *Online Policy*, for a specific p_b and at a fixed transmitter-receiver distance, we compute the number of received packets in the system for all four antenna modes, and we select different schemes interchangeably. In particular, at each time slot t , depending on the remaining energy at the transmitter and the receiver, we choose the scheme $M_{tx}^t \times M_{rx}^t$ that results in having the highest number of received packets for the system, according to Eq. (10). The remaining energy of the system at each time slot is then updated by removing from the energy buffer the energy consumption of the communication scheme chosen in the previous time slot and adding the harvested energy in the time slot (i.e., $B_{tx}^{t+1} = B_{tx}^t - E_{\text{pkt}}^{tx}(M_{tx}^t, M_{rx}^t) + H_{tx}^t$ and $B_{rx}^{t+1} = B_{rx}^t - E_{\text{pkt}}^{rx}(M_{tx}^t, M_{rx}^t) + H_{rx}^t$).

The aforementioned process for dynamic antenna selection in the online policy is applied only for the data packets. The number of antennas employed for transferring the RTS, CTS, and ACK packets is fixed for all distances and BER values among the nodes.

C. MAC-LEAP in JumboNet

In this section, we describe the implementation of the MAC-LEAP protocol in the JumboNet application [11]. JumboNet is an elephant tracking application in which the real-time locations of the elephants are monitored in order to prevent danger to both elephants and humans and improve their co-existence. Each elephant has a single antenna wireless collar that measures the location of the elephant using GPS. In order to prolong the device lifetime, each collar is also equipped with an energy harvester to provide the required energy for communication. Since the amount of harvested energy may be limited depending on the environment, energy efficient communication protocols can be helpful to reduce the energy consumption. MAC-LEAP is a protocol that provides energy balance among the nodes in a MIMO-based network and improves the network energy efficiency.

We assumed that every node in the network is equipped with two antennas and it can either use one or both antennas for communications. The communication pattern between each pair of nodes, depending on the number of antennas they are using, is MIMO, SIMO, MISO, or SISO.

We assume that all the control packets including the RTS and CTS packets are transferred using SISO scheme in MAC-LEAP. After the RTS/CTS handshake between two nodes, the nodes transfer the data using the selected MIMO scheme.

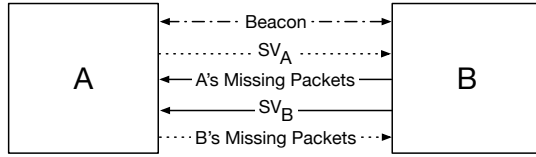


Figure 2. Packet transmission between two nodes in epidemic routing.

Moreover, since JumboNet is a real-time animal tracking application, the data should reach the destination (sink) in a certain amount of time. Thus, we assume that the number of sinks can be more than one and all of the sinks are connected with the others. In case of having multiple sinks, the nodes can send the data messages to any of the sinks.

Moreover, it is assumed that the original JumboNet (without MAC-LEAP) uses a CSMA/CA protocol and all nodes have a single antenna for transferring all the data and non-data packets.

D. Routing Protocol in MAC-LEAP

In this section we describe the Epidemic routing protocol that MAC-LEAP uses in the JumboNet network. Epidemic routing is a routing protocol that is suitable for networks with limited connectivity among the nodes where there is no direct connection between the source and the destination at the time of data generation. Epidemic routing is a store-and-forward protocol, where all the generated and received data are first stored in a buffer and then disseminated to any other node as soon as it is within transmission range. The protocol relies on mutual packet exchange between mobile nodes, and considers that one of the nodes will eventually reach the destination [17].

The packet transmission between nodes using epidemic routing is shown in Fig. 2. According to this packet exchange mechanism, two nodes first use a “Beacon” message to determine if they are in communication range. When this happens, one of the nodes (A in Fig. 2) starts by sending a summary vector (SV_A) of the messages it has in its buffer to the other node (B in Fig. 2). After receiving this vector, B checks its available messages in the buffer and sends to A both the packets that are missing to A and its summary vector (SV_B), which is used by node A to determine the packets that node B is missing. Finally, A sends the missing packets to B.

In sparse MANETs and DTNs, epidemic routing has been shown to outperform traditional routing protocols, in terms of packet delivery ratio and average packet delay [18].

III. PERFORMANCE EVALUATION

In this section we evaluate the performance of MAC-LEAP in JumboNet with the Epidemic routing and various packet sizes using the ns-3 network simulator. In what follows, we refer to the traditional JumboNet protocol simply as “JumboNet”, and we consider three scenarios: a first one where the nodes have an unlimited energy buffer, a second scenario in which the nodes have a limited amount of energy, and a third case where the nodes can harvest energy from the environment. As explained in [11], our simulation is done

Table I
WiFi RADIO PARAMETERS

Channel Parameters		Circuitry Power Consumption	
Parameter	Value	Parameter	Value
$G_t G_r$	5 dBi	P_{DAC}	7 mW
M_l	10dB	P_{ADC}	7 mW
N_f	10 dB	P_{Mix}	30.3 mW
f_c	5.15 GHz	P_{Syn}	50 mW
R_b	1Mbps	P_{Filt}^{tx}	2.5 mW
k	2	P_{Filt}^{rx}	2.5 mW
Tx range	250 m	P_{LNA}	20 mW
		P_{IFA}	5 mW

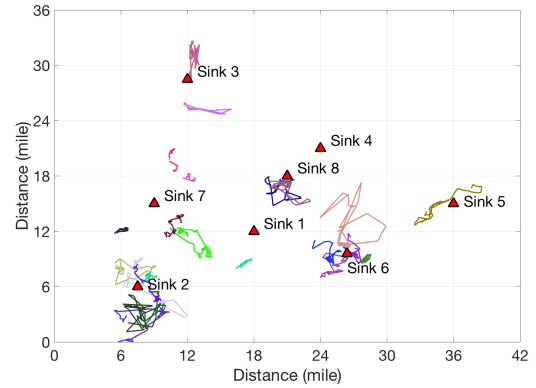


Figure 3. Location of the sinks and the pattern movements of the herd leaders.

based on the movements patterns of the elephants. We assume that each elephant herd has a herd leader that sends the location information every hour. Multiple sinks are located close to the herds to exchange the data from the herd leaders, as shown in Fig. 3. For all the results of this section, we consider a network with 24 elephant leaders, an epidemic routing beacon interval and packet generation rate of 60 minutes, and a total simulation time of 10 days. The WiFi radio parameters are listed in Table I.

A. Unlimited Energy Buffer

In the first experiment, we assume all nodes have unlimited amount of energy in their buffer. In Figure 4(a), we compare packet delivery ratio (PDR) versus different number of sinks for the JumboNet network with MAC-LEAP protocol (referred to as MAC-LEAP in all figures), and the original JumboNet protocol (referred to as JumboNet in all figures). With more sinks around the nodes, more packets can be delivered. Since the amount of energy in the nodes is unlimited, the PDR for MAC-LEAP and JumboNet are almost the same.

Moreover, the amount of delay per packet for various number of sinks has the same behavior for both MAC-LEAP and JumboNet, as shown in Fig. 4(b). We define delay as the time between the generation of the packet and when it is successfully delivered at the destination. Since the nodes' energy is unlimited, as the number of sinks increases, the nodes can reach a sink sooner without running out of energy. Thus, the amount of delay per packet decreases.

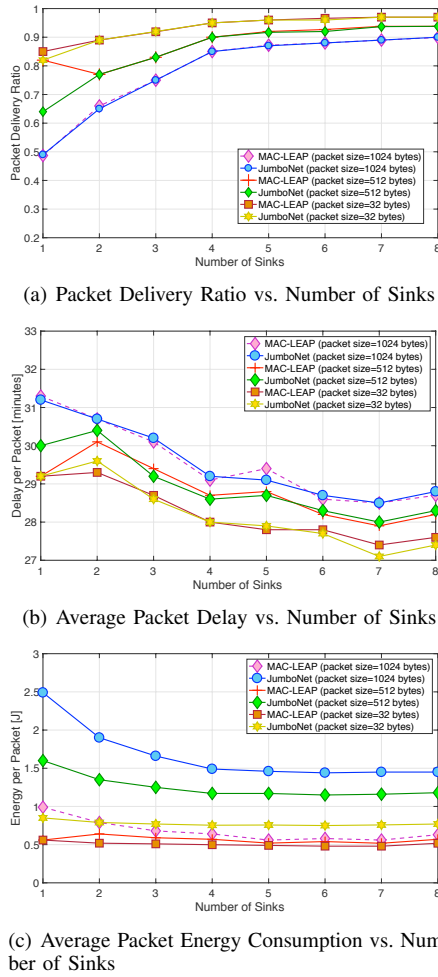


Figure 4. Packet Delivery Ratio (PDR), average delay and energy consumption per packet versus number of sinks with unlimited initial energy.

Since the nodes in the JumboNet network each have a single antenna, the communication between each pair of nodes is SISO and the amount of transmit power is fixed and equal to the power to reach a distance of 250 m. According to Eq. (5), SISO consumes a lot of transmit energy especially for larger distances compared to MIMO, MISO, and SIMO. In MAC-LEAP, however, the Online policy chooses the most energy efficient MIMO scheme for every packet transmission based on certain parameters including the nodes' communication distance and their remaining energy.

Since MAC-LEAP chooses the most energy efficient MIMO communication scheme based on the transmission distance, the amount of energy consumption per packet is much less than JumboNet. Fig. 4(c) shows that the energy consumption per packet in MAC-LEAP is much less than the one in JumboNet. Moreover, the energy consumption per packet is lower with a higher number of sinks because with more sinks around the nodes, each node may have a sink closer to itself. Thus, the distance between a node and one of the sinks is smaller, which results in having lower energy consumption during sending a packet.

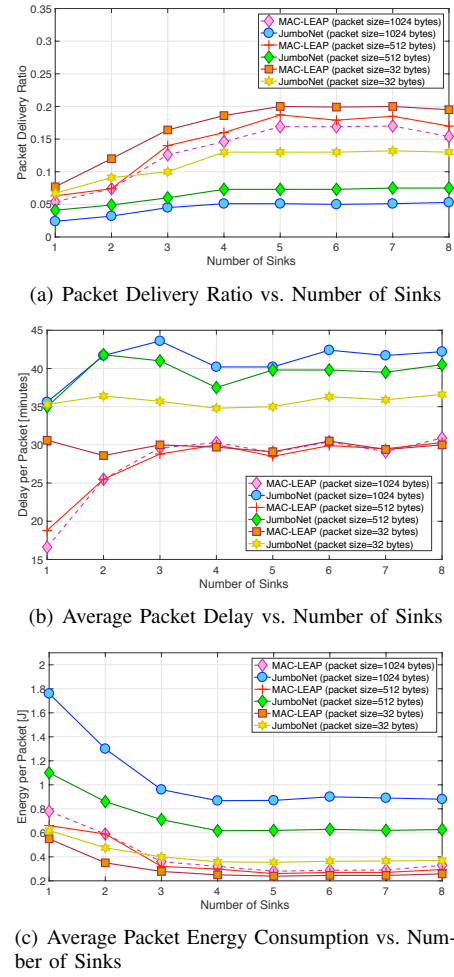


Figure 5. Packet Delivery Ratio (PDR), average delay and energy consumption per packet versus number of sinks with limited initial energy.

B. Limited Energy Buffer

In this scenario, we assume that each node has a limited amount of energy (10 J) and their batteries are non-rechargeable. Fig. 5(a) shows the comparison of PDR versus number of sinks. MAC-LEAP consumes much less energy compared to JumboNet since it adapts the transmit power according to the transmission distance and the remaining energy of the nodes. Thus, the lifetime of the nodes is much longer in MAC-LEAP and more packets are successfully delivered to the sinks. Moreover, with more sinks available in the network, more packets can be delivered.

Fig. 5(b) shows the amount of delay per packet when the number of sinks in the area is changing. For all the different packet sizes, MAC-LEAP requires lower delay per packet compared to the JumboNet protocol.

With a limited amount of energy, MAC-LEAP consumes less energy and thus provides higher lifetime for the nodes compared to JumboNet. As shown in Fig. 4(c), the energy consumption per packet in MAC-LEAP is much less than the one in the JumboNet network. Moreover, as the packet size increases, the amount of energy consumption gets higher.

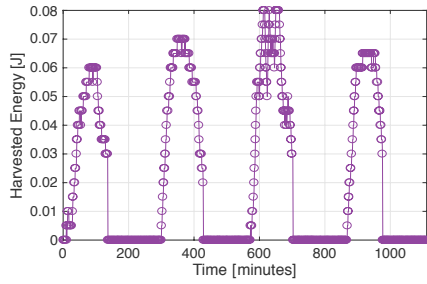


Figure 6. Sampled solar harvested energy every 5 minutes for four days.

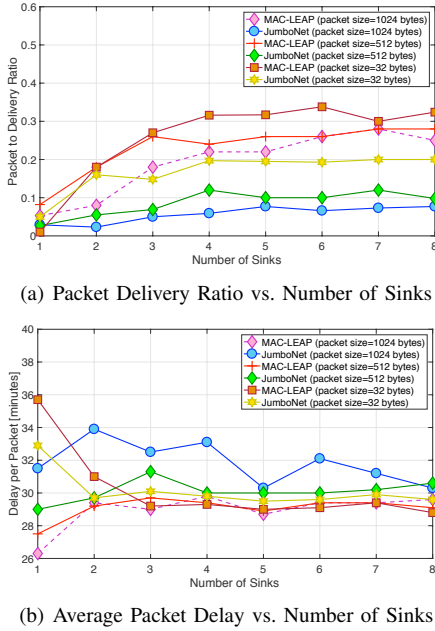


Figure 7. Packet Delivery Ratio (PDR), average delay and energy consumption per packet versus number of sinks with energy harvesting.

C. Limited Energy Buffer with Energy Harvesting

In this section, we assume each node has 2 J of initial energy and is equipped with a solar energy harvester. The harvested energy over time is shown in Fig. 6, where each sample is taken every 5 minutes for a total of four days. Unlike the unlimited energy buffer scenario where we assumed that the nodes always have enough energy in their buffer (Section III-A), the energy coming from the solar harvester is added to the buffer gradually during the day.

As shown in Fig. 7(a), PDR increases as the number of sinks increases with different packet sizes. With larger packet sizes, the PDR is lower. With packet size of 1 Kbytes, MAC-LEAP has a 10% improvement over JumboNet. With packet sizes of 512 and 32 bytes, the improvement is smaller since energy conservation is higher with larger packet sizes. Moreover, PDR of MAC-LEAP is higher than JumboNet since it uses the online policy to select the most energy efficient MIMO scheme for data transmission.

In Fig. 7(b), we plot the average packet delay as the number of sinks increases. Delay per packet in JumboNet is on average

3 minutes higher than MAC-LEAP when the packet size is 1 Kbytes. Moreover, for 512 and 32 bytes packet sizes, the MAC-LEAP delay is 1 minutes less than JumboNet.

IV. CONCLUSIONS

In this paper, we presented MAC-LEAP, a cross-layer energy efficient protocol for animal tracking, and showed its performance in a real elephant tracking application. According to the simulation results, MAC-LEAP outperforms the traditional JumboNet network in terms of packet delivery ratio, transmission delay, and energy consumption for different packet sizes.

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