JumboNet Elephant Tracking Using Delay-Tolerant Routing with Multiple Sinks

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***Abstract*—Wildlife monitoring is vital in areas where humans and animals share the same living area. For instance, in Sri Lanka there are a high number of deaths among elephants and people due to the human-elephant conflict. A possible solution to reduce the number of deaths is to monitor the elephants' locations in real-time, and to promptly intervene when elephants approach human populated areas. Tagging elephants with GPS collars represents a viable solution, but obtaining location information can quickly drain tag batteries. As a result, systems that utilize energy harvesting have been proposed as a promising alternative to ensure very long lifetimes of the tags. As the amount of energy that can be harvested in a given time period is limited, communication protocols must be designed to be energy efficient, while still ensuring a high packet delivery ratio and low delay. In this paper, we analyze the performance of different delay-tolerant network protocols in a real scenario using actual elephant movement data from JumboNet and examine the effects of increasing the number of sinks in the network on the packet delivery ratio, average packet delay, and average energy consumption. We find that epidemic routing outperforms other protocols in terms of packet delivery ratio when using low transmission powers. On the other hand, if enough energy is available and the tracking system can support high transmission powers, direct delivery is superior compared to a multi-hop routing approach.**

I. Introduction

In many parts of Asia, elephants and humans coexist, which causes deaths on both sides. As an example, the Sri Lankan elephant (Elephas maximus maximus) is the largest in size of the three recognized subspecies of the Asian elephant (Elephas maximus). According to the Department of Wild Life in Sri Lanka, the total elephant population in Sri Lanka stood at $5,879$ in 2011 but, since then, an average of more than 200 elephants and more than 70 people have been killed annually as a result of conflicts between elephants and humans [1]. The search for effective measures to deal with Human–Elephant Conflicts (HEC) is one of the most significant challenges for elephant conservation globally.

Real-Time Monitoring (RTM) of positional data using tracking units attached to animals is emerging as an effective tool for ecological monitoring and wildlife conservation. As an example, Wall et al. [2] have performed real-time monitoring of proximity, geofencing, movement rate and immobility detection on 94 elephants to prove the effectiveness of real-time monitoring. Their system is composed of an elephant-mounted collar that uses satellite and GSM networks to transmit GPS and auxiliary sensor data to a cloud based storage where analysis is performed and necessary alerts are generated within 5 minutes (when using the satellite communication or GSM connection is available). In this implementation, the collar is powered by a 130Ah battery and is able to run for about 600 days when acquiring data once every hour. While this represents a viable solution to monitor wild elephants, the large battery used by this study adds substantial weight to the collar ($\sim$ 5Kg), and can be dangerous to the animal due to overheating and potential explosion.

Given the cost and effort of collaring wild animals, solutions that employ energy harvesting for powering the monitoring tag have been proposed to monitor zebras [3] and turtles [4]. More recently, a kinetic energy harvester prototype that uses magnetic levitation and ferro fluid bearings to generate energy from an elephant's movements was presented in [5]. When mounted on a wild elephant, the harvester is able to generate 88.91J of energy per day that, according to commercially available wireless sensor mote specifications, can be sufficient to power the tags to acquire and transmit locations 24 times a day to a remote sink up to a distance of 114 Km (line of sight) [5]. However, in practice, it can be difficult (if not impossible) to reach such a long distance, especially when considering the Asian elephants' natural habitat. While satellite communication can be considered a possible solution [2], the considerable additional cost and energy consumption of such a connection make it impractical for large scale deployments.

Recent studies on wild elephants have shown that, on average, Asian elephants travel 3.2 km per day in herds, while lone males travel 3.6 km per day and up to 8.9 km per day in musth [6]. Typically, elephants visit a water source at least once a day and, depending on the particular natural environment, can come in the vicinity of other elephants at ponds and other locations on several occasions [7]. Hence, the elephants can be represented as a sparse mobile ad hoc network or a delay tolerant network. We note that, in most cases, only the herd leader is tagged since the other members of the herd closely follow their leader.

Given the above, in this paper we discuss and evaluate the performance of different routing techniques that use either a conventional direct connection to the sink, or by interconnecting the tags on the elephants to form a delay-tolerant network, so that the location information generated at each elephant can be propagated to the remote sink via multi-hop communication.

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Figure 1: Elephant monitoring using a JumboNet collar. From [5].

The work presented in this paper is part of the JumboNet project [8], a collaborative effort between the Sri Lanka Institute of Information Technology and the University of Rochester to explore solutions to HEC using wireless communication technologies.

The rest of the paper is organized as follows. In Section II, we discuss routing protocols proposed for delay tolerant networks, and we present the extension needed for the epidemic routing with vaccine protocol to work with multiple sinks. In Section III, we present a performance evaluation of the system in a real life elephant tracking scenario. Finally, conclusions are drawn in Section IV.

II. DTN Routing Protocols

In this section, we provide a brief description of some of the routing protocols proposed for delay tolerant networks, their parameters, and a discussion of how these protocols would operate in the case of a multiple sinks network.

A. Spray and Wait

The authors in [9] proposed the "Spray and Wait" protocol, in which the node spreads message copies in the network until an adequate number of copies are disseminated, at which point the node switches to direct transmission, whereby the node only sends the packet directly to the sink once in range. There are many techniques for spraying message copies in the network; in this paper, we focus on source spraying, in which, each source node starts with L message copies, and forwards them to the first L encountered nodes. In our implementation, the source node sends its packets to all nodes it encounters, then these nodes cannot forward these packets unless they are in transmission range of a sink.

B. Epidemic Routing

Epidemic routing has been proposed as a viable approach for routing data in networks 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,

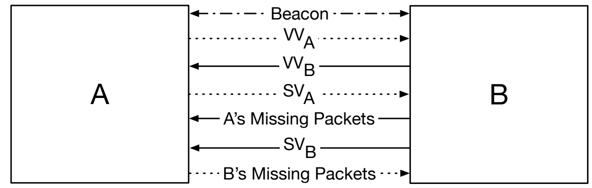


Figure 2: Summary vector exchange with vaccine scheme.

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 [10].

C. Epidemic Routing with Vaccine

In some situations, the traditional epidemic routing protocol can result in buffer overflow and energy waste that results from storing and exchanging messages that have already been delivered to the destination. Hence, many approaches have been proposed to overcome this issue, such as limiting the time the messages are forwarded [11], limiting the hop count [11], optimizing beaconing rate [12], [13], using explicit notification via vaccine [14], and immunity [15].

The different elements required for the epidemic routing operation are described in detail in [16]. In what follows, we provide a brief overview of each component for completeness, in addition to a description of all the parameters that we can control.

1) Beacon Mechanism: The epidemic routing ns-3 implementation uses an automatic beaconing mechanism, where each node automatically broadcasts a control packet that contains information about the sender. This beacon packet is used to notify nearby nodes of the presence of a node so that the summary vector exchange with vaccine can be performed, as described in Section II-C2.

2) Summary Vector Exchange with Vaccine: The summary vector exchange with vaccine mechanism represents the core of the epidemic routing protocol, and its main objective is to avoid the transmission of packets that are already delivered to the sink or are present in the other node.

According to this mechanism, when two nodes meet, they exchange their vaccine vectors and data vectors as shown in Figure 2, where $VV_{A,B}$, $SV_{A,B}$ represents a vaccine vector and a summary vector, respectively. At the end of this five-way handshake, both nodes have the same set of packets, unless they moved out of connectivity range before the process could be completed.

3) Epidemic Buffer: Each node is equipped with a buffer to store its own data, in addition to accepted data from other nodes. Two parameters can be tuned to control the buffer size, `QueueLength`, which determines the maximum size of this queue, and `QueueEntryExpireTime`, which determines the maximum time a packet can live in the epidemic queue since it was generated at the source.

4) Vaccine Buffer: An extra buffer is needed when implementing the vaccine with epidemic routing. This buffer is required to store the IDs of the packets already received by any sink. Vaccine buffer size can be tuned using `VaccineQueueLength` that determines the maximum size of this queue, and `VaccineEntryExpireTime` that determines the maximum time a vaccine can live in the vaccine queue since generated at the destination.

5) Hop Count: The `HopCount` field determines the maximum number of exchanges each packet encounters beyond the source before it is dropped, and it was introduced to work as a time to live (TTL) field in IP packets, to limit the number of packet exchanges in the network [10].

6) Host Recent Period: `HostRecentPeriod` contains the time in seconds in which hosts cannot re-exchange summary vectors. This value can be tuned based on the probability of acquiring new messages in a certain period of time.

D. Multi-Sink Extension

In real time monitoring, tracking data must reach the destination within a specific delay bound; this can either be done by increasing the nodes' transmission power or by adding more sinks to increase the probability of a node being in the vicinity of one of the sinks. For direct delivery, spray and wait, and epidemic routing without vaccine, the extension of these protocols to the case of multiple sinks is straightforward. The nodes simply deliver the packets to any of the sinks.

On the other hand, in order to support the delivery of the packets to multiple sinks, our epidemic routing with vaccine extension allows us to directly specify the list of sinks as a protocol parameter. This list is used by the protocol to establish separate point to point connections between the sinks so that, as soon as one of the sinks receives a data packet from one of the nodes, the corresponding vaccine entry can be added to the vaccine buffer of all the other sinks. This extension allows for a further reduction of the traffic generated by the network by avoiding the delivery of the same packet to different sinks, as well as by spreading the vaccine of a packet through multiple generation points (i.e., each sink).

III. Performance Evaluation

In this section, we study the performance of different delay-tolerant routing protocols in single and multiple sinks networks by simulating the scenario where the nodes move according to the wild elephants' movement data provided by the Centre for Conservation and Research, Sri Lanka [17], and shown in Figure 3, and compare it to two direct delivery approaches: one in which the nodes can only buffer 1 packet and the second one in which the nodes can buffer the data until they are delivered. In our implementation, the transmission power is varied from 0 dBm to 14 dBm, which translates to a transmission range from 6 Km to 30 Km, respectively, based on the free space propagation model [18].

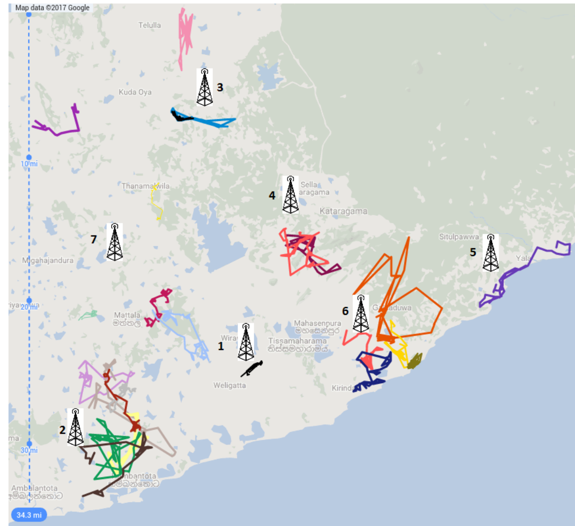


Figure 3: Wild elephants' movements recorded in Sri Lanka for 24 tagged elephants and the locations of the sinks. Each line represents the movement of a herd of elephants over the course of 10 days.

We provide analysis on the achievable packet delivery ratio, average delay and the energy consumption per received packet. In order to evaluate the performance of the protocols, we consider two applications: movement patterns analysis and real time tracking.

A. Movement Patterns Analysis

When studying animals' grazing habits and movement patterns, obtaining as much information about all the elephants' locations as possible will provide better analysis and helps in developing future mobility models. For this scenario, packet delivery ratio is the most important metric.

In our implementation, we simulate the scenario in which each herd leader generates its location information once every hour for a total of 24 times per day, which is feasible using the energy harvested from the elephant movement as described in [5]. We set the interval between beacons to be 60 minutes, which is the same as the location generation rate, and we set the time in which the elephants do not re-exchange the summary vectors also to 60 minutes to limit the energy consumption. Moreover, based on the information in [5], we set the size of the position updates to be 32 bytes. We assume the nodes have limited buffer size and can only store half the maximum number of packets in the network.

Figure 4 shows the packet delivery ratio (PDR), delay, and energy consumption per received packet as a function of the transmission power for a single sink network with nodes with limited buffer size. As shown in Figure 4(a), increasing the transmission power allows the nodes to connect to additional nodes, which increases the packet delivery ratio. In the case of the epidemic routing with vaccine protocol, a 100% PDR can be achieved using 4 dBm transmit power compared to about 10 dBm needed in the spray and wait

Table I: Movement pattern analysis parameters

Parameter	Value
Number of elephants	24
Area	60 Km * 60 Km
Number of packets per node over simulation time	24 packets
Packet size	32 Bytes
Hop Count	6
Maximum epidemic buffer occupancy	288 packets
Maximum vaccine buffer occupancy	576 IDs
Maximum Tx Current	23.5 mA
Rx Current	5.5 mA
Idle Current	0.12 μA
Rx Sensitivity	-107 dBm
Interval between sending packets	60 minutes
Beacon Interval	60 minutes
Host Recent Period	60 minutes
Queue Entry Expire Time	10 days
Vaccine Queue Entry Expire Time	10 days
Simulation time	10 days

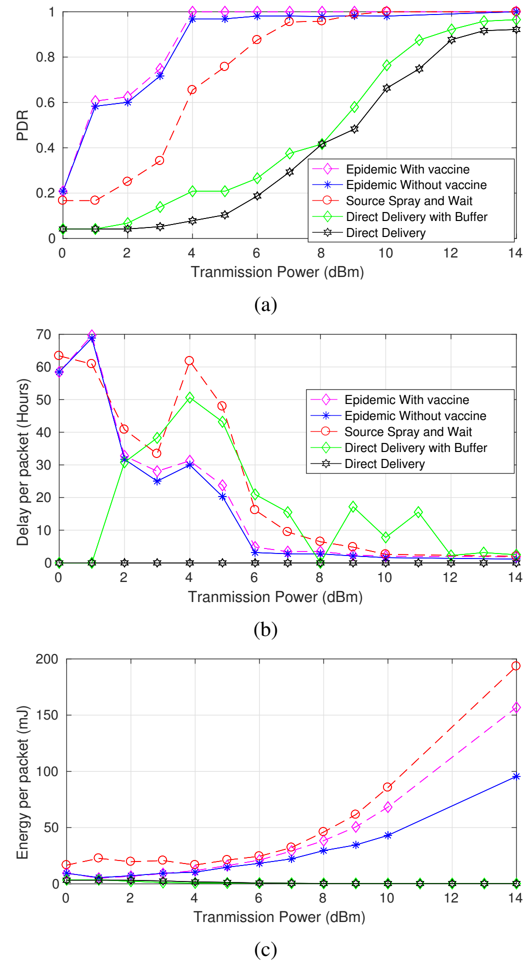


Figure 4: PDR, delay and energy consumption per received packet for the movement patterns analysis in a single sink architecture.

protocol. Even with the maximum transmission power of 14 dBm, direct delivery with/without buffer achieves only about 95% PDR. It is clear that having a buffer increases the PDR for direct delivery. While increasing the transmission power results in a higher PDR and a lower delay, it increases the energy consumption of the nodes and hence requires more harvested energy to operate. Depending on the energy and delay constraints, different transmission powers can be used.

The average delay per received packet for the movement patterns analysis is shown in Figure 4(b). For epidemic routing with/without vaccine and the spray and wait protocols, the average delay per received packet rises when using 4 dBm compared to 3 dBm as a higher number of packets are received that could not be received with a lower transmission power, although these additional packets are received with a high delay that increases the average delay. Due to the elephants' movement patterns, the delay of the direct delivery with buffer varies with the transmit power. For instance, for a transmit power of 8 dBm, all the packets are received instantly while for 9 dBm, more packets are received with a high delay, which increases the average delay. A direct delivery without buffer approach has the lowest delay and energy consumption per received packet; however, this corresponds to a low packet delivery ratio as shown in Figure 4(a).

In order to limit the energy consumption of the nodes, installing more sinks enables nodes to decrease their transmission power while still achieving a high PDR. Since the sinks' locations are a crucial parameter to the protocols' performance and to maximize the benefit of multiple sinks, their positions and order were determined after extensive simulations, and are shown in Figure 3.

Figure 5 shows the effect of increasing the number of sinks on the PDR, delay and energy consumption per received packet when the nodes use 4 dBm as their transmission power. At this transmission power, only one sink is needed to achieve a 100% PDR for the epidemic routing with vaccine protocol, 4 sinks for the spray and wait protocol and 7 sinks for the two direct delivery approaches. Having a buffer results in a higher PDR in direct delivery, as shown in Figure 5(a).

Figure 5(b) shows that increasing the number of sinks decreases the average delay per received packet from more than 30 hours when using 1 sink to about 45 minutes when using 7 sinks. From Figure 5(c), it is clear that for a multi-sink architecture, the epidemic routing with vaccine protocol has the lowest energy consumption per received packet compared to the epidemic routing without vaccine and the spray and wait protocol, as the vaccine disseminates more efficiently through the network.

Figure 6 shows the transmission power required to achieve at least a 90% PDR and the corresponding delay and energy consumption per received packet for both single sink and multiple sinks architectures. We see from Figure 6(a) that the epidemic routing with/without vaccine protocols require the least transmission power of 4 dBm for one sink and 0 dBm when 7 sinks are installed. Figures 6(b) and 6(c) show the trade-offs between the average delay and the energy consumption per received packet. For instance, for a 2 sinks

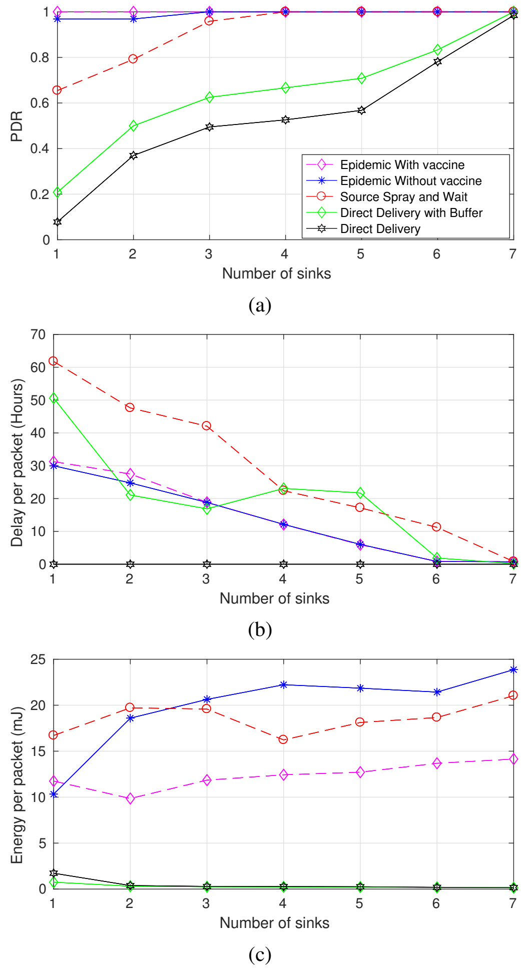


Figure 5: Effect of number of sinks on PDR, average delay and energy consumption per received packet at 4 dBm transmit power for the movement pattern analysis.

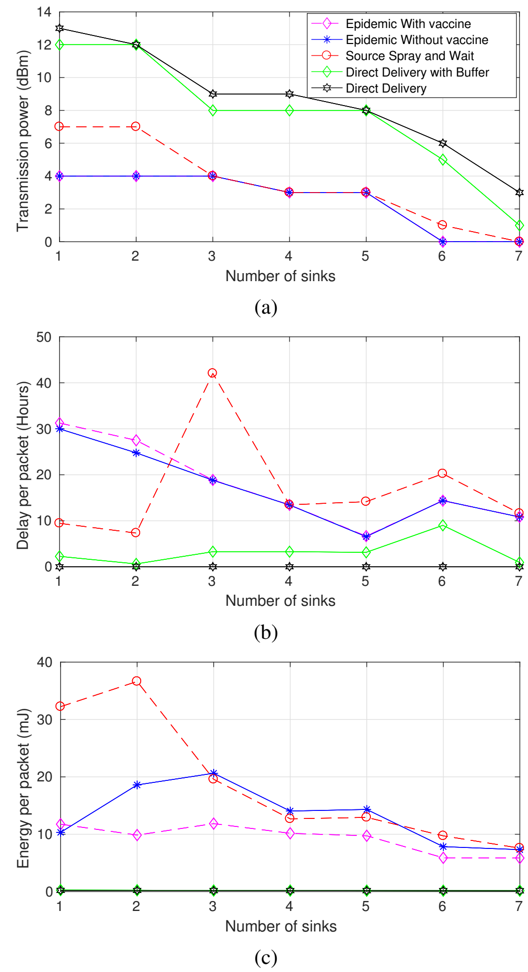


Figure 6: Required transmission power, the corresponding average delay and energy consumption per received packet to achieve 90% PDR for the movement pattern analysis in a single sink architecture.

architecture, the source spray and wait protocol has a lower delay compared to the epidemic routing with/without vaccine protocols at the expense of requiring a higher transmission power that results in an increase in the energy consumption per received packet.

As shown in Figure 6(c), using a low transmission power of 0 dBm with 7 sinks results in a lower energy consumption per received packet compared to using 4 dBm in a single sink network, which demonstrates the benefits of the multi-sink architecture.

B. Real Time Tracking

In real time tracking applications, the current locations of the elephants are considered to be the most important data, as this will help avoid any human-animal conflict. Therefore, packets must be delivered to the sink within a predetermined bound for the location information to be of value. In our implementation of real time tracking, the nodes keep generating packets every hour for the entire simulation time, and any location information older than 1 hour is discarded from the node's queue, hence we consider only epidemic routing without vaccine. Table II shows the parameters used for real time tracking. The beacon interval and the host recent period decrease from 1 hour as used for the movement patterns analysis to 10 minutes to receive the elephants' locations more frequently.

Table II: Real time tracking parameters

Parameter	Value
Interval between sending packets	60 minutes
Beacon Interval	10 minutes
Host Recent Period	10 minutes
Queue Entry Expire Time	60 minutes
Simulation Time	10 days

Figure 7 shows the packet delivery ratio, delay and energy consumption per received packet for the real time tracking in JumboNet. It can be seen from Figure 7(a) that the epidemic routing protocol achieves a higher packet delivery ratio than the other protocols. For transmit powers below 8 dBm, and

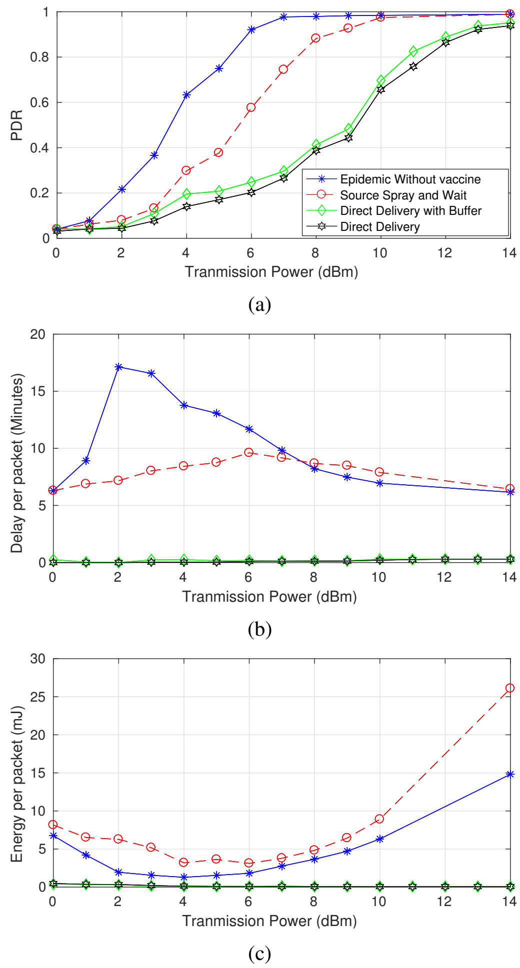


Figure 7: PDR, average delay and energy consumption per received packet for real time tracking in a single sink architecture.

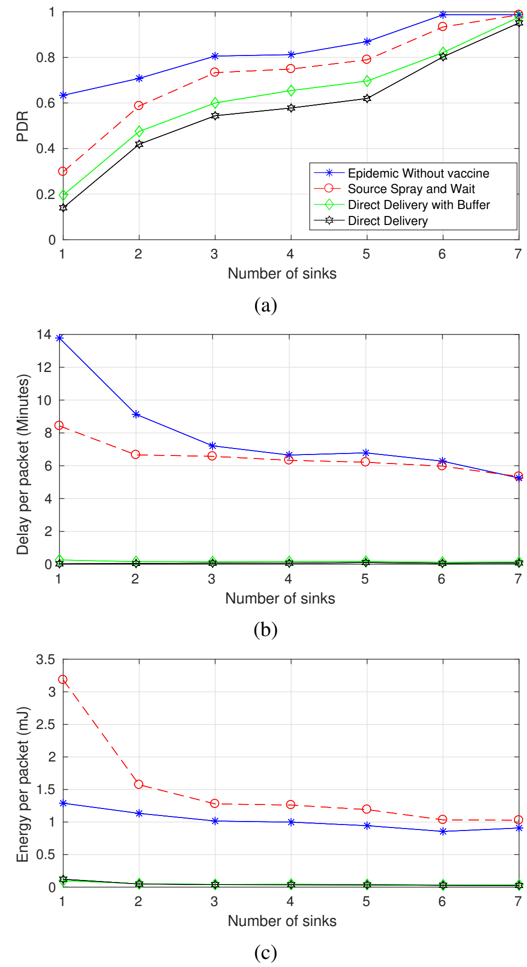


Figure 8: Effect of number of sinks on PDR, average delay and energy consumption per received packet at 4 dBm transmit power for real time tracking.

due to the lower packet delivery ratio, the average delay of the spray and wait protocol is lower than that for epidemic routing. On the other hand, for higher transmission powers, the PDR of the epidemic routing and the spray and wait protocols are close, and the epidemic routing protocol has a lower average delay and a lower energy consumption compared to the spray and wait protocol, as shown in Figures 7(b) and 7(c).

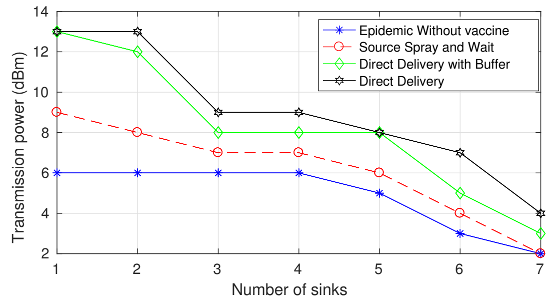
Figure 8 shows the effects of the number of sinks on the PDR, delay and energy consumption per received packet. As shown previously, adding more sinks increases the PDR. Due to the delay constraints, to achieve a 100% PDR in a real time tracking application, a higher transmission power must be used compared to the movement patterns analysis.

From Figure 8, we can conclude that for a large number of sinks, a direct delivery approach is superior to delay tolerant routing protocols in term of delay and energy consumption per received packet as shown in Figures 8(b) and 8(c).

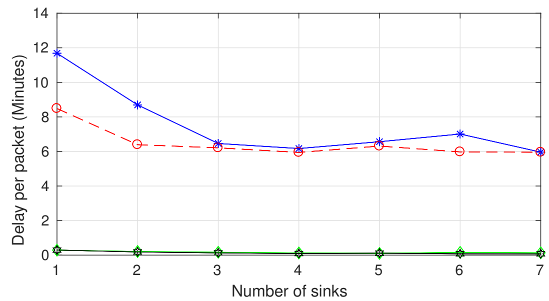
Figure 9 shows the required transmission power to achieve at least a 90% PDR within an hour from generation. For the same transmission power, epidemic routing has the highest delay and the lowest energy consumption compared to the spray and wait protocol. Furthermore, due to the delay constraint, using a large size buffer does not have much affect on the direct delivery approach as shown in Figure 9(a).

In a single sink network, epidemic routing can achieve more than 90% PDR with only 6 dBm transmission power compared to 9 dBm when implementing the spray and wait protocol. The trade-off between the lower energy consumption of the epidemic routing at 6 dBm and the lower average delay of the spray and wait protocol at 9 dBm is clear from Figures 9(b) and 9(c).

Figure 10 shows the minimum value of the hop count parameter of epidemic routing (`HopCount`) to reach a 90% PDR for real time tracking. It is clear that as the number of sinks increases and/or high transmit powers are used, the required hop count decreases until it reaches a hop count of 1. At this point, direct delivery is a better approach due to its lower energy consumption.



(a)



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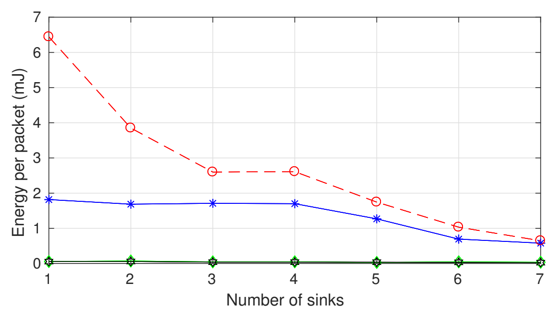

(c)

Figure 9: Required transmission power, the corresponding average delay and energy consumption per received packet to achieve 90% PDR for real time tracking in a single sink architecture.

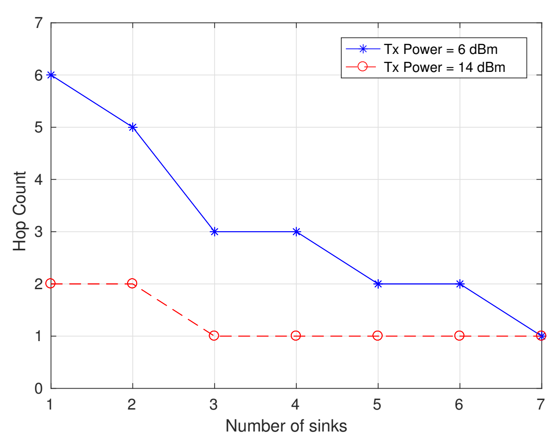

Figure 10: Minimum required hop count in epidemic routing (`HopCount`) to achieve 90% PDR for real time tracking in a single and multiple sinks architecture.

IV. Conclusions

In this paper, we evaluated the performance of different delay-tolerant routing protocols in the elephant tracking JumboNet application, for both single sink and multiple sinks architectures. For a single sink network, the epidemic routing protocol outperforms the spray and wait and direct delivery approaches in terms of PDR. On the contrary, if enough sinks are installed, or if the nodes can afford a high transmission power, a direct delivery approach would be most efficient to implement as the nodes consume the lowest energy and the packets experience the shortest delay compared to other approaches. A trade-off between the cost of adding a new sink versus the gain in terms of a packet delivery ratio, delay, and the energy consumption must be considered.

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