Beacon Trains: Blazing a Trail through Dense BLE Environments

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ABSTRACT

Bluetooth Low Energy (BLE) was designed as a low power alternative to classic Bluetooth. However, the use of BLE in dense, Internet of Things (IoT) deployments results in high collision rates and wasted energy. In response, we present an in-depth evaluation of the effects of having a high density of both transmitting tags and scanning devices in IoT environments. Based on our evaluation, we introduce *Beacon Train Mode*, an additional mode targeting dense IoT deployments with large numbers of both tags and scanning devices. Our results show that although active scanning breaks down when there are 5 or more scanning devices, beacon trains scale to any number of scanning devices.

1. INTRODUCTION

Bluetooth Classic, introduced over twenty years ago to provide a short range wireless alternative to USB cables, is unsuited to current sensing and Internet of Things (IoT) application demands due to its high energy cost and complex discovery mechanisms. To compensate for these limitations, Bluetooth Low Energy (BLE) was designed to eliminate pairing and simplify discovery, while still supporting short data exchanges [4, 12]. These improvements in delay and energy are triggering a flurry of new devices, services and applications, with predictions of 60 million BLE devices within the next 5 years [2], positioning BLE to be a major technology to enable the community's vision of IoT [7].

Given these improvements, BLE is quickly infiltrating a wide range of devices, including IoT-enhanced sports equipment and clothing as well as current smartphones and wearables. Essentially, the vision of IoT encompasses massive deployments of everyday objects augmented with communication and computation capabilities. However, as more BLE devices, commonly called beacons or tags, are deployed into public spaces, such as large retail stores, there could be tens, hundreds, or even thousands of tags advertising products and services at the same time. Similarly, the number of smartphones and other devices scanning for and interacting with these tags could reach very high numbers. Before more of these BLE devices are deployed, it is essential to understand the impact of this increasing density of advertising and scanning on access to advertised data.

While it is commonly expected that future IoT ecosystems will deploy a large number of tags, the impact of the density of scanning devices has been largely ignored in prior work [10, 1, 5]. However, the number of scanning devices can have a dramatic impact on access to BLE services and data. Although there have been some analytical and empirical studies on the behavior of BLE (*e.g.*, [6, 9, 11]), the impact of tag and scanner density on the performance of BLE has not been well evaluated. In response, we present a comprehensive evaluation of the behavior of BLE active and passive mode in dense environments (see Section 3). Essentially we show that BLE active mode breaks even in the presence of only a few scanning devices. To enable tags to increase their advertising data capacity without the overhead of active scanning, we present an extension to BLE, called *beacon train mode*, which allows BLE tags to send a series of different 31 byte "beacons". We show that beacon train mode improves data collection, even up to five beacons in a train, over active mode for BLE. In comparison to active mode, beacon trains of length two, which enable the same amount of data as active mode, significantly improve delay and energy consumption.

2. BLUETOOTH LOW ENERGY (BLE)

Given the energy and delay overhead for discovery in Classic Bluetooth, Bluetooth Low Energy (BLE) was designed to reduce the energy cost for device discovery and the delay for simple data exchanges. In BLE, every advertising tag sends an advertising message once every *advertising period* (or *beacon interval*), which can be configured per tag. Typical advertising periods are between 100ms and 1s. Shorter advertising periods can lead to faster data access. However, shorter periods also introduce more contention into the shared wireless channel, which can ultimately increase access delay in some environments.

To help alleviate contention and avoid poor channel conditions on a single channel, Bluetooth divides its frequency space into 40 channels and implements a channel-hopping protocol. Since the goal of BLE is to reduce cost and delay, and increase performance of discovery, BLE separates connected communication from advertising by reserving dedicated advertising channels. Using only one channel for advertising would lead to massive contention on that channel. However, too many channels would lead to the long access

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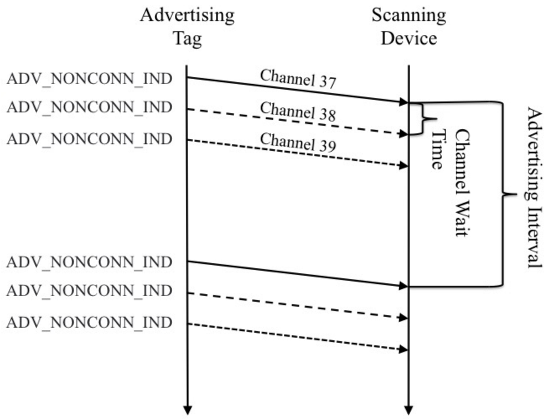

Figure 1: Passive Advertising

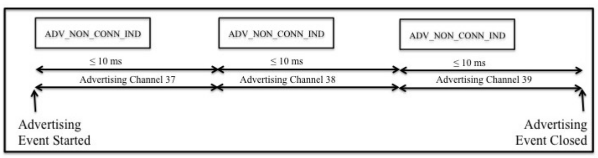

Figure 2: Timing for Passive Advertising

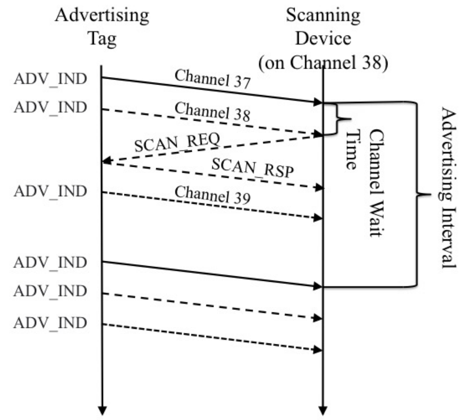

Figure 3: Active Advertising

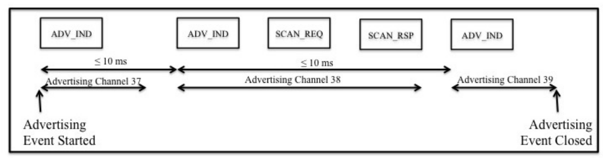

Figure 4: Timing for Active Advertising

delays associated with Classic Bluetooth as well as reduce the available bandwidth for data communication. To balance contention and delay, BLE restricts advertising to three advertising channels (37, 38 and 39), which fall outside the main frequencies used for IEEE 802.11 (1, 6, 11), allowing better co-existence with WiFi.

BLE tags follow a periodic advertising protocol. At the beginning of every advertising period, each tag transmits its advertising message on channels 37, 38 and 39, in that order. Scanning devices cycle through the advertising channels listening for advertising messages. The behavior of scanning devices is determined by the type of advertising message: passive or active. For both types, the scanning interval is designed to guarantee that a scanning device can receive an advertising message from an advertising tag once every advertising period, assuming no loss or contention. The exact time spent on a channel is device and OS specific.

2.1 Passive Scanning

With passive scanning, each tag periodically sends a passive advertising message (`ADV_NONCONN_IND`) on the three advertising channels (see Figure 1). The advertising message can contain up to a 31 byte payload. Passive scanning devices simply listen for the advertising messages and there is no direct interaction between tags and scanning devices (see Figure 2).

2.2 Active Scanning

Although 31 bytes may be sufficient for some applications, many applications need to send more data, but do not want to initiate a full data connection. To support this, BLE defines active scanning, where active advertising messages (`ADV_IND`) trigger a three-way handshake. All scanning devices receiving an active advertising message respond immediately with a scan request message (`SCAN_REQ`) unicast to the tag and the tag finishes the data exchange with a scan response message (`SCAN_RSP`), which can contain up to an additional 31 byte payload, effectively doubling the available payload space over passive scanning (see Figure 3). As per the BLE specification, scan response messages are broadcast to all potential requesters (as opposed to unicast to the tag that triggered the response) .

Tags only respond to the first request message in an advertising period on each channel (see Figure 4). So, either after the exchange of scan request and scan response messages or after a timeout, the tag switches channels and sends the next advertising message. After channel 39, the tag sleeps until the start of the next advertising period.

Although the scan response message is broadcast, the BLE specification mandates that a scanning device only accepts and processes a scan response message if that scanning device sent a scan request message to that tag on the same advertising channel during that advertising period. All non-requested scan response messages are dropped. Thus any device that intends to send a scan request message and, prior to sending, hears a scan response message will discard the response and proceed in the next period to send its own scan request message, thus wasting resources.

To reduce the contention from scan request messages, scanning devices implement a backoff mechanism, which unfortunately introduces its own problems. The basic idea for backoff in BLE is that if a requesting device does not get a response, there are likely many other co-located devices and the requesting device backs off in the next period to avoid collisions.

In the end, active scanning quickly becomes ineffective as increasingly more scanning devices are in range of the tags and so respond to the advertising message. Between request collisions and an aggressive backoff for transmitting the scan request messages when contention is detected, many scanning devices are unable to receive the second 31 bytes of data from the desired tag.

3. ACTIVE SCANNING PERFORMANCE

BLE active scanning was introduced to allow tags to send an additional 31 bytes of data. While advertising periods can be set independently for each device, common periods are less than 1s. As the advertising period shrinks, the probability of collision increases. In this paper, we present the results for 1 s advertising intervals, which demonstrate the contention problem and highlight the limitations of active scanning.

To understand the impact of the number of scanning devices on successful receipt of extra data requested using BLE active scanning, we explore the number of scan response messages successfully received by scanning devices. Recall that for a scan response message to be successfully received, a scanning device would have first had to receive a tag's active advertising message and at least one scan request message would have to have been received by the tag (see Figure 2.2).

Since individual losses can negatively impact receipt of data and many applications have limited delay tolerance, we consider data reception within a given time frame. For example, if the extra data contained in the scanning response is received only after a 10s delay, that data may no longer be useful to the application, and thus should be considered a failure. In our experiments, we use a 1s advertising period, which is on the high end of the advertising period spectrum (see Section 2). Based on the general expectation of a user's attention [8], we chose a 5 s success window, meaning that a response message has been successfully delivered if at least one of the tag's scan response messages is received by a scanning device within 5 s. To evaluate the 5 s success metric, success is calculated per scanning device for every 5 s window starting on the second across the entire experiment. For our experiments, the results represent the average across all scanning devices.

We ran a set of experiments with 1, 3, 5 and 9 Nexus 5 phones scanning for 1, 3, 5, 7 and 20 tags in active mode. We used a combination of Estimote beacons pre-configured with advertising periods of 950 ms and NRF Smart Beacon Kits configured to match the 950 ms advertising period. Experiments were run for 10 minutes across each combination of phones and tags. All devices, tags and phones, were put into a Faraday cage to eliminate any interference from external wireless sources.

For 1 and 3 scanning devices, 5 s success is almost 100% (see Figure 5). Essentially, allowing the scanning device to wait can compensate for many losses. For 5 scanning devices, success decreases, but stays within an acceptable range. The 5 s success starts to dip down to 95%. However, as the number of scanning devices increases to 9, success drops to below 75% in all cases.

This rapid drop in success is a reflection of the choice of three advertising channels. Although the scanning devices are not synchronized in any way, the use of three advertising channels allows for limited load-balancing across the channels for the request-response exchange. With up to three scanning devices, there should be limited impact. Essentially, there is a high probability that one scanning device

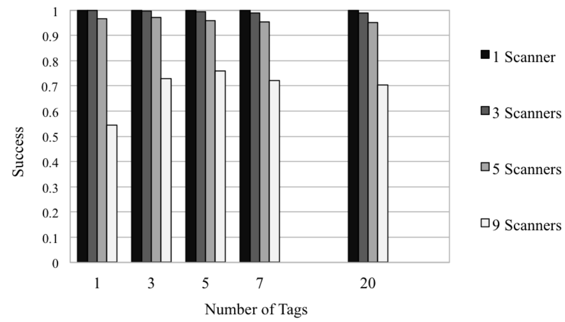

Figure 5: 5s Success for Active Scanning

may be scanning alone on a given channel and so there are no collisions. With five or six scanning devices, there may still be channels with only one scanning device sending a request. However, by the time nine scanning devices are scanning, there is excessive contention and the success rate drops dramatically.

Our results clearly show that in the face the expected large numbers of IoT-enhanced devices, applications requiring more than 31 bytes of data will rapidly degrade the performance of the network. Thus, a different solution is required to support such applications. In the next section, we present our beacon train mode as an answer to this problem.

4. BEACON TRAINS

In our *beacon train mode*, each advertising tag creates a set of N beacon messages that encompass the desired data. Each tag then iterates through its beacons, embedding them within passive advertising messages, one per advertising period, to successfully transmit the entire train of beacons (see Figure 7). For such beacon trains, the measure of success is when a scanning device receives all N beacon messages within a specific window of time.

Successful reception of advertising messages is governed by the advertising period, payload size, and density of tags. Additionally, the advertising period directly impacts the energy consumption of the advertising tag: longer advertising periods consume less energy. In this section, we evaluate the performance of beacon trains both through simulation to stress tag density and through real-world experiments to test feasibility in noisy environments. Our simulations were performed using ns-3 [3], in which we created a BLE extension using parameters directly from the BLE specification.

4.1 Baseline: Impact of Advertising Period

To get a baseline and understand the impact of advertising period length, we first evaluated passive scanning, varying density of tags and scanning window size, using our success rate metrics. Although a 1 s advertising period was short enough to exhibit significant contention with active scanning, smaller advertising periods can be used since there is no request-response handshake causing excessive contention.

The ultimate goal of a shorter advertising period is to reduce the listening time needed by the scanning device to receive data from a tag. Therefore, for each advertising period tested (1 s, 500 ms, 250 ms, and 100 ms), we evaluated success across varying scanning window sizes that reflect mean-

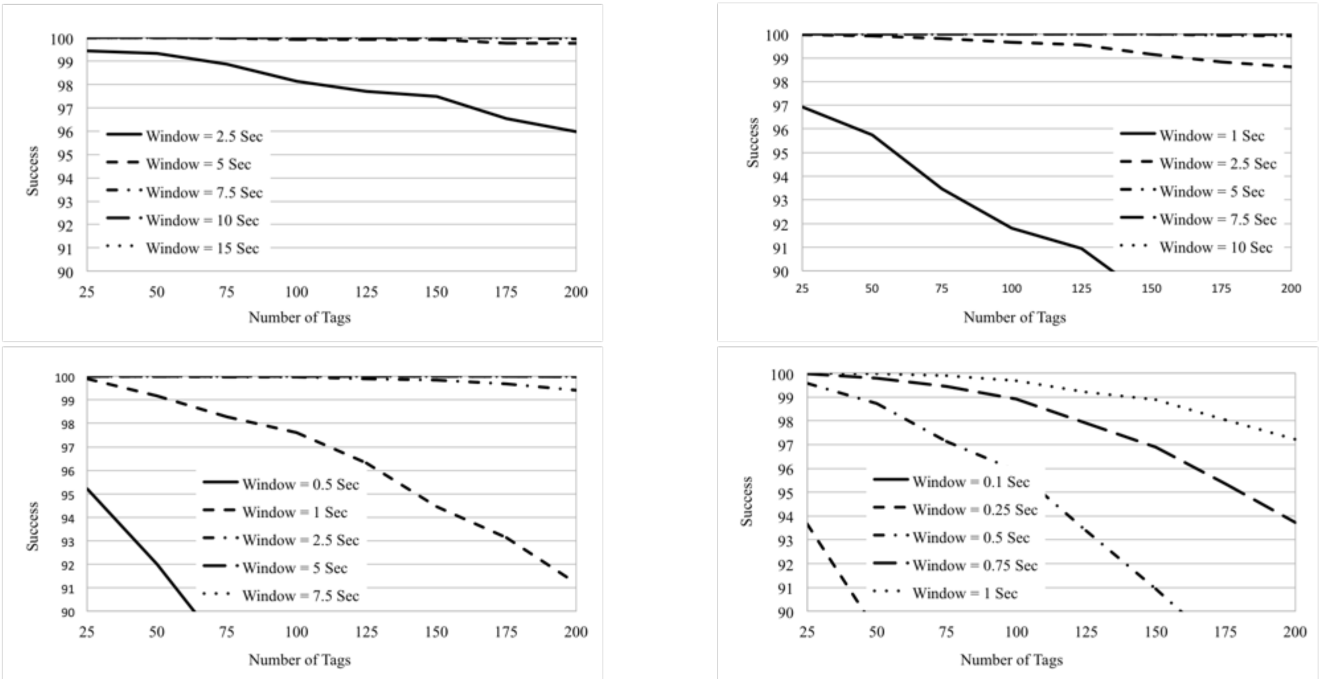

Figure 6: Passive Scanning with Advertsing Period = 1s (top left), 500ms (top right), 250ms (bottom left) and 100ms (bottom right)

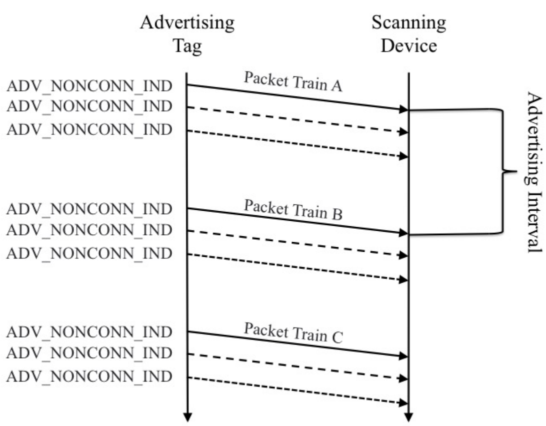

Figure 7: Beacon Trains (N=3)

ingful wait times. For example, window sizes of 2.5 s, 5 s, 7.5 s, 10 s, and 15 s were used for a 1 s advertising period. To be able to scale up to hundreds of advertising tags, this evaluation of passive scanning uses our ns-3 simulation.

As we can see in Figure 6, even with a scanning window of 2.5 s, success stays over 95% up to 200 advertising tags. Essentially, the longer advertising period leaves enough time for the tags to send their advertising messages with minimal collisions. This indicates that the scanning device needs to scan up to 2.5 times the 1s advertising period. It is important to note that the longer a device needs to scan, the higher the delay to the user and the more scanning energy consumption.

As the advertising period is decreased, collisions between advertising messages also increase. For an advertising period of 500 ms, only the 1 s scanning window does not have a high success ratio. Similarly, for the 250ms advertising period, contention starts to show its effects for the 1s scanning window. However, at 250 ms, the 1 s scanning window represents a scanning time of 4 times the advertising period. Essentially, the 500 ms advertising period achieves a similar success and delay to the 250 ms advertising period at half the cost to the advertising tag. Finally, with a 100 ms advertising period, the scanning device also needs to scan for 1 s to maintain high success, totally eliminating any delay or energy benefits from the lower advertising period.

4.2 Beacon Trains

To validate our approach, we implemented beacon train mode on Nordic Semiconductor nRF51 devices. Our testbed was run in a lab with other ambient interference, including other BLE advertising and scanning devices out of our control. Essentially, although advertising in BLE should be impacted very little by any Wi-Fi traffic, non-testbed devices running in both active and passive mode introduce additional cross-traffic to our experiments.

For our test suite, we varied advertising period, beacon train size, number of advertising tags, and success window. Since the number scanning devices does not impact the performance of beacon trains, we used four scanning devices throughout the experiments. The results presented are the average of the results from each of the four scanning devices, although the variance between devices was virtually non-existent.

Our experimental test evaluated beacon trains using 1, 3, 5, 7, 11, and 20 advertising tags with beacon train sizes of 2, 3, 4, and 5, advertising periods of 100 ms, 250 ms, 500 ms, and 1 s. Finally, we evaluated all data across scanning win-

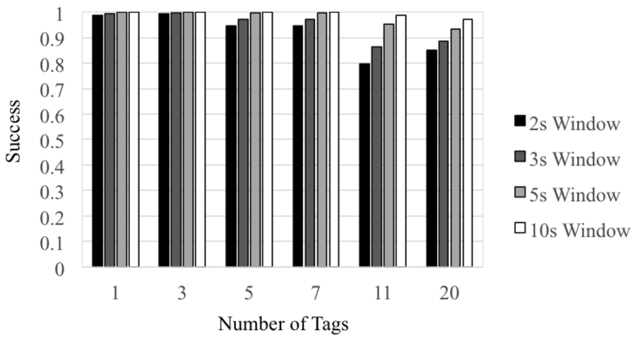

Figure 8: Exp: N=2, Adv Period = 1s

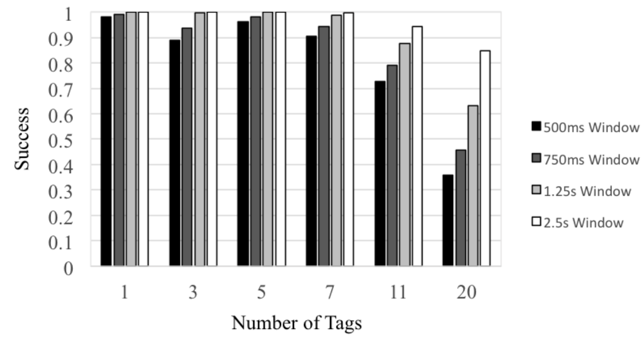

Figure 10: Exp, N=2, Adv Period = 250ms

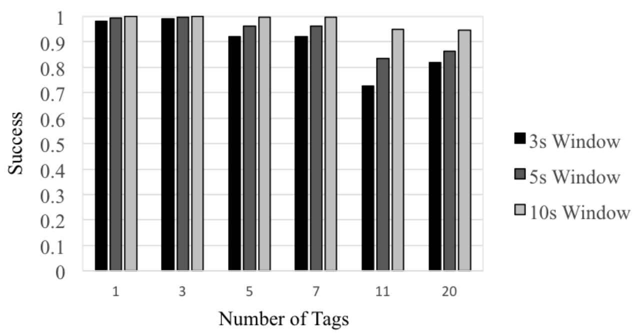

Figure 9: Exp, N=3, Adv Period = 1s

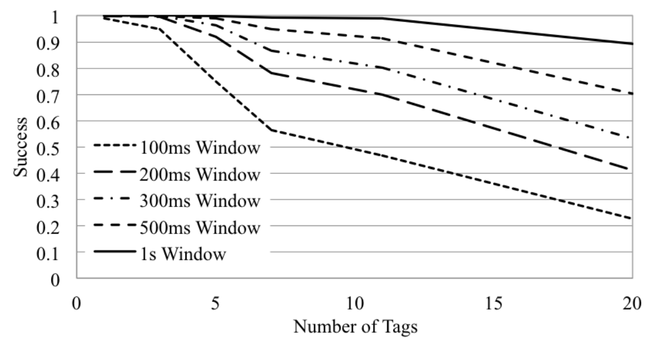

Figure 11: Exp, Passive Scanning, Adv Period = 100ms

dows of varying sizes depending on the advertising period, similar to the methodology used in the simulation studies.

With a beacon train of length 2 and a 1 s advertising period, success rate for 20 tags is roughly 85% with a 2 s window, increasing for each additional second in the window size (see Figure 8).

In comparison, active scanning can not provide over 80% success rate for 9 scanning devices for 3 or more advertising tags (see Figure 5). Given that a beacon train of size 2 enables scanning devices to receive the same amount of data as active scanning, beacon train mode outperforms active mode, as predicted. Furthermore, increasing the train size has limited impact on the success rate, given a proportionate increase in scanning window size. For example, Figure 9 show the results for a beacon train length of 3 (allowing 93 bytes of data to be transmitted). Here, the results are nearly identical, the moderate decrease in success rate being accounted for by increased probability of collision given the extra data that needs to be transmitted.

By reducing the the advertising period is 250 ms with a train length of 2 and 20 advertising tags, a 2.5 s window is needed to achieve an 85% success rate. This is due to the shorter advertising periods causing a rapidly overused channel in an uncontrolled environment.

Finally, we present results from the worst case we tested: a beacon train length of 5 with an advertising period of 100 ms. In this case, the channel quickly became flooded as the number of advertising tags increased (see Figure 12). Furthermore, to rate a success, the number of successful receptions increases. More than 3 advertising tags begin to crowd the channel, making it generally unusable with a train length of 5 (see Figure 12). It is worth noting that our experiments showed that with 5 advertising tags and a beacon train length of 2, it is possible to get about a 90% success rate with a 5s window given a 100 ms advertising period. Although very short advertising periods could be useful in environments with few advertising tags, the cost would be an unusable channel and high energy consumption for any scanning devices.

5. CONCLUSIONS AND FUTURE WORK

Our evaluation of BLE in diverse environments shows that for applications requiring the transmission of more than 31 bytes of data, active scanning is not feasible if multiple devices are scanning in the same area. In response, we have presented beacon train mode, which outperforms active scanning in dense IoT environments, where the expected number of scanning devices is high. We have validated our extension through simulation and experiments on deployed devices.

Finally, our future work is aimed at deploying beacon trains in various real-world scenarios to further study the impacts of other mechanisms, such as those related to privacy and security, on the performance of large scale, IoT deployments.

6. ACKNOWLEDGMENTS

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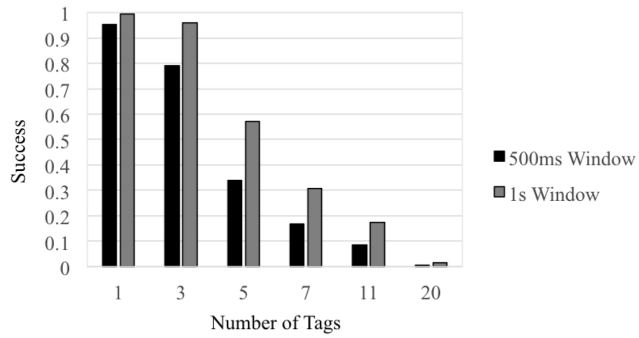

Figure 12: Exp, N=5, Adv Period = 100ms

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