Measuring the Accuracy of Crowd Counting using Wi-Fi Probe-Request-Frame Counting Technique

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***Abstract*— Wi-Fi in smartphones are designed to periodically transmit probe-request-frame to determine when a known access point is within range and by capitalizing this Wi-Fi behavior, crowd counting and analysis have been done by continuous monitoring and counting these Wi-Fi frames. The proliferation of Wi-Fi enabled mobile devices and the ever-increasing number of mobile devices in use, suggests opportunities for developing low-cost crowd counting and analysis solution. This work attempt to measure how well do monitoring and counting these Wi-Fi frames correlate with the actual number of people presence in a crowd. In this paper, we also compare the pros and cons of various crowd counting technologies, describe the system that we used for counting Wi-Fi frames and compare its accuracy against manual crowd counting technique in an event involving the public continuously for 8 hours. The results are promising, the correlation between manual counting and Wi-Fi frames counting is 0.89322. In addition to that, the Wi-Fi frames counting technique can even reveal the retention rate of the crowd.**

***Index Terms*— Crowd counting; Wi-Fi sensing; 802.11 frames capturing.**

I. INTRODUCTION

Crowd counting has always been an interesting research topic. In many years, there were many techniques employed to detect people presence, to count people and to estimate crowd density. Traditionally the motivation of crowd counting was solely for security purposes [1][2][3]. However, in the age of Internet-of-Things (IoT), crowd counting found its use in the business domain [4][5]. For instance, using the crowd size to provide better insights of business fluctuation.

Monitoring and counting Wi-Fi probe-request-frame is not a new technique and it has been used to track the movement and location of specific mobile devices [6], to infer socioeconomic status of a large crowd [7], to estimate the number of people in an enclosed space using the Wi-Fi signal interference caused by human [8], and to detect the density and movement of crowd in public spaces [5]. Unfortunately, to our best knowledge, none of the existing work have attempted to measure the correlation between counting Wi-Fi probe-request-frame and actual number of people in a crowd.

Although the penetration of Wi-Fi usage on mobile devices in Malaysia is growing and is much higher than the world's average [9], this does not imply that counting Wi-Fi probe-request-frame can be used to estimate the crowd size. For instance, not everyone will turn on the Wi-Fi module of their smartphones, and some might have multiple Wi-Fi enable devices. All the crowd counting and analysis using Wi-Fi frame counting technique will be meaningless when there are no correlation between Wi-Fi probe-request-frame and actual number of people in a crowd.

Therefore the objective of this work is to investigate the correlation between counting Wi-Fi probe-request-frame and actual number of people in a crowd. This work developed a system that passively listen and count Wi-Fi probe-request-frame and compared its accuracy against manual counting technique in a small scale 8 hours event which involved approximately 850 people (visitors and staff) where visitors are free to join and leave.

II. OVERVIEW OF CROWD COUNTING TECHNIQUES

Table 1 summarizes the different common crowd counting techniques. Different crowd counting techniques have different pros and cons in terms of accuracy, coverage, cost and reliability depending the needs of their respective applications.

Wi-Fi crowd counting technique has multiple advantages compare to the more popular video counting technique in terms of higher coverage as it is not easily occluded by walls and other moving objects, higher coverage will eventually reduce deployment cost due relatively lower number of sensors required. Specifically to Wi-Fi frame counting technique, it is also more reliable in terms of detecting the presence of a device compare to video crowding because it is less prone to noise that exists in video and image such as lightning of the environment. In addition to that, Wi-Fi frame counting can uniquely identify all the device that presence within is vicinity because the Wi-Fi frame consists of the MAC address of the corresponding device. This means that, Wi-Fi frame counting technique can also be used to estimate the retention rate of people in a crowd. Unfortunately, all this will only be meaningful when there are good correlation between Wi-Fi probe-request-frame and actual number of people in a crowd.

Table 1
Summary of Different Crowd Counting Techniques

Type	Advantages	Disadvantages
Manual Counting: The counter will increase each time the human operator clicks on it.	Accuracy can be high with well-trained operator and can even provide demographic information.	Reliability: Prone to human error and the human labor cost is high for prolonged period of monitoring.
Infrared Beam Counting: A pair of devices installed at a doorway. The counter will increase when objects cross the infrared beam.	Cost: It is a relatively low cost solution, easy to install and operate and is automated.	Accuracy is low as it unable to distinguish human and other moving objects and unable to detect people walking side by side while crossing the infrared beam.
Thermal Counting: Using sensors to detect the object's heat source.	Accuracy will be high and it is able to distinguish human and other objects.	Long range and wide angle thermal sensor camera are very expensive.
Video Counting: Using image processing to determine people.	One of the most commonly used technique. Good accuracy depending on algorithm and environment.	Very expensive to achieve good coverage and high reliability.
Wi-Fi Counting: Counts the number of unique Wi-Fi Probe-Request-Frame.	High coverage as it is not easily occluded by other objects in the environment and low cost for deployment.	Cannot be used if an accurate counting system is needed.

Table 2
Comparison of Crowd Counting Raw Results on Hourly Basis

Hour	9.30am	10.30am	11.30am	12.30pm	1.30pm	2.30pm	3.30pm	4.30pm
Manual Counting	67	67	80	74	20	56	38	0
Wi-Fi Frame Counting	104	117	122	130	112	101	63	43

Table 3
Comparison of Crowd Counting Results on Hourly Basis Including the Number of Staff on Duty

Hour	9.30am	10.30am	11.30am	12.30pm	1.30pm	2.30pm	3.30pm	4.30pm
Manual Counting	124	124	137	131	77	113	95	57
Wi-Fi Frame Counting	104	117	122	130	112	101	63	43

III. System Overview and Test Environment

A. *Wi-Fi Monitoring Overview*

The system is designed to listen for all Wi-Fi frames transmitted over the air and store these data in the cloud, Microsoft Azure, for further processing. The cloud filters all the frames and only interested with Wi-Fi probe-request-frames identified with the hex-code 0x04 and extracts all the MAC address corresponding to the frame and store with the timestamp when the particular frame is observed into a relational database. The purpose of the IoT gateway is to store and forward the data from Wi-Fi monitor to the cloud. Figure 1 illustrate the system overview.

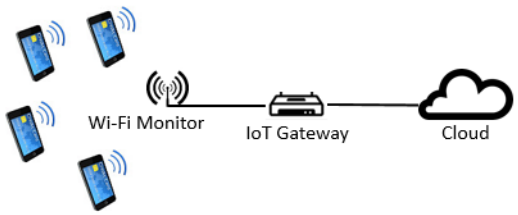

Figure 1: Wi-Fi Monitoring System Overview

B. *Test Environment*

In order to measure the correlation between counting Wi-Fi frames and the actual number of people, we need a medium size event where manual crowd counting is feasible, we need an event that allow people to join or leave freely. We chose our university open day as the test environment and has a volunteer to perform manual crowd counting. The data are collected on per hour basis for the entire day. The event lasted for 8 hours from 9.30am to 4.30pm. Figure 2 illustrate the hall layout, the position and coverage of the sensor.

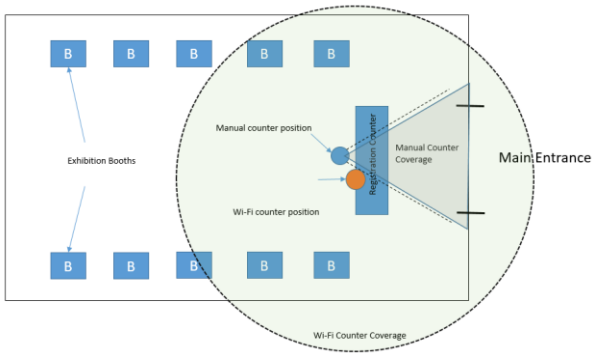

Figure 2: Hall layout, crowd counters position and coverage

IV. RESULTS

The manual counting technique counter increases by one every time the volunteer sees a new visitor whereas the Wi-Fi frame counting counter increases by one every time it detects a MAC address and data are recorded in an hourly basis for both techniques. Because of the counting approach is slightly different, the results at first glance varies significantly. Table 2, we compared the raw results from both counting techniques.

This is because the manual counting technique has yet to include the number of staff on duty. Staff are required to stay in the event for the entire day, and the number of staff is exactly 57 including all volunteers. The Wi-Fi frame counting techniques indiscriminately count every frames, it will also capture the presences of the staff. Therefore in Table 3, we compared the results from both counting techniques after including the number of staff on duty. Figure 3 depicts Table 3 figures using line graph. The correlation between the two sets of data is measured using Pearson correlation. Pearson correlation coefficient of the two sets of data is 0.77658 with the p-value equals to 0.02342 given with such small sample size.

In addition to that, similar to the manual counting technique, we use the Wi-Fi frame counting technique to generate the list of MAC address that is first seen for each hour. Table 4 shows the list of mobile devices that we never seen before in the previous hours against the data of manual counting technique. Pearson correlation coefficient of the two sets of data shown in Table 4 is 0.89322 with the p-value equals to 0.00281.

Discrepancies between Manual and Wi-Fi Counting

From the Table 3 and 4, by going through the values between manual counting and Wi-Fi frame counting, there are some column with great discrepancy. For instance the 4.30pm column in Table 4 where the manual counting technique showed 0 visitor while our Wi-Fi counting technique showed that there are 12 unique visitors during that time. One of the possible explanation is due to timing difference between when the visitor first arrive and when the Wi-Fi probe-request-frame is being transmitted and detected by our sensor.

V. CONCLUSION

Our experiment results showed that there are high correlation between manual people counting and Wi-Fi frames counting technique. Although Wi-Fi frames counting technique cannot accurately count the number of people in a crowd, it does able reveal the trends of people joining and leaving a crowd. In addition to that, Wi-Fi probe-request-frame counting technique can be used to estimate the visitor retention rate which are relatively difficult to achieve with other crowd counting techniques. The Wi-Fi frames counting solution used in this project is a low-cost and an effective method to monitor crowd trends.

Table 4
Comparison of Crowd Counting Results (first seen) on Hourly Basis

Hour	9.30 am	10.30 am	11.30 am	12.30 pm	1.30 pm	2.30 pm	3.30 pm	4.30 pm
Manual Counting	67	67	80	74	20	56	38	0
Wi-Fi Frame Counting	44	43	48	53	34	33	23	12

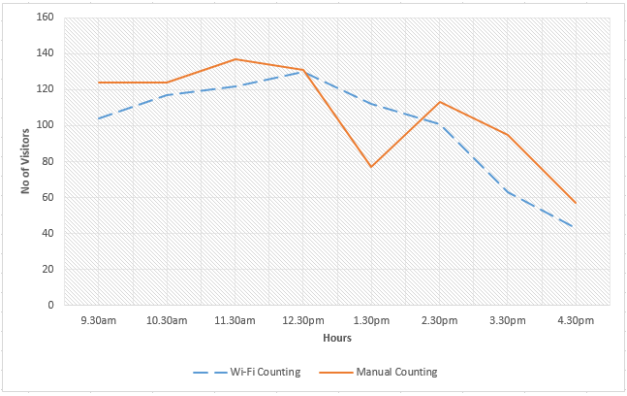

Figure 3: Comparison of Crowd Counting Results on Hourly Basis Including the Number of Staff on Duty (see Table 3. for the figures)

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