# DEMO: Dense Mode Mobile Crowd Sensing for Collision Prediction and Protection

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**ABSTRACT**

In a densely-populated event, a chaotic accident can result from a sudden human stampede. For instance, Hajj, an annual gathering of millions of Muslims in Mecca, Saudi Arabia, is one of the most crowded events in the world. During this event, human stampedes have costed at least several hundreds of casualties during the last few years. Despite many mitigation efforts, the stampede prediction and prevention is still very challenging problems. In this paper, we are proposing a Dense Mode (DEMO) mobile crowd sensing framework that predicts and prevents any potential upcoming collision risks caused by crowd movements. We first identify that one of the highest risk locations is an area with two roads meeting from the opposite directions. Although it will be safe if the crowd follows the flow in the defined direction at an appropriate speed, a large group of pilgrims often takes the opposite direction to be trampled in a serious stampede incident. To sense and track the group movement in time, we propose to harness a passive Bluetooth Low Energy (BLE) device for each group of pilgrims and install a few BLE scanning towers on the roadside. We designed effective and efficient message protocols and algorithms on the BLE tower, specifically, to detect a suspicious group movement within a coverage range such as an asynchronous speed among the crowds or an opposite direction flow. We also facilitate an alert relay towards a central commander station in order to briefly dispatch an appropriate preemption method to the location such as changing traffic flow or deploying a police in charge.

## Introduction

Hajj is the Muslim pilgrimage to Mecca that takes place in the last month of the Islamic calendar year. All Muslims are expected to do this pilgrimage at least once during their lifetime [1]. Usually, around 2 million Muslims from around the world gather in Mecca, Saudi Arabia. This number does not include the native Saudi Arabians who regularly go to Hajj. The actual Hajj period lasts for 5 days. During the period, people move among multiple locations including Mina, Mozdalifa, Arafat, and Jamarat (in addition to Mecca) that are a few miles apart from one another [1]. Some people walk while others use public transportation to get to the locations, but in most cases, they all end up walking because cars are not allowed during the most crowded times. Due to the lack of adequate crowd management methods, except the traditional manual approaches during the event, many serious incidents such as children who go missing and crowds that collide are not uncommon sights. [2]. Often, the identities of some of those involved in the casualties are not discovered. Hence, they are buried in Saudi Arabia. Furthermore, in trying to identify the casualties, the government of Saudi Arabia has to do extra work, which includes DNA testing that usually takes a very long time to process [3]. For example, sharing the

DNA samples with other countries isn't an easy task for Saudi Arabia [3]. In addition, for the many children who get lost during the Hajj, trying to find their group or family is a very difficult manual process considering the huge mobile population at the event.

In this paper, we propose a novel approach to enhance the safety of the Hajj event by using a wireless-based, efficient and a scalable crowd/group tracking technology. Specifically, we propose a tracking bracelet and monitoring infrastructure as well as a couple of abnormality detection algorithms. This tracking bracelet is an inexpensive and light weight identification device that every attendee at the Hajj pilgrimage (or other densely packed event) can wear. The pilgrims'/attendees' information such as names, ID numbers, camp numbers and locations, contacts, and basic health information can be securely placed into the tracking bracelet during the registration process. In case of an emergency, the information could be retrieved by the public safety personnel to facilitate help such as looking for the group or camp for a lost child or identifying a specific casualty. A Bluetooth Low Energy (BLE) communication device in the tracker bracelet enables information retrieval without contacting the gear [4] [5]. Furthermore, the BLE is used to monitor and manage a group's movement in a crowd. By using the BLE, the location of a specific group of people can be collected by the monitoring infrastructures. We do not assume a GPS-based localization, but rather, an indirect localization within the infrastructure. By using a couple of algorithms, we are able to identify any suspicious movement scenarios. We can detect asynchronous speed among the moving groups as well as identify a potential collision by measuring the flow density. The proposed monitoring approach is designed specifically for heavily crowded environments. It is efficient because we reduce the power consumption by applying an adaptive passive scanning technique, and it is scalable because we decrease the message overhead (and the collision possibility) by using probabilistic sampling-based monitoring.

## Motivation

Due to targets that move and unexpected factors, mobile crowd management in real-time is considered one of the hardest and most complex processes in crowd control. However, as deficient and inappropriate crowd management often results in disastrous repercussions such as injuries and casualties [6], the community needs to provide their best efforts to properly maintain the crowds. For example, as illustrated in Figure 1, the map shows many cases of crowd disasters that cause human losses around the world. The largest blue circle means the largest event and disaster, and that happens in Mecca, Saudi Arabia. More than 2000 people were killed in 2015 alone during the Hajj period [15].

Our motivation for this paper is to develop an efficient wireless framework for monitoring and controlling densely populated mobile crowds. Furthermore, we make a practical and field usable framework that ensures energy efficiency, improves data accuracy, embraces a user-friendly wearable technology, as well as provides scalability of handling the crowds.

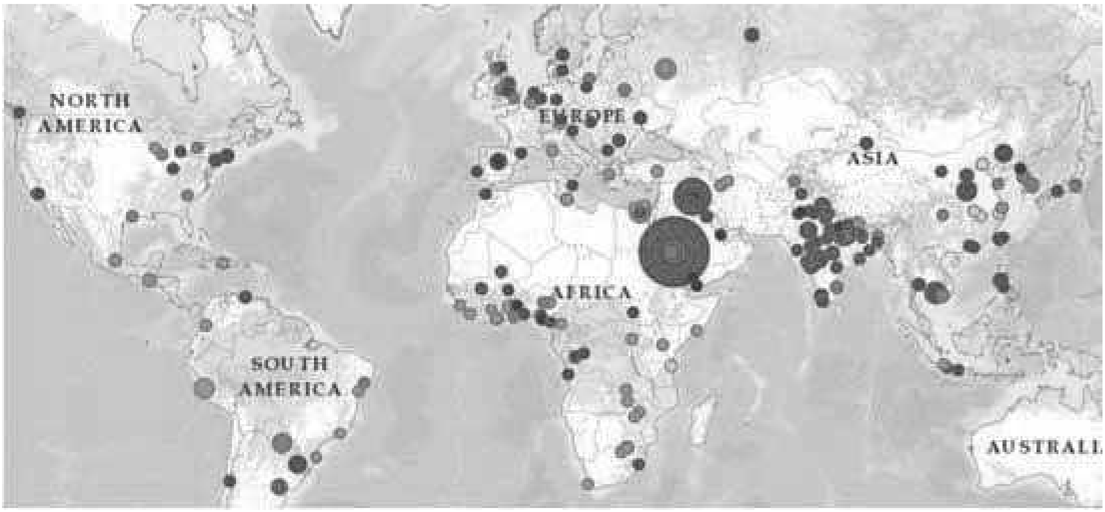


Figure 1. World Crowd Disaster Map [15]

## Demo Design and Features

The proposed ***Hajj*** tracker bracelet is intended to provide the flexibility of wearing the bracelet to ensure the users' efficiency and convenience as well as to ensure easy accessibility to the information about any and all victims. A water resistant material will be used for the bracelet, so that those attending Hajj can keep wearing the bracelet while performing ***Wudu*** (*washing parts of the body before each prayer*) for prayers. The Hajj tracker bracelet will be encased in various colors, not only to represent their group and country by the color itself. The Hajj tracker bracelet is equipped with a small flash memory that maintains each pilgrim's information such as name, nationality, camp number, camp location, list of emergency contacts, basic health information, etc. For example, in case someone lost his/her group or camp, all he/she would need to do is find the closest policeman who could scan the bracelet with the bracelet scanner and then direct him/her to the right location. It not only can give the direction of their group, but it also can check on the camp information including where their group is supposed to be going according to the most updated flow table for each group. In another example, if someone gets hurt or injured during the Hajj, the Emergency Medical Technicians (EMTs) can easily check on the health record of the injured person (who may already be unconscious or have difficulty talking) by scanning the bracelet to give the correct first aid to the victim. Another example is when an accident causes a human death casualty, a government officer of Saudi Arabia would not need to take a DNA sample nor send a DNA request for identifying the deceased. Scanning the bracelet's information simplifies the identification process as well as shortens the identification time. In addition, a Bluetooth Low Energy (BLE) communication device in the bracelet will help to send location updates to the closest BLE detectors along the pilgrimage paths. As illustrated in Figure 2, the BLE detector will send the information to the Hajj police control room where they can gather all the information needed. This real-time crowd flow information can be used by the control room authorities to manage and control the pilgrimage flow. With those updates, the control room authorities can manage the crowds with detailed information such as the locations, directions, and speeds of the pilgrimage groups. For example, if one group is moving in the opposite direction on the road, the control room can give a warning notice by sending nearby policemen to the group location to guide the flow to the correct direction. The information can also be used to predict any potential congestion and suspicious movements that may cause future disasters. The scanning device application has an authentication feature that allows only the authorized people with the scanning device to access the personal information of the Hajj tracker bracelet. The person who holds the device has to log in with his/her account username and password to activate the application. When a policemen scans the Hajj tracker bracelet, encrypted information will be sent to the centralized control room and the control center decrypts and decides which information can be seen by the policemen at the location. This authentication approach ensures the privacy of the person(s) in need by showing only the minimum necessary information is seen by the authorized person in charge of the situation. The scanning device or the software application (installed on any existing police scanning devices) can be distributed to different locations around Mecca during the Hajj event in order to cover any emergency cases.

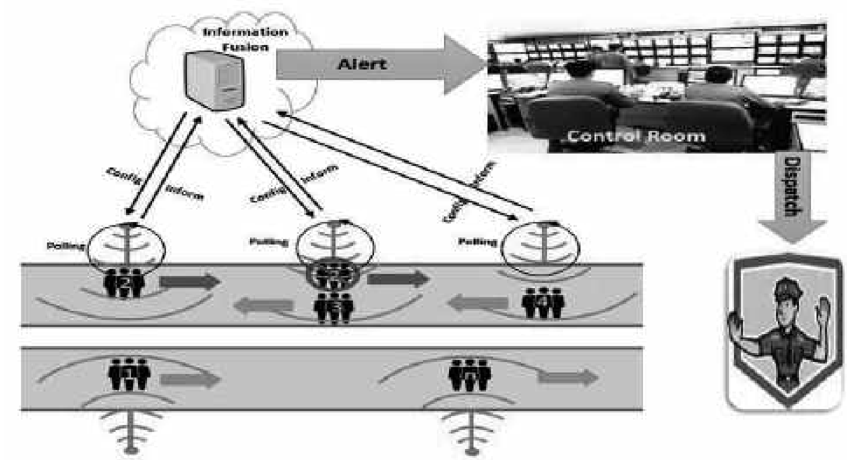

Figure 2. DEMO Framework and Direction Detection

## Demo Framework

DEMO framework is implemented by using a Bluetooth Low Energy (BLE) communication method. BLE is known to be more energy efficient than other wireless technologies such as classic Bluetooth and Wi-Fi. The coverage area of BLE is still as good as others that cover more than 100 meters. The coverage range is enough for the densely populated crowd situation like the Hajj event. The proposed framework consists of the Hajj tracker bracelets worn by pilgrimages, the BLE detectors placed on the pilgrimage paths, and the scanning device applications. Each Hajj tracker bracelet has a unique identification-ID in order to identify each bracelet. The BLE detector sends the regular polling and special probing messages to the pilgrimage groups to detect the locations of each group. Both polling and probing messages include a few sampling factors that indicate the replying patterns. For example, the BLE detector can specify the BLE ID to ask a few members of the groups to reply or only a designated member to reply. Using this methodology will not only decrease the interference between BLE detectors and BLE bracelets, but also decrease the probabilities of collisions. Using a BLE ID will also help to decrease the power consumption of the Hajj tracker bracelet because only the bracelet with the specified ID will reply in response to the polling messages, while the other bracelets are in the passive mode.

*Detecting Flow Direction*

The flow direction of each group can be detected by the BLE detectors. Each BLE detector scans the location of the groups within its monitoring range and shares its scanning results with others in real-time. By comparing the location change, the control room can detect the moving directions of each group. For example, when group 1 is detected by the BLE detector A and later is detected again by the BLE detector B, then group 1 is moving in the direction from A to B. As presented in figure 2, group IDs 3 and 4 are moving in the right direction, but group ID 2 is moving in the wrong direction. In practice, the situation often happens when the group ID 2 members take the opposite direction road (when it is empty) instead of using the slow and crowded path so that they can move faster. However, as the moving group cannot predict the upcoming traffic from the opposite direction, it may cause a potential collision later. The BLE detector will be able to identify the suspicious movement of the group ID 2. The control room can dispatch an alert to the nearby policemen so that they can guide the ID 2 group to the right direction.

### *Detecting Flow Speed*

The moving speed can be different form one group to another. Even groups moving in the same direction, if the moving speeds are different, it may cause congestion and collision by the fast-moving groups. In our research, we detect the moving speed of each group by applying the timestamp from each BLE detector. If the distance from BLE detector A to the BLE detector B is known, the moving speed can be easily calculated. Assuming the normal walking speed of a human is 3.1 mph (5 kph), we can identify the fast moving groups. For example, as shown in Figure 3, if the speed of the ID 3 and 4 groups can be detected earlier, the system could predict any potential collision between the  ID 3 and 4 groups. Likewise, if the ID 3 group is moving slower than the normal speed, the system can alert nearby policemen to guide the group's appropriate movements. If there are unavoidable reasons, the system can give a low-down warning to the following moving group.

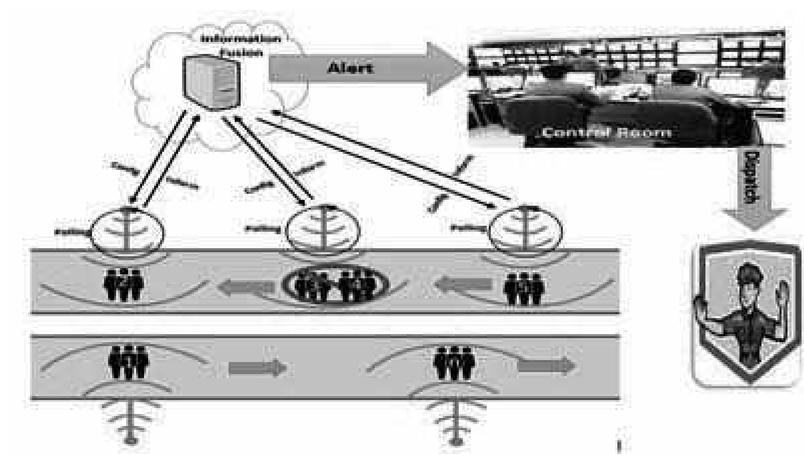


Figure 3. Flow Speed Detection

### *Scanning Approaches*

There are a couple of  scanning modes. One is a passive scanning mode and the other is an active scanning mode. As illustrated in Figure 4, the combination of these two modes is used between the BLE detectors and the Hajj tracker bracelets according to the crowd situations. The tuple of the ***detector mode / Hajj tracker bracelet mode approach*** is designed to ensure efficiency in power usage, increase the scalability in message communications, and improve the accuracy in event detection.

- ***An Active / Active Approach*** has a better chance of capturing most of the crowd density because the scanning point is both sending a request and waiting for a response, in the same time the pedestrians' bracelets are on active mode, sending requests, and waiting for responses. However, this will cause higher power consumption on both sides, which is one of our big concerns in improving battery consumption. This not only increases battery consumption, but it also increases the number of requests and responses causing overhead and increasing the probabilities of data collisions.
- ***A Passive / Passive Approach*** does not perform any active probing. Both the BLE detectors and the Hajj tracker bracelets are on listening mode. Although this approach can save power usage, it does not provide any meaningful information about the moving groups. A possible option is if the control room can detect a low traffic situation (during the off-peak times) by using other methods such as CCTVs.
- ***A Passive / Active Approach*** is a pure scanning approach for the BLE detectors. The Hajj tracker bracelets keep on sending their locations. The BLE detectors listen and respond upon receiving messages. As the Hajj tracker bracelets are always active, the power consumption on the bracelet is one of the main concerns and the major research focus should be to reduce the power consumption on the bracelets. Also, the number of messages is proportional to the number of bracelets. Hence, for a densely populated environment, the approach may increase the message overhead and cause a high chance for message collisions. ***An Active / Passive Approach*** is a BLE detector driven approach. The BLE detectors are sending polling or probing requests. The Hajj tracker bracelets are listening and responding upon receiving the request messages. As the Hajj tracker bracelets are passive, the power on the bracelet is efficiently utilized. Also, the number of messages is kept to a minimum as the bracelets are responding upon the requests. As the control is in the BLE detector side, the responding messages from the bracelets can be efficiently controlled as well. The approach can decrease the message overhead and maintain a smaller chance of message collisions. The DEMO takes this approach.

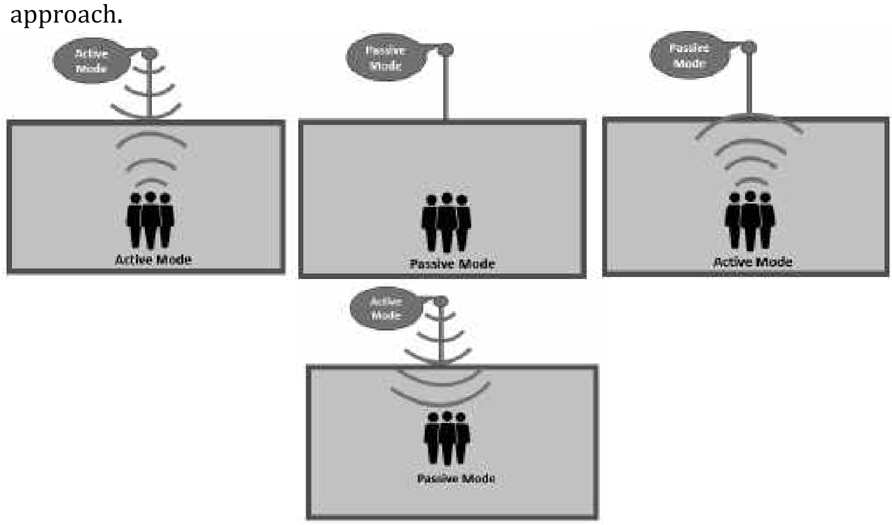


Figure 4. Detection Mode Classification

## Evaluation

Communication scalability is one of the most important issues in the Internet of Things (IoT) research. Especially, as we tackle the mobile cyber physical systems in a densely populated environment, the communication scalability issue should be addressed effectively [6]. In the proposed framework, by using an active / passive approach, the BLE detector maintains the scalability by sending probe requests for a sampling of responses. In addition, during Hajj, as most pilgrims walk very close to each other, the BLE signals between the BLE detectors and the bracelets could be affected.. Furthermore, as the bracelets will be worn on the hands, they could be blocked by another pilgrim's body in the crowd movements. Hence, via experimenting, we verify how human body movements could affect the BLE signal in a crowded environment. We have performed an experiment in one of UMKC's largest events called "Culture Night" to figure out the characteristics of the BLE signals in a crowded environment. The experimental results showed that the beacon messages in the crowd environment were blocked differently, according to the height of the BLE detectors. The experiments were conducted in a couple of different environments. The first test was executed before starting the event and the other test was done during the event. In the experiment, we measured the signal coverage and capabilities of the BLE scanner device in sensing multiple devices by counting the number of received beacons. Figure 5 presents the results of the BLE scanner ratio for the different heights in both crowded and not-crowded environments. We configured the BLE detector heights for 1 meter (low) and 3 meters (high), respectively. They showed that the greater number of human bodies there were, the greater number of beacon messages were blocked. The results showed that the message-receiving ratio in the crowded environment was 50% less than that in the uncrowded environment. Furthermore, the receiving ratio of the higher BLE detector (3 meters) was about 11% to 44% higher than that of the lower BLE detector (1 meter). In this result, we can see that the efficient BLE detector location (in height) is above every human height in order to avoid any signal absorption by the crowds.

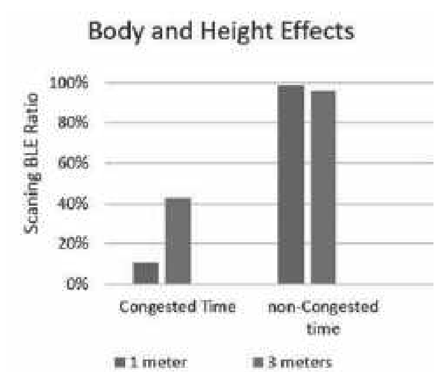


Figure 5. BLE Effect in Crowd

## Related Work

There have been several recent crowd management studies that address the issue of controlling the massive moving crowds including Hajj. Some of them used various wireless technologies. ANAS [8] used an active mode Bluetooth Low Energy (BLE) tag. The beacon messages were scanned by the smart phones (detectors). However, the active BLE tags consumed the battery power quickly. It also increased the chance of packet collisions in the crowded environment. In addition, this approach decreased the data accuracy since the smart phones (detectors) were carried by the people within the crowd. In opposition, our approach takes a passive mode tag that improves data accuracy, scalability, and power consumption. In Jens et al. [9], they use smart phones to scan for other Bluetooth devices to estimate the crowd density. However, this work did not provide any additional intelligent measurements for managing the crowds. In addition, their work mainly focused on estimating the static crowd density, while our work tackles a mobile crowd to manage the crowd flow and safety. Arsham et al. [7] tackles mobile crowd sensing by using Wi-Fi in an urban environment. The study took place in Edinburgh [7]. The study focused on the characteristics of Wi-Fi in different environments such as the 2.4 GHz and 5 GHz bands and their spectrums' usage. Also, in their work, they compared crowd sensing by using the mobile devices to verify that the mobile crowd sensing was as affective as a WiFi war driving [3]. Their work is different than ours, because they used Wi-Fi. Furthermore, their approach requires access to the APs (indirect communication). Mohammed et al. [14] uses a smart crowd sensing during Hajj and Umrah by taking advantage of cloud computing. Their work assumes that all pilgrims are carrying their smart phones, as well as they require a subscription from the local internet providers. The requirement makes it harder to deploy the solution. Mohammed Yamin et al. [10] uses GPS equipped RFID tags connected to a centralized data base in order to track pilgrims. However, the RFID system cannot support any communication based intelligent monitoring approaches. This also applies to Abdullah et al. who proposed using RFID connected to a data center to track pilgrims during Hajj [13]. In Ricardo et al., their paper also mentioned the possibilities of using RFID along with smart phones to track the pilgrims during Hajj [12]. Using smart phones is not an ideal solution, especially in a crowded environment due to various scalability, usability, power efficiency, and cost issues. Our approach is an ideal solution in a crowded environment by solving the aforementioned issues.

Conclusion

Hajj is considered the largest and most intensive crowd event in the world. Therefore, appropriate crowd management of the event is extremely important. However, in practice, the application of crowd management is still very challenging. The lack of adequate management often causes several hundreds of casualties. In this paper, we propose a Dense Mode (DEMO) mobile crowd-sensing framework that predicts and prevents any potential upcoming collision risks caused by crowd movements by using BLE based wireless technology. The DEMO framework consists of a Hajj tracker bracelet and a monitoring infrastructure (BLE detector) as well as a couple of abnormality detection algorithms. A prototype is implemented on a Raspberry Pi. The experiment results exhibit that the DEMO system achieves effective and efficient monitoring in a densely crowded environment.

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