Received May 5, 2017, accepted May 23, 2017, date of publication June 16, 2017, date of current version July 17, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2716782

Towards a Secure Mobile Edge Computing Framework for Hajj

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This work is financially supported by the King Saud University, Deanship of Scientific Research, Research Chair of Pervasive and Mobile Computing.

ABSTRACT The cloud computing paradigm faces the challenges of providing low latency, high availability, and real-time location-aware services where millions of people are mobile with respect to time and geographic location. In this paper, we propose a mobile edge computing framework that can support real-time, location-aware personalized services to a very large crowd. The framework uses a hybrid of cloud at the server end and fog computing terminals (FCTs) at the crowd edge. The concept of FCT is realized by adding a middle layer acting as a proxy between the user end and cloud infrastructure. Each FCT node covers a geographic zone and provides a subset of services and resources based on the geographic location of a mobile user. When a user moves from one FCT-covered zone to another, the secure handshaking of metadata about the user is shared with the new FCT node. The communication between mobile users' terminals, such as smartphone and the FCT, is assumed as 4G/5G networks, while the communication between the FCT and cloud is based on a high speed, always available, and reliable Internet connection. The location of each mobile user is made secure and shared according to our novel privacy policy paradigm. The framework is designed to switch between FCT and cloud, depending on the task, network condition, geographic nearness, and resources available within the client unit. We have implemented the framework to support context-aware services to millions of pilgrims that gather together in a very small area of land each year. We will share the inspiring results that we have gathered after initial deployment.

INDEX TERMS Fog computing, mobile edge computing, cloudlets, crowd sourcing, crowd sensing.

I. INTRODUCTION

Hajj is a yearly event where millions of people from almost every country gather together in the Holy land of Makkah and Madinah to perform their religious duties [1]. Since most pilgrims are coming for the first time, their old ages as well as different languages, cultures, and educational and social backgrounds make their journey a quite challenging environment. Providing security, safety, accommodation, health, and transportation services, to name a few, is a daunting task for such a large crowd. In other words, knowing the contexts of each pilgrim such as location, time, geographic zone, and events around the ambience within the crowd and then providing inter-pilgrim and intra-pilgrim context-aware services is a challenging task. Since the pilgrims move around different holy zones or boundaries, they face several challenges. Thousands of people get lost; they face trouble locating places of interest such as the nearest hospital, money exchange, and restaurants due to the huge crowd and language barrier; traffic conditions are unstable during Hajj, so it is difficult to find the best route to one's places of interest; and finding transportation at the right place and right time is hard [2]. Pilgrims thus need location-aware, highly available, and mobility-aware services to make their pilgrimage safe, secure, and comfortable.

The Hajj social network is composed of an ad-hoc network, which starts growing once pilgrims arrive in the holy land and diminishes once the Hajj pilgrimage ends; hence, the lifespan of this dynamic ad-hoc social network is about a month. Every year, a new Hajj social network is formed. The Hajj social network is composed of entities such as pilgrims, their family members, Hajj organizers, vehicles and transport systems, municipalities, governments, health institutions, and emergency handling agencies. Once connected, all these entities can share geo-tagged multimedia spatio-temporal data to support different scenarios, both real-time and offline [3], [4]. This poses several challenges. First, the Hajj social network requires a big data repository to store the content created by and shared among different entities in the very large Hajj crowd [5], [6]. Second, collecting users' context and location data sharing need to consider the privacy requirements of each user. Finally, spatio-temporal real-time queries need to be answered by the framework in the scenarios (e.g. an elderly person is lost, a fire or accident in a tent, emergency evacuation), which requires low latency, always available, and live query processing [7].

Thanks to current advancements in high speed Internet availability over 4G/5G networks, cloud computing, smartphone technology, mobile edge and fog computing, ubiquitous M2M (machine to machine) connectivity, monitored or completely ad-hoc device to device (D2D) direct connectivity via LTE-A, BLE, or Wi-Fi Direct, location-aware systems, crowdsourcing using social network events [15], and web services, to name a few, providing location-aware services to the Hajj crowd is no longer a dream. In our previous work, we developed [2], [8], [9], [10] a cloud-based big data framework where all the entities related to Hajj and Umrah are connected to the services offered through the Hajj and Umrah management system. The system has been deployed since 2014 where the framework collects pilgrim data using smartphone apps and a backend cloud-based system stores, processes, and replies to both real-time user queries and historical spatio-temporal queries. However, in our previous design [8], we observed the latency and high availability of real-time location-aware queries for the following reasons:

1) Each user interaction, user query, and sensory data are routed from the pilgrim's smartphone to the backend cloud server for processing, mining the phenomena, and finally storing or preparing results to be sent to the user terminals via the core backbone. This poses a significant bottleneck, especially on the 9th, 10th, 11th, and 12th days of the 12th Arabic month when millions of pilgrims gather in a tiny land. Figure 1 shows this bottleneck scenario. In the case the Internet service provider is down, the whole location-aware communication system is compromised, even in emergency situations.

Although two pilgrims (all pilgrims have similar clothing) that are lost in the crowd are in close proximity, the location sharing still goes through the cloud-based backend architecture. Since the pilgrim management system uses the backend cloud to store the multimedia payload originating from each pilgrim's smartphone and the metadata about the user, location, and smartphone, security and privacy can be compromised if the cloud environment is hacked.

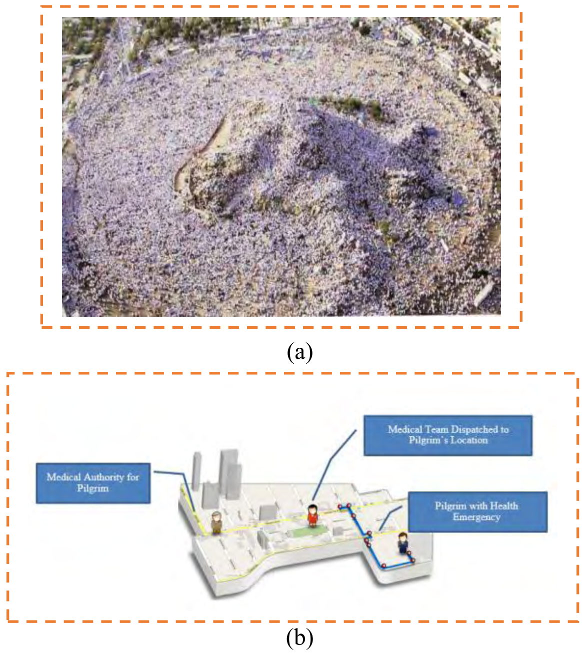


FIGURE 1. Location and other multimedia data shared with the cloud in real-time for various emergency scenarios. (a) Millions of people gather near Mount Arafat during their pilgrimage. (b) In the case of a medical emergency, the location of a sick pilgrim is shared with the emergency response team and the medical team in close proximity handles the patient.

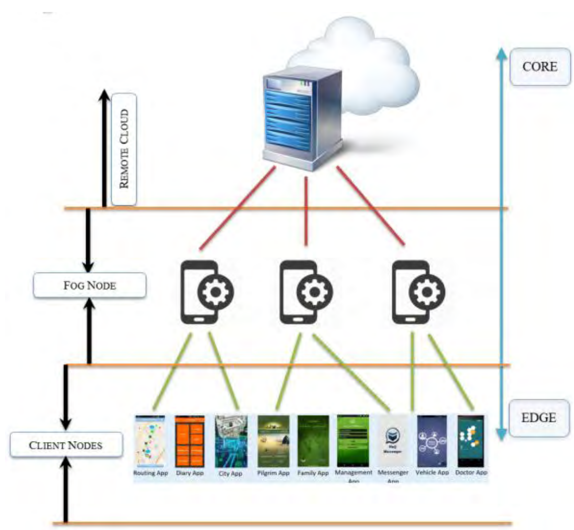


FIGURE 2. Fog nodes sit between user terminals and the remote cloud.

Thanks to advancements in mobile edge [13], [14], [16], [46] and fog computing [32]–[34], [44], the above-mentioned three challenges can be addressed by making the following two approaches:

1) The storage, computation, and communication capabilities of the cloud can now be brought close to the pilgrim crowd by leveraging the fog computing paradigm [35]–[39]. This can avoid sending a very large amount of payload to the backend cloud,

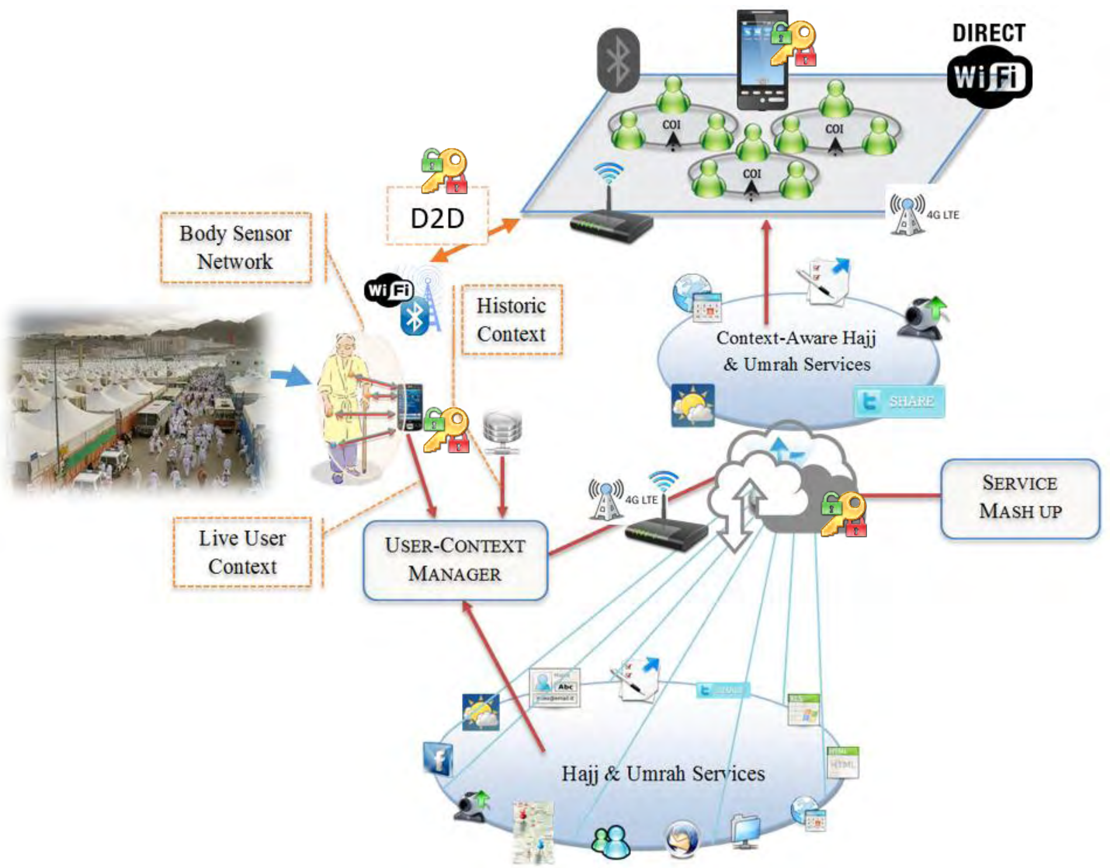


FIGURE 3. High Level System Architecture of the proposed system.

following the "share only when needed or when favorable" option (see Figure 2). Relatively few computing needs or little real-time location-based computing can be performed in mobile edges and the ultimate storage and very large and complex analytical computation can be pushed to the cloud [40]–[42].

2) Recent advancements in LTE-A, Bluetooth Low Energy, and Wi-Fi Direct D2D can help use the licensed mobile operator spectrum or unlicensed frequency spectrum to communicate among smartphones to share location and data [17]–[20]. This will help offline yet real-time communication among the pilgrims in the case of emergency, poor Internet, or no Internet situations [21]–[24]. The following features of D2D communication is ideal for Hajj scenarios [25]–[29]
    a) One-hop distance between client-to-client or client-to-fog nodes
    b) QoS is guaranteed
    c) Due to one-hop distance, an end-to-end security mechanism can be implemented
    d) Efficient client and fog node resource utilization can be guaranteed, which is not possible in multi-hop best-effort networks

In this manuscript, we envision the leverage of the fog computing paradigm by assuming that "end user pilgrims' or nearby pilgrims' edge devices or smartphones will perform a large portion of the cloud activities such as storage, communication, and processing and in return receive a substantial number of incentives for sustainable growth". Moreover, depending on the scenario and available bandwidth, edge devices will carry out as much local processing as possible and offload to the cloud backend only when a favorable network condition is observed. Hence, each pilgrim takes control of their usage data, granting permission to who they want and when they want. In this literature, we propose an extension of our earlier framework [5] by envisioning the support of fog computing and propose the following:

1) Design a suite of Smart Apps to act as both end user and mobile edge or fog node to collect geo-tagged multimedia big data from different Hajj-related entities. The smartphone app should be able to collect sensory data, provide context-aware services, and act as a mobile edge or fog node by allowing either D2D communication or sending data to the cloud.
2) Share spatio-temporal data with nearby devices in the case of the D2D communication mode or share big data with the cloud in the case of the available mobile edge bandwidth.

3) Visualize either a subset of spatio-temporal multimedia data from the fog-edge nodes while in the D2D mode or Very Large-Scale offline data from the cloud via either cloud or fog.

To this end, we propose a three-tier architecture (see Figure 2) to handle such a large crowd: the client tier consists of millions of pilgrims' smartphones as service consumers or data producers, the fog tier consists of smartphones as edge devices as mini-clouds, and the cloud tier has a fixed IP-based infrastructure. Tier 1 comprises human intelligence, namely human sensors that can sense real-life events, answer queries from other pilgrims, and use smartphone resources to respond to fog tier requests. The fog tier helps in the real-time processing of spatio-temporal collaborative or individual processes, while the cloud tier serves as massive big data storage, heavy duty analytical computation, and offline query processing. The fog nodes within the framework generally follow a one-hop communication paradigm in the case of D2D communication. However, the communication between distributed fog nodes and the cloud tier is done via the multi-hop communication paradigm. We show our design considerations and initial prototypes in all the tiers.

The rest of this paper is organized as follows. Section II describes the proposed framework that uses the three-tier architecture. Section III presents the implementation, results, and discussion. Finally, Section IV concludes the paper.

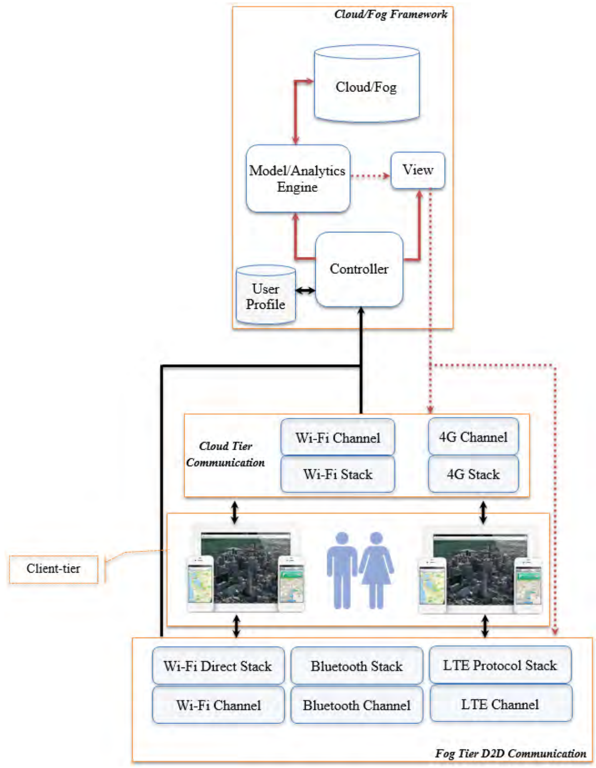


FIGURE 4. Three tier protocol architecture.

II. PROPOSED THREE-TIER ARCHITECTURE

A. HIGH-LEVEL SYSTEM OVERVIEW

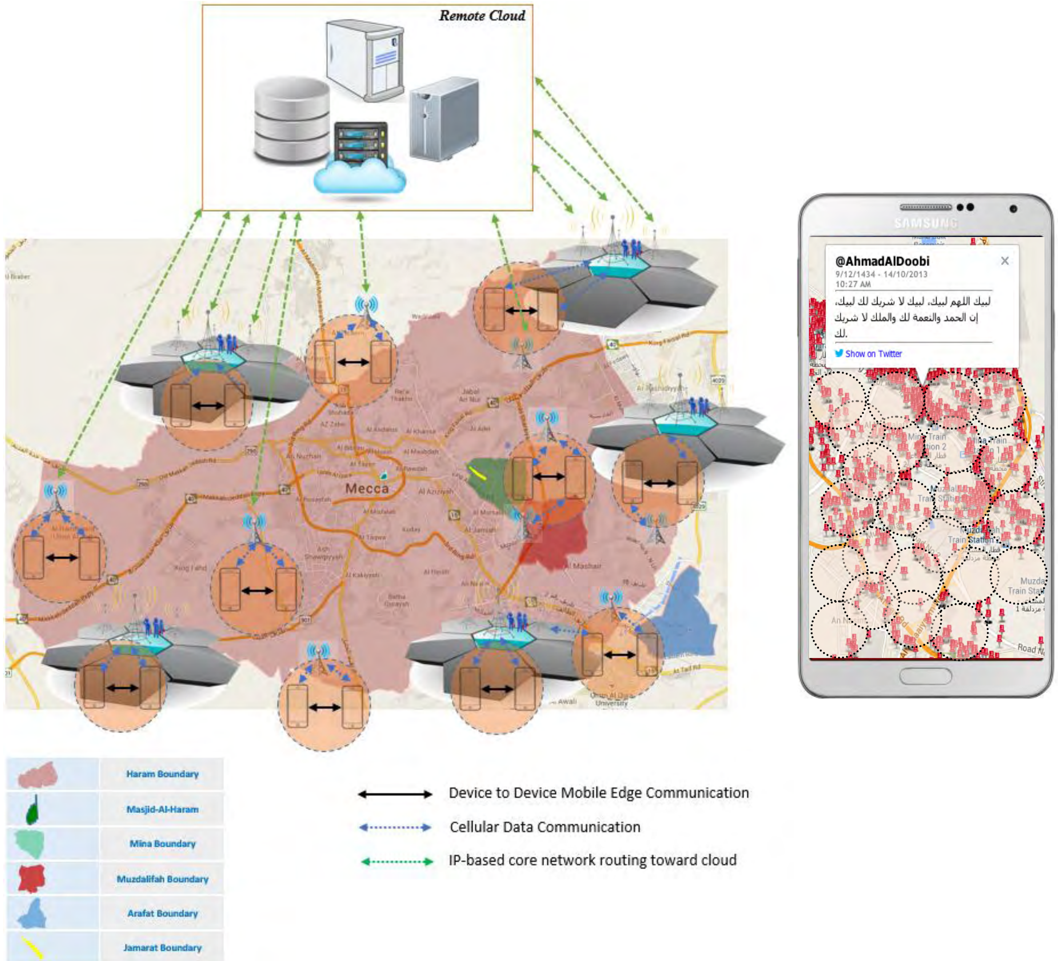
Hajj is a yearly event at which millions of pilgrims, most of them for the first time, visit a tiny land (see Figure 1(a)) for a week. Due to rapid advancements in smartphone technologies, most pilgrims have smartphones with GPS, LTE-A, Wi-Fi direct, and Bluetooth capability [30], [31]. As a result, it has become easy to run location-aware applications within the smartphone as well as share data with nearby compatible smartphones or with the remote cloud via Wi-Fi or 4G/LTE networks.

Figure 3 shows the high-level architecture of the proposed framework. We assume that each smartphone has both cellular data and Wi-Fi capability so that it can leverage communication opportunistically. In order to provide incentives, the framework offers around nine Hajj-related apps specifically tailored for pilgrims. Details of these apps can be explored in [5]. By using these apps, a pilgrim can consume different services and invoke collaborative services in which each smartphone device can connect to the fog tier and share information locally or with the cloud.

The smartphone acts as both a service consumption terminal and a fog node. As the service consumption tier, a pilgrim can consume a set of offline and online services from a pool of services to incentivize pilgrims, depending on the current context or previous context history of a pilgrim. Depending on the available connectivity, the smartphone application can also be used to be in touch with a subset of one's community of interest (COI), either via the deep cloud tier or via the fog tier. Within close proximity, the fog node can initiate D2D communication, while remote users have to rely on Internet connectivity. Another D2D mode is that some fog nodes form a cluster, where one of the client nodes having good cloud connectivity can act as a cluster head. D2D communication can then be shared with the cloud via the cluster head [12]. Figure 3 shows the high-level direct D2D communication under the two scenarios: the mobile cell tower may have partial control or full control over the D2D communication. Each smartphone client shares the location as well as other forms of multimedia content with the fog nodes, other client nodes, or the cloud node via an end-to-end security protocol to support different forms of security measures. This will allow the pilgrim's private data to be protected from unauthorized access, details of which are explained in the design section.

B. SAMPLE UPPER BOUND OF THE PAYLOAD OF THE D2D DATA COMMUNICATION REQUIREMENT DURING THE PEAK HOUR OF HAJJ

The following shows the overall multimedia data envisioned on average to be exchanged among different client, fog, and cloud entities within the Hajj scenario. This data model will allow us to deduce the D2D communication and fog node storage analysis requirements where 10 million pilgrims are expected by the Saudi authorities. We assume the following data requirements



(a) (b)

FIGURE 5. **Boundary model showing the D2D communication paradigm. (a) Projected zones on the actual map of the holy place. (b) Pilgrims' location during Hajj within the D2D zones.**

Projected Location Data for Client-to-Fog and/or Fog-to-Cloud Tier

$$T_L = F_L + P_L + V_L. \quad (1)$$

Where T_L is the total location data, F_L is the family members' and friends' location, P_L is the pilgrim's location, and V_L is the vehicles' location.

Each location data point (L_D) contains user ID (4 bytes) + latitude (8 bytes) + longitude (8 bytes) + date and time (16 bytes). Hence, the payload of the L_D of each instance of F_L, P_L, and V_L = 36 bytes

Case 1: Pilgrims and their COI in the inactive mode

We assume, in the case of an inactive pilgrim and his/her COI, that the location is shared with the fog nodes and/or cloud nodes, depending on the network availability, after each 30 minutes. Hence, location data are shared per day per client node

$$L_I = 48^*36 = 1728\text{bytes}. \quad (2)$$

Case 2: Pilgrims and their COI active in sharing the location without the need for continuous tracking

Let us assume that an active pilgrim or a COI uses two location-based services in an hour during the peak time of Hajj. Hence, location data are shared per user per day

$$L_A = 48^*36 = 1728\text{bytes} . \quad (3)$$

Case 3: Active pilgrims and their COI in the continuous location sharing mode

When an application uses a continuous tracking service, the location is shared continuously i.e. every 10 seconds. Generally, when a pilgrim visits a new place or some situation occurs, he/she uses this service more frequently. Let us assume that each pilgrim uses this type of service on average 20 minutes per day during the stay of 40 days. The total location data that will be shared per node in the span of 40 days are

$$L_T = 4800^*36 = 172,800\text{Bytes} . \quad (4)$$

Case4: Hajj vehicle data

When we use a tracking service for vehicles, the location is shared continuously i.e. every 10 seconds. If we assume

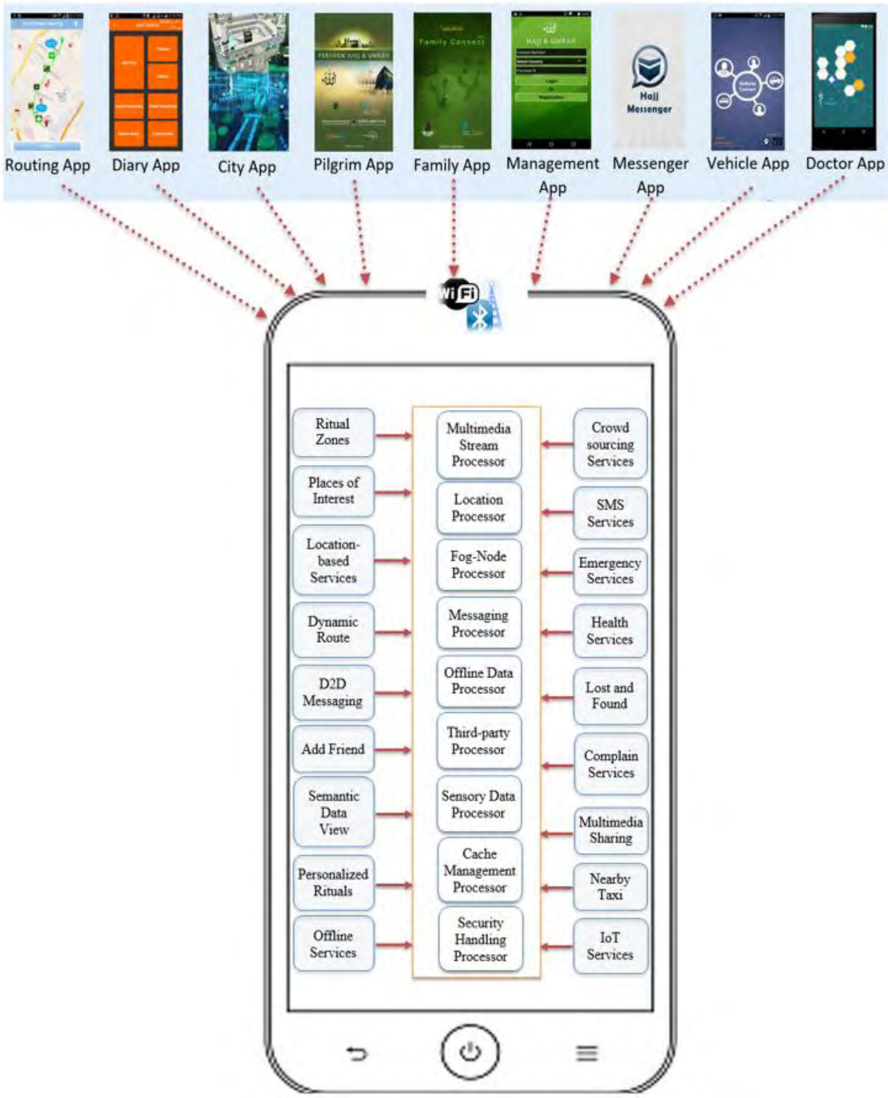


FIGURE 6. Software Components within smartphone applications.

vehicles for authorities and buses travel around 10 hours per day, the total location data per vehicle for the span of 40 days of the Hajj period are:

$$V_T = 144,000^{*}36 = 5,184,000 \text{ Bytes}. \tag{5}$$

Total pilgrim location data assuming 10 million pilgrims by Hajj 2020

$$\begin{aligned} P_L &= 10000000^{*}(1728 + 1728 + 172800) \\ &= 10000000^{*}176256 \\ &= 1762560000000 \text{ bytes} \\ &= 1641.5 \text{ Gigabytes}. \end{aligned} \tag{6}$$

Let us assume each pilgrim has on average three family members or friends. We can deduce the location data

$$\begin{aligned} F_L &= 1641.5^{*}3 \\ &= 4924.5 \text{ Gigabytes} . \end{aligned} \tag{7}$$

Let us assume 20,000 vehicles in Hajj 2020 carrying pilgrims, their food, and other taxies or emergency purposes. Based on (5)

$$\begin{aligned} V_L &= 5,184,000^{*}20000 \\ &= 103680000000 \text{ bytes} \\ &= 96.5 \text{ Gigabytes} \end{aligned} \tag{8}$$

So, total location data projection for 10 million pilgrims, 30 million friends, and 20 thousand vehicles

$$= 6,662 \text{ Gigabytes}. \tag{9}$$

Projected Multimedia Data for the Client-to-Fog and/or Fog-to-Cloud tier

We assume that at its peak, all 10 million pilgrims are connected with other pilgrims, friends, family members,

FIGURE 7. Screen flow of the "Lost and Found" service and subsequent location-based messaging communication. (a) Location of a lost pilgrim and relative location of a nearby COI to which a pilgrim can connect and ask for help. (b) Multimedia messaging with one of the nearby COI. (c) Sharing multimedia while meeting at the rendezvous point.

vehicles, doctors, and Hajj authorities by sharing multimedia data such as texts, SMSs, images, videos, audio in health, complaints, traffic updates, Twitter, and messenger services. Regardless of whether the communication goes via the fog node only or is propagated to the cloud in the delay tolerant mode, we assume the following types of multimedia data communication take place per day:

- M number of multimedia messages,
- T number of tweets,
- C number of complaints,
- H number of health data,
- Tr number of traffic updates,
- I number of images,
- V number of videos,
- Tm number of text messages,
- A number of audio,
- S number of SMSs.

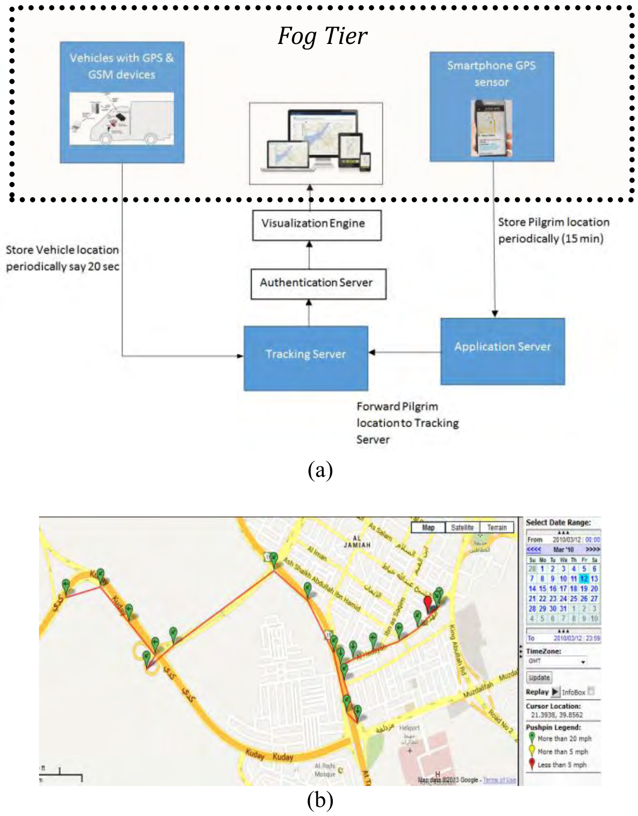


FIGURE 8. Screen flow of the "Emergency vehicle approaching a pilgrim who is sick" service and subsequent location-based messaging communication. (a) Location of a sick pilgrim and relative location of nearby emergency vehicles to which a pilgrim can connect and ask for help. (b) Location of vehicle is visible to the pilgrim.

Hence, the total multimedia payload per day per client can be deduced as

$$T_{MD} = (M+T+C+H+Tr+I+V+Tm+A+S). \tag{10}$$

$$\begin{aligned} &\text{Total multimedia payload per node for} \\ &\text{the duration of 40 days} \\ &= T^{*}_{MD}40. \end{aligned} \tag{11}$$

$$\begin{aligned} &\text{Considering the multimedia payload from} \\ &\text{all the pilgrims and their COI, total} \\ &= T^{*}_{MD}40\text{days}^{*}(10\text{million pilgrims}+30\text{million friends}) \\ &= 40000000^{*}40\text{days}^{*}T_{MD} \\ &= 1600000000^{*}T_{MD}. \end{aligned} \tag{12}$$

$$\begin{aligned} &\text{If we assume the value of } T_{MD} \text{ on average is 500 MB,} \\ &\text{the total multimedia payload that passes through} \\ &\text{the fog nodes to the cloud backend} \\ &= 152590^{*}5000\text{GB} = 762.950\text{Petabytes}. \end{aligned} \tag{13}$$

Hence, in the average case, based on equations (9) and (13), more than 762.950 petabytes of data are envisioned to be passing through the D2D or cloud-based communication path for the 40 days of pilgrimage, which can be much more if applications are used with a huge volume of multimedia data or more frequencies. Assuming such a sheer volume of data communication need, it is justifiable to use a hybrid

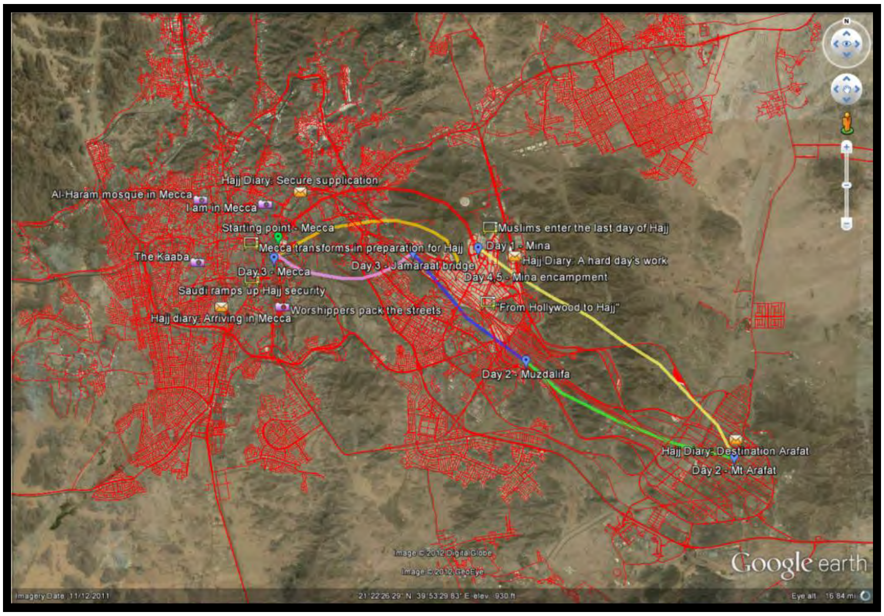


FIGURE 9. **A KML-based metaphor of a single pilgrim's journey during the Hajj event showing the important date, location, and route of events during the Hajj period.**

of D2D and cloud-based communication because a cloud-only solution would definitely become a bottleneck and cause real-time service interruption, as observed in our previous cloud-only deployment [5].

C. PROTOCOL STACK

Figure 4 shows the envisioned protocol stack that would allow millions of pilgrims within a tiny land acting as a smart city to share a very large amount of geo-tagged multimedia data in both real-time and offline modes by leveraging both Internet and intranet (i.e. D2D mode) based on the opportunistic mode. The hybrid protocol stack consists of a three-tier architecture: client, fog or edge, and cloud tiers. The interface between the client and edge tiers comprises Wi-Fi, Bluetooth, or 4G/LTE/LTE-A protocol stacks, while the interface between the client and cloud tiers relies on either the Wi-Fi or the 4G protocol stack. Whatever the communication protocol available for the framework, the payload transmitted between a client terminal and an edge terminal or between a client terminal and the cloud follows standard MVC architecture.

D. DETAILS OF THE EDGE COMPUTING ARCHITECTURE

Figure 5 shows the cloud, edge, and client nodes and their communication pattern. The fog nodes act as virtual clouds within the fog tier to handle the Internet issue and reduce the latency time. The advantages of the fog tier [33]–[36] are as follows:

1. Answer most of the queries from the fog tier such as if a pilgrim wants to be in touch with another person of COI and they are in the same tier zone
2. High bandwidth
3. Low latency
4. Low battery consumption
5. One-time installation cost
6. Local and low computation need that can be used to provide navigation to users in the same physical proximity

Figure 5 shows an imaginary distribution of cell towers, fog nodes, and client nodes within the fog tier. The boundary and coverage of each client node and fog node determine the sub-boundaries of the fog tier and those of the D2D communication possibility. If two or more client nodes are within the same fog tier boundary, they can start a D2D communication. However, each fog node acts as an opportunistic node such that whenever good network bandwidth is available, the fog nodes upload the fog tier transactions to the core IP-based cloud backend.

E. SECURITY CONSIDERATIONS

To provide a secure communication channel between any two smartphone client nodes within a D2D communication or between a smartphone as a client node and another smartphone as a fog or edge node and the client node and the cloud [11], [45], [47]–[49], we assume that the following types of connection or traffic-oriented security breaches might be possible: a) passive eavesdropping attack, b) impersonating attack, c) man in the middle attack, d) trust forging attack, e) independent negative attack, and f) collusive attack. To overcome the above attacks, we adopt several layers of security measures. First, we encrypt the smartphone payload with a symmetric AES key. Each client side smartphone app uses AES 256-bit encryption/decryption to secure the content at the packet level. The end-to-end signaling protocol is inspired and followed similar to Open Whisper Systems. To support forward and future secrecy, new AES keys are used for every message shared between two

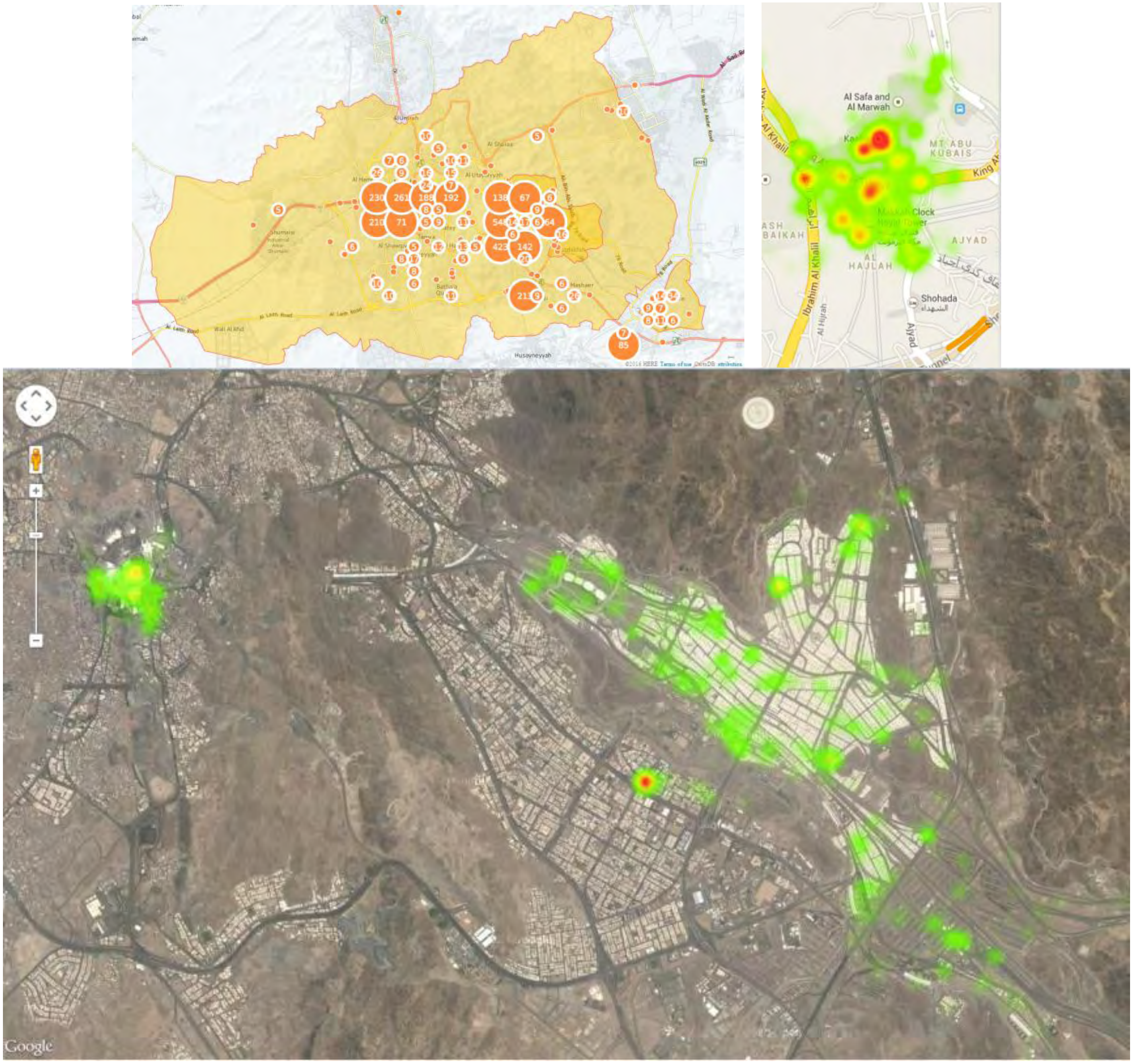


FIGURE 10. **Pilgrim crowd within different geo-grids of Hajj and its venues shown as a heat map.**

client applications. The AES keys used to encrypt messages are stored on the pilgrim's devices only. However, the local keys can be protected by an additional layer of encryption using a passphrase. For two smartphone apps intending to share any secure content via D2D (Bluetooth or Wi-Fi Direct) or via the Internet, the key negotiation, key generation, and finally key verification process takes place. Finally, data exchange such as location sharing and multimedia message sharing can take place. To add another level of security, we use two-way mobile number-based authentication.

III. IMPLEMENTATION

A. SMARTPHONE APPLICATION

We adopt a cyber-physical incentivized environment (see Figure 6) that can bridge the physical and virtual worlds and help pilgrims find the necessary path and resources within the very large Hajj crowd to get in touch with one's COI. Figure 6 shows our developed smartphone applications, each which is packed with numerous context-aware pilgrim-oriented spatio-temporal free services. These applications will allow different scenarios of Internet-based and offline consumption of spatio-temporal services [3], [5], [7]–[9]. The figure also shows the different salient software components that will allow both Internet-based and offline services.

B. ENVISIONED D2D COMMUNICATION SCENARIO

1) LOST AND FOUND SERVICES

One of the biggest problems is that pilgrims come as a group and have to be with the group as all the services and itinerary are preplanned and the whole pilgrimage is performed under a team leader. Because all pilgrims wear similar clothing, the tiny land is overcrowded, the land is hilly, and people have to move between places during Hajj, it is easy to get lost in the crowd. Finding the way back to the tent or finding lost persons in such circumstances is a challenging task for many people [8]. This service (see Figure 7) will help a pilgrim find his/her friends and places of interest in three modes.

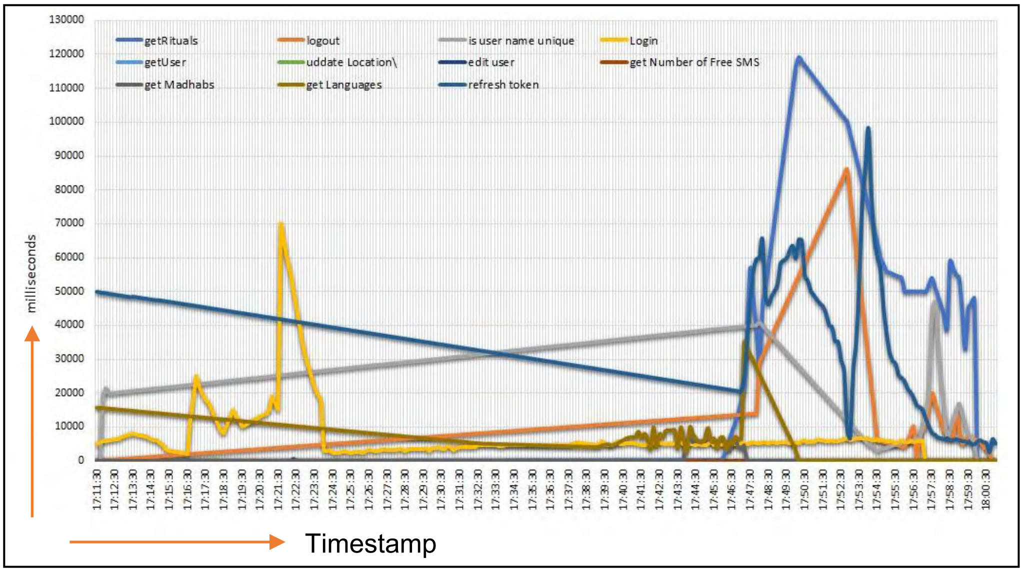


FIGURE 11. Server-side response time to support spatio-temporal communication during the peak hour of Hajj.

TABLE 1. Statistics of the ad-hoc social network during the Hajj event.

No of Nodes	371
No. Of Links	748
Average Degree Distribution	2.016
Average Weighted Degree	5.243
Network Diameter	8
Connected Components	22
Average Clustering Co-efficient	0.522
Average Path Length	3.354

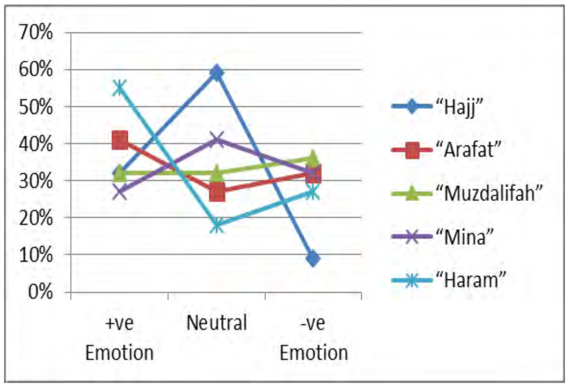


FIGURE 12. Emotion results based on keywords related to Hajj and its venues.

The first mode assumes that both the lost pilgrim and some members of his/her COI have a smartphone. If a pilgrim who is lost has a smartphone, s/he can use our incentivized SMS and location service (for free) to send an SOS message containing her location with a message. If some members of her community are also online or within a proximity of around 300 m, the lost pilgrim can also see their location, distance, and route to reach a friend. The friend can also see the location of the lost pilgrim. In the second scenario, where a pilgrim who is lost has a smartphone but without Internet access, a pilgrim can use the GCM gateway or D2D messaging service to send an SMS containing the location and message of the pilgrim to his/her COI. If the receiving friends do not have a smartphone, they will get the message from the lost pilgrim and a hyperlink to a map that shows the lost pilgrim's location. In the third scenario, we assume some people discover the right path or a few people who have come to Hajj before or act as a guide and hence know the way out and can come to the rescue.

2) WE NOW DETAIL THE LOST AND FOUND SERVICES WITH TWO USE CASES

a: PILGRIM HAS A SMARTPHONE BUT NO ACCESS TO THE INTERNET

A lost pilgrim can use the D2D features to share his/her current location with nearby friends or family members and vice versa as well as can see the approximate distance between the pilgrim and each member of the COI. A pilgrim can then select one member of the COI and start sharing multimedia content, to see the route dynamically [8] in D2D mode, without throttling the traffic to the cloud. The routing algorithm uses offline maps available to smartphone applications. Local transactions are, however, cached in the fog nodes and once a favorable uplink path is found, the metadata and multimedia payload is uploaded to the cloud from the fog nodes.

b: PILGRIM HAS A SMARTPHONE AND ACCESS TO THE INTERNET

This scenario is rare given the total number of pilgrims trying to communicate during the peak hours of the pilgrimage. If a pilgrim looks for a nearby member of the COI, the fog node receives a request to share his/her location (using HTTP), which is then sent back to the lost pilgrim via GCM or APNs (if the relative is offline). If the member of the COI is also online, s/he sends his/her location through the HTTP server every time his/her location changes and this live location

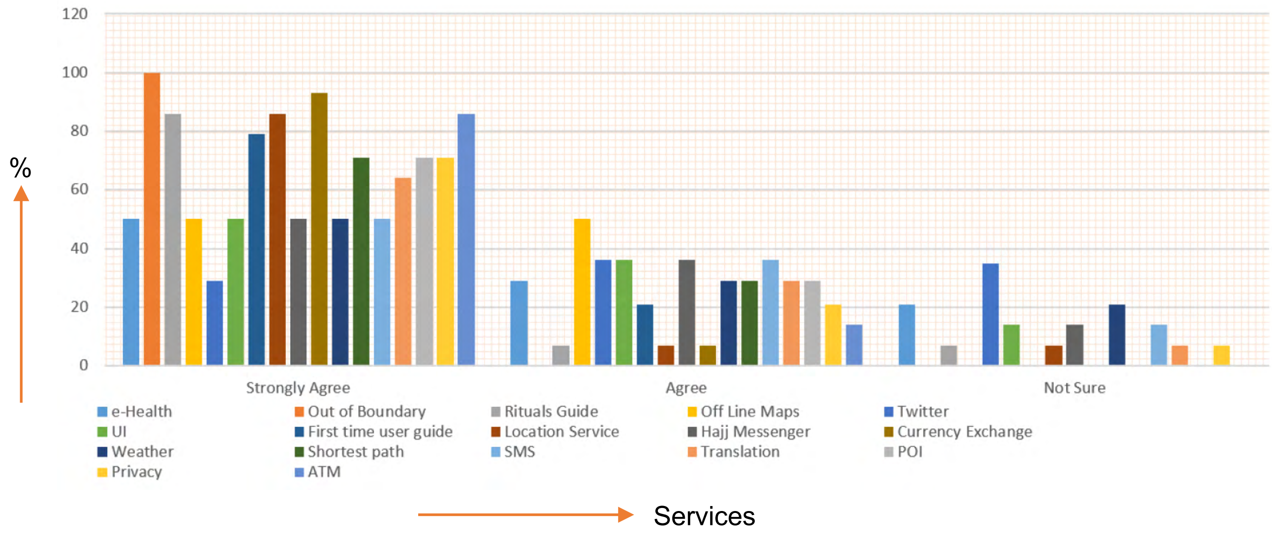


FIGURE 13. **User feedback on different services.**

of members of the COI is pushed to the lost pilgrim via GCM/APNs instant updates. All the communication between any two nodes goes via the fog–cloud links using the architecture proposed in [5].

3) EMERGENCY VEHICLE TO PILGRIM CLIENT NODE D2D COMMUNICATION

Figure 8 shows a scenario in which pilgrim client nodes and vehicles acting as client nodes can discover each other and share location and other multimedia content through the D2D channel.

IV. TEST RESULTS

A. FRAMEWORK DETAILS

The framework has been deployed since 2014 by introducing smartphone applications as mentioned in Figure 6 to the pilgrims and local residents of Makkah and Madinah. Table I shows the different social network parameters among the significant client nodes. The number of nodes refers to the edge nodes that act as hub nodes. Details of the architecture of the hub nodes and its distribution can be found in [9]. Figure 9 shows a pilgrim's trajectories that are tracked during different days of his/her visit within the places where the Hajj event takes place.

Figure 10 shows the distribution of pilgrims within different regions of the pilgrimage area with density shown as heat maps. The framework is able to project users' spatio-temporal presence over the map, their social connectivity, and the communication link, namely online or offline status with the cloud or the edge network. The heat map can also be used to project the best regions for cloud connectivity. Figure 10 shows a live map of how many pilgrims are within a geo-zone. As shown in Figure 1, the pilgrims generally move within a pocket so that they are not lost in their journey from one region to another. As a result, the D2D communication is envisioned to be more efficient during the days of pilgrimage.

B. SYSTEM EVALUATION

Figure 11 shows the server-side response time of the framework for different applications and services that were designed to incentivize the pilgrims. Since most of the pilgrims come to their pilgrimage for the first time in life, As shown in the figure, the worst response time is about two minutes for cases where Internet connectivity is poor, and hence collecting the cloud takes longer. This delay is challenging for real-time applications such as emergency evacuations or accident handling. Switching to the D2D mode should greatly enhance the response time for real-time applications. Some of the applications such as lost and found requires continuous location sharing with the database server at the cloud. Hence, it is challenging for D2D nodes to keep a tight communication with the edge node.

C. USER FEEDBACK

We conducted a survey about the global sentiments of the developed services, especially the most negative issues, to continuously improve the framework. A summary of the results is shown in Figure 12. User sentiments based on spatio-temporal events in the locations "Arafat", "Haram", "Mujdalifah", and "Mina" are analyzed based on "positive", "neutral", and "negative" emotions. Users rated the services as per their experience in different locations.

Figure 12 shows the tweets posted from Mina, Mujdalifah, Arafat, Jamarat, and Haram. Grouping tweets with sentiment analysis gives a great insight into the government agencies that track certain disaster phenomena based on some emotional aspects. As we see from the analysis, the most negative

TABLE 2. Analysis of list of questionnaire.

Question	Strongly Agree	Agree	Not Sure	Disagree	Strongly Disagree
Provided proper privacy model is implemented, collecting user health data and sharing with appropriate medical authority would give pilgrims to get health services in emergency.	50%	29%	21%	0%	0%
Out of Boundary Service will help a pilgrim to stay inside the Arafat, Mina, Mujdalifah and Haram boundary. What do you think about this service?	100%	0%	0%	0%	0%
Showing the correct way to haram will save a lot of time. Do you agree with this?	57%	43%	0%	0%	0%
To keep the pilgrims updated about Hajj and Umrah news is very useful feature.	36%	43%	21%	0%	0%
The guide to perform Hajj and Umrah rituals based on Hajj days and time of the day will be very useful.	86%	7%	7%	0%	0%
Availability of ritual services based on time and location will help a pilgrim to perform rituals easily.	86%	14%	0%	0%	0%
Did you like the services of navigation and offline map rendering?	50%	50%	0%	0%	0%
The twitter service is envisioned to collect information about other pilgrims' experiences during the Hajj. What do you think?	29%	36%	36%	0%	0%
The user interfaces in the app was easy to understand the functionality and the service it provided.	50%	36%	14%	0%	0%
For the pilgrims especially coming first time to perform Hajj and Umrah, this App will act as an excellent guide.	79%	21%	0%	0%	0%
The "Location Service" determined my location correctly.	86%	7%	7%	0%	0%
Hajj messenger will be an excellent idea to easily communicate with one's friends and Hajj fellows.	50%	36%	14%	0%	0%
The "currency exchange service" was useful to know the exchange rates and the location of the nearest facility?	93%	7%	0%	0%	0%
Check weather service is nice and forecast will help to get prepared for the upcoming weather.	50%	29%	21%	0%	0%
Finding the shortest path is very useful service in such a massive crowd during Hajj.	71%	29%	0%	0%	0%
SMS exchange service for emergency cases will be very useful to handle accident cases.	50%	36%	14%	0%	0%
Translation service, especially text to speech in Arabic will be very useful for pilgrims to read and follow the instructions.	64%	29%	7%	0%	0%
The application will show the nearest friends and places of interest in case someone is lost in a crowd. How useful do you think this feature would be?	71%	29%	0%	0%	0%
Provided privacy is protected, relevant Government and relatives will be able to locate a lost pilgrim. What do you think about this feature?	71%	21%	7%	0%	0%
Showing points of interests such as toilets in Arafat and Mujdalifah, ATM machines, country specific restaurants etc. would be a very useful for those who are coming for the first time	86%	14%	0%	0%	0%

emotion feedback posts were concerning Mujdalifah. Figure 12 takes into consideration tweets based on spatial attributes; we parse the tweet content based on hashtags or keywords. Figure 13 shows a set of services and users' feedback about their satisfaction level with each service. Most of the services that require cloud-based location-aware services earned the least scores as these services were offered without any support of edge nodes. Table II shows a summary of the questionnaires that volunteers filled after they downloaded the applications, used them during the Hajj event, and then answered the questions. The user feedback and system analysis gave us rich sources of insight into the positive and negative issues of the framework. While 5G technologies penetrate further into local network operators, we hope to embrace the D2D protocols and architecture in our future endeavors. Thanks to Mr. Akhlaq, Mr. Faizan, Dr. Mohamed Ahmed, and other members of KACST GISTIC for the collection, analysis of the sensory, smartphone data, user feedback data and analysis.

Since 5G architecture is evolving and still not adopted widely by the Saudi telecom operators, we had to resort to the Wi-Fi direct or BLE architecture to design the framework. We could not secure any MOU with the telecom operators such as Mobily, STC and Zain due to licensed spectrum and D2D communication policy. Another area that we are working with the Hajj authority is to allow University of Prince Mugrin (UPM) to install fixed cloudlet nodes with always Internet connectivity to support offloading of spatio-temporal, geo-tagged multimedia data during D2D or fog-to-cloud communication. Another challenge of implementing D2D at a larger scale is that not all the pilgrims come with Wi-Fi direct or BLE capable smartphones. However, due to the rapid growth of smartphone technologies at both consumer end and the mobile operator end, we are hopeful that most of the challenges mentioned above can be addressed in the coming days.

V. CONCLUSION

In this paper, we analyzed the leverage of D2D communication using the fog or edge nodes sitting between the mobile clients and the remote cloud. Since Hajj brings together millions of pilgrims, in addition to city residents and visitors, maintaining real-time communication with a very large amount of multimedia payloads is a challenging factor, which we tried to address with the state-of-the-art edge computing paradigm. The edge nodes are portrayed as a smartphone node for this experiment. We hope to deploy some fixed node cloudlet architecture with more powerful nodes to act as edge or fog node in the coming days. Also, we are working with the telecommunication operators in Saudi Arabia by building proper incentive model so that our developed framework can use the 5G licensed spectrum for the purpose of D2D communication and proper handshaking between mobile clients and the edge nodes.

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