Hybrid Cellular-MANETs in Practice: A Microblogging System for Smart Devices in Disaster Areas

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***Abstract*—Our dependence on mobile communications continues to grow; however, wireless devices may encounter inadequate coverage due to a variety of shortage and outage circumstances. In particular, in disaster situations, the access to communications is critical for rescue operations while local wireless infrastructure may have suffered damage. In this paper, we demonstrate the concept of hybrid cellular mobile ad hoc network (hybrid cellular-MANET) to extend wireless coverage by showing a fully functioning microblogging system for smartphones and tablets without requiring modifications of the existing wireless infrastructure in an emulated disaster area. Participating devices connect to each other through WiFi radio to form a hybrid cellular-MANET, relaying data off the MANET through the nodes that have sufficient cellular forwarding capability. We have proposed a self-organizing, mobility-aware, multi-path routing protocol (HMANET) to control the data forwarding in the hybrid cellular-MANET. We compare its performance with the classic Hybrid Wireless Mesh Protocol (HWMP) used in the IEEE 802.11s standard in the built microblogging system. Our experimental results show that the HMANET protocol statistically outperforms the HWMP protocol in terms of adaptiveness to role change and mobility in the hybrid cellular-MANET.**

***Index Terms*—hybrid cellular-MANET; microblogging system; disaster area; wireless coverage extension**

I. Introduction

The importance of mobile communications is well recognized in our society. However, the coverage to wireless devices can be inadequate due to a variety of shortage and outage circumstances. In disaster situations, such as search and rescue for victims of hurricanes, earthquakes, or tsunamis, network access to the outside world is critical for information dissemination, resource allocation, and rescue command and control. However, local wireless infrastructure may have been damaged, which causes serious communication issues for mobile devices in the disaster area.

A hybrid cellular mobile ad hoc network (hybrid cellular-MANET) [1] can be used to address the above coverage problem, in which wireless devices can connect to each other through WiFi interfaces without the dependence on the wireless infrastructure, e.g., WiFi Access Points (APs) or base stations, and the participating devices that have strong access to wireless infrastructure and sufficient battery charge level can relay data of other devices to destinations off of the MANET.

There are several major challenges for designing such a hybrid cellular-MANET, among others. First, the system must be adaptable to topology changes in the network, caused by the mobility of the devices. Second, the system must efficiently utilize the available communication and battery energy resources of the whole network. Third, the system should not require modifications of the existing wireless infrastructure, because of the difficulty of deploying wireless infrastructure in a disaster area in a timely manner.

Several primitive hybrid architectures have been proposed for integrating the MANETs and cellular networks. However, there are various limitations that make them impractical when directly used to provide communication solutions between the nodes in the hybrid cellular-MANET and the hosts in the Internet. Some architectures have not provided networking layer data forwarding solutions, see, e.g., [2], [3], [4], while a few others use additional ad hoc relay stations, see, e.g., [5].

We have designed a self-organizing, mobility- and energy-aware, muti-path routing protocol, which we refer to as HMANET in this paper, to address the aforementioned challenges in the hybrid cellular-MANET [6]. HMANET contains a baseline routing component which generates an effective connectivity graph for an energy-aware routing component that controls the data forwarding based on local information. The baseline routing contains a locally reactive routing sub-component based on the device's built-in accelerometer to handle mobility.

To demonstrate the concept of utilizing the hybrid cellular-MANET to extend wireless coverage and evaluate the performance of its data forwarding mechanism, we build a microblogging system for smart devices in a disaster area based on Android and Weibo APIs. People can install the corresponding Android application on smartphones and tablets, use it to form a hybrid cellular-MANET, and perform microblogging activities in areas with inadequate wireless coverage. Indeed, recent research has showed that people in a disaster situation may rely heavily on microblogging services such as *Twitter* [7] and *Sina Weibo* [8] for communicating with the outside world. This type of short-text dominant communications is preferable in the bandwidth (and/or energy) constrained environment. By using these services, people not only post continual information updates on their own status and the surrounding environment to the outside world for rescue-assisting and social-comforting purposes, but also retrieve periodic information updates from the outside world for selfrescue and emotion-easing.

In the built system, we compare the performance of our HMANET protocol with the classic tree-based proactive Hybrid Wireless Mesh Protocol (HWMP) adopted in the IEEE 802.11s standard [9] for controlling the data forwarding in the hybrid cellular-MANET. Our experimental results show that the HMANET protocol statistically outperforms the HWMP protocol in terms of adaptiveness to the role change and mobility in the network.

The rest of the paper is organized as follows. Section II describes the system design of the self-organizing hybrid cellular-MANET including its routing and data forwarding scheme. Section III describes the implementation details and the challenges of the microblogging system for smart devices in the disaster areas. Section IV presents the performance evaluation of self-organizing HMANET and tree-based proactive HWMP data forwarding protocols. Finally, Section V concludes the paper.

II. Hybrid Cellular-MANET Architecture

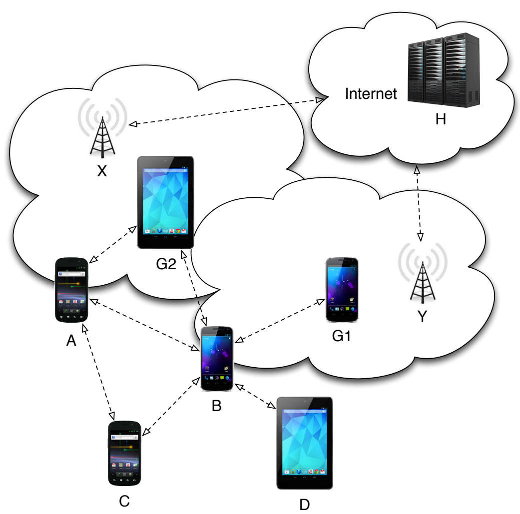

Fig. 1: Hybrid Cellular-MANET Architecture

Figure 1 shows the system architecture of the hybrid cellular-MANET [1]. Wireless devices are connected with each other through their WiFi interfaces. They individually determine their role based on their battery charge level and cellular forwarding capability. The devices such as $G1$ and $G2$ that have sufficient cellular forwarding capability and battery charge level will act as *gateway nodes*. They relay packets from other peers to the Internet. The devices such as A and B that have adequate battery charge level act as *relay nodes*. They relay packets for the devices such as C and D that have no or limited cellular access, i.e., *terminal nodes*, to the gateway nodes. Notice that a node can assume different roles at the same time. For instance, a terminal node can be a relay node as long as it has adequate battery charge level.

A. Role Determination

We register the callback functions for battery level and cellular signal strength in the mobile operating system of the participating devices. Each time their battery level or the cellular signal strength changes, the role determination function shown in Algorithm 1 will be called.

Algorithm 1 Function for Role Determination

```
Require: batteryLevel cellularSignalStrength
if cellularSignalStrength ⩽ CELL_POOR then
    terminalBit = TRUE;
else
    terminalBit = FALSE;
end if
if not relayBit and batteryLevel ⩾ 50% then
    relayBit = TRUE;
end if
if relayBit and batteryLevel < 30% then
    relayBit = FALSE;
end if
if not gatewayBit and batteryLevel ⩾ 70%
and cellularSignalStrength ⩾ CELL_GREAT then
    gatewayBit = TRUE;
end if
if gatewayBit and (batteryLevel < 50% or
cellularSignalStrength < CELL_GREAT) then
    gatewayBit = FALSE;
end if
```

We select two battery charge level thresholds for the role determination of relay (or gateway) nodes. The battery charge level of a non-relay (or non-gateway) node needs to be more than the higher threshold to make the node a relay (or gateway) node. When the battery charge level of a relay (or gateway) node drops below the lower threshold, the node no longer acts as a relay (or gateway) node. This mechanism is used to improve the utilization of the participating devices. In our implementation, we use 50% and 30% for the relay thresholds and 70% and 50% for gateway thresholds, but other threshold values can be used as well.

B. Routing

For data forwarding in the hybrid cellular-MANET, we have designed a self-organizing, mobility- and energy-aware, multi-path routing protocol HMANET [6]. It includes a locally reactive mechanism to handle mobility, based on hints inferred from the built-in sensors. The classic HWMP [9] used in the *802.11s* standard can also be used for data forwarding in the hybrid cellular-MANET. However, it does not contain mobility-handling and energy-aware components. We implement both routing protocols on actual devices and compare their performances by experiments.

1) Self-Organizing HMANET Protocol: HMANET includes a baseline routing component that generates an effective connectivity graph for the participating devices, and an energy-aware multi-path routing component for data forwarding on this effective connectivity graph. The Expected Transmission Number (ETN) is used as the link metric.

In the upstream baseline routing, we assume that the gateway nodes are connected to a virtual destination d in the Internet. The gateway nodes announce their existence and initialize a distance-vector routing algorithm. During this process, each node is able to find the shortest paths to d. To enable multi-path data forwarding, each node keeps track of those neighbors who have a closer shortest path to d.

In the downstream baseline routing, each node keeps track of downstream path ETN values for nodes from whom it receives their upstream data packets. A node i only announces the downstream ETN of a node k to a neighbor j, if it forwards upstream packets from k to j. To enable multi-path data forwarding, the node j maintains a set of neighbors who have a closer shortest path to the node k. This design builds a sub-graph for downstream data forwarding during the upstream data forwarding process, which incurs much less overhead comparing to a distance-vector algorithm.

To handle mobility, HMANET includes a locally reactive routing scheme that will be initialized by the moving node. This scheme updates ETN values in the group that consists of the moving node itself and the neighbors it encounters during traveling. A moving node asks all of its neighbors to announce their ETN values to other nodes in the group. Each node then updates its local ETN values based on the received announcements. Movement of a device is detected based on the hint inferred from the built-in accelerometer sensor [10].

2) Tree-based HWMP Protocol: HWMP is a hybrid routing scheme that contains two component. An AODV-inspired reactive component is designed to establish P2P communication amongst regular mesh points like classic MANET protocols. A tree-based proactive component is developed to build routes between regular mesh points (in terms of hybrid cellular-MANET, the terminal nodes) and root mesh points (in terms of hybrid cellular-MANET, the gateway nodes).

There are two modes in the tree-based component of HWMP. The *proactive PREQ mechanism* lets gateway nodes periodically broadcast *path request messages (PREQs)* to the entire network. During this process, other nodes are able to find paths toward the gateways. The *Proactive Path Reply* flag contained in a PREQ determines whether a *path reply message (PREP)* should be unicast from the received node to the gateway in order to establish bi-directional communication. If this flag is not set, the received node sends a proactive PREP to the gateway before sending the first data packet and during the entire communication period.

Unlike the 2-way handshake process in the *proactive PREQ mechanism*, the *proactive RANN mechanism* uses a 3-way handshake mechanism. Gateway nodes periodically broadcast *root announcement messages (RANNs)* to the entire network to distribute the next hop information toward them. However, this process does not update the routing tables of other nodes. When they need to communicate with the gateways, they unicast PREQs to the gateway and start data communication after receiving the corresponding PREP messages.

In HWMP, the established routes and known gateways in local routing tables time out after not receiving the corresponding control packets. If a link breaks in a dynamic hybrid cellular-MANET, the node that detects the link break generates a *path error message (PERR)* and sends it backward to the precursors of all paths that contain this link. A node that receives this message removes the broken path in its routing table. If this node cannot find alternative paths, it will initialize a global path discovery procedure as in AODV.

III. Prototyping and Implementaion

To demonstrate the concept of hybrid cellular-MANET and evaluate its performance in actual smartphones and tablets, we build an Android application that enables people in areas with inadequate coverage to communicate with the outside world through microblogging. We implement both HMANET and HWMP protocols as an Android service that runs in the background with a high priority for data forwarding in the network. Figure 2 shows its user interface.

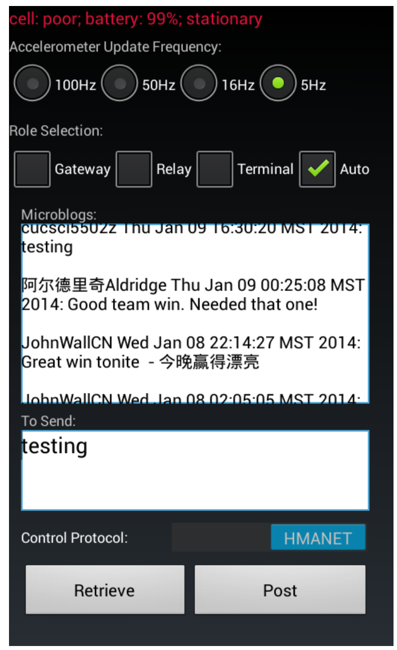

Fig. 2: Hybrid Cellular-MANET Application Screenshot

A. Role Selection

Algorithm 1 is implemented for the users that choose the "Auto" option in role selection. It is based on Android APIs of battery status and cellular signal strength. The users can also manually choose their role based on their willingness to participate as follows after disabling the "Auto" option:

Terminal — With this option, the node will communicate with Internet through the relaying of other nodes, regardless of its own cellular forwarding capability.

Relay — With this option, the node will relay packets for other nodes regardless of its own battery charge level.

Gateway — With this option, the node will relay packets of other nodes off the MANET.

B. Movement Detection

Movement detection is a critical component to enable HMANET to respond to mobility. During the movement of a device, its locally reactive routing scheme will be carried out amongst the group that consists of the moving node and its encountering neighbors. Once the application detects that the device becomes stationary, the locally reactive routing will be suspended.

We borrow the idea of *movement hint* from Ravindranath et al. [10] to detect the movement and stabilization of a device. We choose this movement detection mechanism over GPS based on three considerations: (1) precision: GPS requires the user to change location. However, change of device orientation in the same place might already have changed the wireless link quality. The movement detection mechanism is more responsive to this type of scenario; (2) availability: GPS requires the reception of satellite signal, while the movement detection mechanism only needs local calculation; and (3) energy-efficiency: the accelerometer of a smartphone or tablet usually stays on in order to provide functionalities such as detecting rotation of the screen. In addition, GPS consumes more battery energy.

The users can manually select the acceleration sample rate. There are four levels at 5Hz (the frequency suitable for detecting screen orientation changes), 16Hz (the frequency suitable for the Android user interface), 50Hz (the frequency suitable for mobile gaming), and 100Hz (the maximum sample rate). Based on preliminary experiments, we find that 16Hz is the best rate to keep the movement detection mechanism moderately sensitive.

C. Phone-to-Phone Communication

WiFi-Direct and WiFi ad hoc are the two mainstream mechanisms to enable phone-to-phone communication in a MANET. Both mechanisms do not require the WiFi interface to operate in the WiFi infrastructure mode. This makes the data forwarding of gateway nodes possible, since the mobile operating system will shut down the 4G/LTE interface if the infrastructure mode of the WiFi interface is on.

WiFi-Direct [11] is designed for connecting groups of equipped devices. A device acts as a soft access point, i.e., *the P2P Group Owner (P2P GO)*. Other neighboring devices act as *P2P Clients* to form a communication group. The process of role negotiation and group formation requires user interaction and can take up to 2 minutes. Once the group is formed, WiFi-Direct has advantages of high throughput, long range communication, and energy-efficiency. However, a P2P Client can only connect to one P2P group, and the transferring of the role of P2P GO within a P2P Group is prohibited. This brings scalability issues to the hybrid cellular-MANET.

WiFi-Direct has been integrated into Android operating systems since Android 4.0. Initially, it was built as a separate module from WiFi and 4G/LTE in Android 4.0. In Android 4.1 and above, using WiFi-Direct requires explicitly turning on the WiFi interface. This shuts down the 4G/LTE interface and makes forming a hybrid cellular-MANET impossible in these mobile operating systems.

WiFi ad hoc has been widely used in MANETs and Wireless Mesh Networks (WMNs). To deploy it in smartphones and tablets, the users need to have root privilege of the device. In addition, different Original Equipment Manufacturers (OEMs) may have different architectures to utilize *wpa_supplicant* functionality to control the WiFi interface, which makes it difficult to provide a globally applicable solution to enable phone-to-phone communication for different devices.

WiFi ad hoc is now available in CyanogenMod nightly builds [12] of various types of devices with updated kernel patches for the WLAN driver "bcmdhd". To avoid user interaction and scalability issues for setting up phone-to-phone communication, we flush 5 Google Nexus devices with these images, including Nexus 7 tablets and Galaxy Nexus / Nexus S phones. When initializing, our android application calls a shell script that first turns off the WiFi interface in infrastructure mode, and then inexplicitly sets up the WiFi ad hoc network by utilizing *iw* functionality on *wlan0* interface. By doing this, we also avoid the shutdown of the 4G/LTE interface by the mobile operating system.

D. Routing Implementation

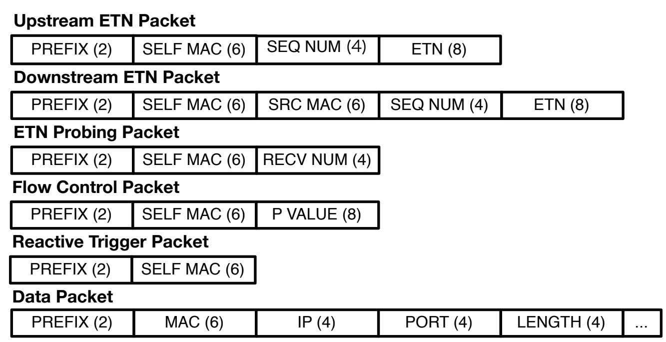

Fig. 3: Packet Format of HMANET Protocol

Figure 3 shows the packet formats of the HMANET protocol. The data packet size is 512 bytes. The number of octets for a field in a packet is shown in parentheses. The upstream ETN packet and the downstream ETN packet are used by the baseline routing component to build an effective connectivity graph in a self-organized manner. The flow control packet is used by the energy-aware component to inform neighbors of the current node congestion price from the flow conservation of a node. The upstream IPv4 data packet and the downstream IPv4 data packet are used for data communication between the nodes in the hybrid cellular-MANET and the hosts in the Internet.

We select ETN as the link metric in both the HMANET and the HWMP protocols. It incorporates the effect of asymmetry in the loss ratios between both directions of each link, which is useful for the downstream data forwarding of the HMANET protocol. The procedure proposed by De Couto et al. [13] is implemented to measure the ETN value of a link using ETN probing packets.

The reactive trigger packet is used to trigger locally reactive routing when a node detects its movement. When a gateway changes to other roles, this packet is also used by the gateway to request neighbors to provide alternative upstream routes.

In the user interface, people can manually switch the routing protocol between HMANET and HWMP. The hybrid cellular-

MANET Application will select the corresponding background Android services to control the data forwarding of the installed device.

E. Microblogging Functionality

As shown in Figure 2, people are able to post and retrieve microblogs. We select *Sina Weibo* as the microblogging service provider and implement the microblogging functionality based on its APIs.

Weibo users need to first authenticate the application before it can post and retrieve microblogs for them. After this process, an access token is generated for the application. The application only needs to use this access token as a log-in to perform the posting and retrieving action. Based on security concerns, we cannot let terminal nodes send the access token to gateway nodes. In that case, intermediate nodes are able to forge microblogs of terminal nodes using the obtained access token.

We create a virtual server on the cloud, which will take the responsibility of posting and retrieving microblogs for all the nodes in the hybrid cellular-MANET. After obtaining the access token, the device and the server exchange their public keys over secured channels, the device also sends its *Weibo access token* to the server. Once a node in the hybrid cellular-MANET wants to post a message, it digitally signs this message with its private key and sends it to the server through the relay of intermediate nodes. After verification, the server posts the message for the node using its access token. Once a message from Weibo arrives at the server, it also digitally signs the message and sends it to the corresponding terminal nodes through the relay of intermediate nodes.

IV. Performance Evaluation

We install the hybrid cellular-MANET Android application on Google Nexus devices and use them for real-time microblogging. We aim to demonstrate the concept of the hybrid cellular-MANET by showing a fully functioning microblogging system, and comparing the performance between the proposed self-organizing HMANET protocol and the classic tree-based proactive HWMP protocol in an actual environment that emulates a disaster area in terms of wireless communications.

A. Scenario

We use 5 Google Nexus devices for the experiment. Each device is carried by a different person. The group hikes in a mountain area with sporadic loss of telecommunication service, and post and retrieve microblogs to communicate with the outside world. Two hikes are performed with different data forwarding protocols, i.e., HMANET and HWMP. Each hike takes about 1.5 hours and on average 0.23 microblogs per minute are posted by each person. During the hike, the devices change their role in the hybrid cellular-MANET based on their own battery charge level and cellular signal strength.

Even though our experiment is performed with a small network, there are several advantages in our design that make the system scalable. First, based on security consideration in Section III-E, we move the energy-demanding Weibo posting and retrieving actions from the mobile application installed on devices (e.g., nodes $A - G2$ in Figure 1) to a virtual server (e.g., the server H in Figure 1) in the cloud. In other words, the server H acts as a proxy that takes the responsibility of performing HTTP interactions with the Weibo system for devices in the hybrid cellular-MANET. This reduces major energy consumption of the devices.

In addition, as demonstrated by Shu et al. [14], the energy consumption of transmitting a fixed amount of data is inversely proportional to the available bandwidth, and the data arrival rate in microblogging like mobile applications is mainly determined by the number of a users' peers. In our system, we only use gateway nodes which have sufficient cellular networking bandwidth to communicate with the virtual server, and as the network becomes larger, more gateway nodes become available.

B. Adaptiveness

In our implementation, both HMANET and HWMP protocols use ETN as the link metric. When they initially converge, they generate similar effective connectivity graphs. However, their mechanisms for handling changes in the hybrid cellular-MANET are different.

Admittedly, the microblogging service is a delay tolerant service. People may not retrieve updates all the time. In addition, there is often a time interval between two consecutive browsing actions. Comparing to the time for HTTP interactions between the virtual server and *Sina Weibo*, the delay of UDP data forwarding inside the hybrid cellular-MANET is negligible.

However, the underlaying HMANET and HWMP protocols maintain the devices' connectivity to the Internet. We evaluate their adaptiveness in terms of the time it takes for them to initially establish connectivity to the Internet, and the time for re-establishing connectivity after changes take place. Notice that the time we report here is the delay that is experienced by the microblogging application on each device.

We select the proactive PREQ mechanism with the Proactive Path Reply flag set in HWMP. In this mode, HWMP is most responsive to changes in the network. The following three scenarios are examined with protocol parameters set as in Table I, and the results are listed in Table II.

Parameter	**Value**
HMANET Upstream ETN Interval	1s
HMANET ETN Probing Interval	1s
HMANET Flow Control Interval	25ms
HWMP Gateway PREQ Interval	1s
HWMP Path and Gateway Timeouts	5s
HWMP PERR Minimal Interval	0.1s

TABLE I: Parameters of HMANET and HWMP Protocols

1) Initialization Time: In this scenario, we compare the time it takes for the nodes that join the hybrid cellular-MANET to establish connectivity to the Internet under the HMANET and HWMP protocols. The 95% confidence intervals are calculated of the time between when a user starts

	HMANET			HWMP		
	Upper	Mean	Lower	Upper	Mean	Lower
Initialization	1001.30 ms	869.33 ms	737.37 ms	1522.96 ms	928.33 ms	333.71 ms
Role Change	652.85 ms	407.10 ms	161.35 ms	1117.58 ms	890.45 ms	663.32 ms
Movement	150.69 ms	139.60 ms	128.51 ms	413.73 ms	300.20 ms	186.67 ms

TABLE II: The 95% Confidence Intervals for Response Times

the application and when the local routing table converges. We see that their confidence intervals overlap. This indicates the self-organizing HMANET protocol can achieve similar convergence performance for network initialization as the proactive tree-based HWMP protocol.

2) Adaptiveness to Role Change: In this scenario, we compare the time it takes for the nodes under the HMANET and HWMP protocols to re-establish connectivity to the Internet after certain gateway and relay nodes change their roles. The 95% confidence intervals are calculated of the time between when a node loses Internet connectivity due to a role change in the network and when this same node establishes new routes to communicate with the the host in the Internet. We see that HMANET statistically outperforms HWMP. When a node changes its role, with HMANET it immediately sends a reactive trigger packet to its neighbors in order to ask for new routes to update the corresponding routing table entries. With HWMP, a node needs to first wait for the detection of a broken link and the timeout of the gateway, and then initialize the reactive path discovery procedure if necessary.

3) Adaptiveness to Movement: In this scenario, we compare the time it takes for the nodes under the HMANET and HWMP protocols to re-establish connectivity to the Internet after certain nodes move. The 95% confidence intervals are calculated of the time between when a node loses Internet connectivity due to movement in the network and when this same node obtains new routes to communicate with the host in the Internet. Notice that movement can change the ETN of a path, break an existing link, create a new link, and change the role of a node.

We see that HMANET statistically outperforms HWMP in this scenario as well. With HMANET, when a node moves, its movement detection component detects the change and the reactive trigger packet is immediately sent in order to initialize the locally reactive routing. The neighbors that are encountered by a moving node update their routes correspondingly. This is different from HWMP where the nodes need to wait for the detection of a broken link before initializing a globally reactive path discovery procedure. We also see that the confidence intervals of HWMP for the role change scenario and the initialization scenario overlap. This indicates that the adaptiveness of HWMP in both scenarios is similar due to the same handling mechanism.

V. Conclusion

We have presented a fully functioning microblogging system for smart devices, to demonstrate the concept of hybrid cellular-MANET for extending wireless coverage without the modification of the existing wireless infrastructure in a disaster area. For this system, we have designed a self-organized, mobility-aware, multi-path routing protocol for data forwarding in the hybrid cellular-MANET, and compared its performance with the classic tree-based proactive HWMP protocol adopted in the IEEE 802.11s standard. The results from real experiments show that the proposed routing scheme statistically outperforms HWMP in terms of adaptiveness. Admittedly, the current WiFi ad hoc mechanism for phone-to-phone communication requires flushing of the device; we plan to improve this component in the future.

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