A Software-Defined Device-to-Device Communication Architecture for Public Safety Applications in 5G Networks

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***Abstract*—The device-to-device (D2D) communication paradigm in 5G networks provides an effective infrastructure to enable different smart city applications like public safety. In future smart cities, dense deployment of wireless sensor networks (WSNs) can be integrated with 5G networks using D2D communication. D2D communication enables direct communication between nearby user equipments using cellular or ad-hoc links, thereby improving the spectrum utilization, system throughput, and energy efficiency of the network. In this paper, we propose a hierarchal D2D communication architecture where a centralized software-defined network (SDN) controller communicates with the cloud head (CH) to reduce the number of requested LTE communication links, thereby improving energy consumption. The concept of local and central controller enables our architecture to work in case of infrastructure damage and hotspot traffic situation. The architecture helps to maintain the communication between disaster victims and first responders by installing multi-hop routing path with the support of the SDN controller. In addition, we highlight the robustness and potential of our architecture by presenting a public safety scenario, where a part of the network is offline due to any disaster.**

***Index Terms*—Software–Defined, 5G networks, D2D, WSN, smart cities, public safety, device discovery, spectrum efficiency, energy efficiency**

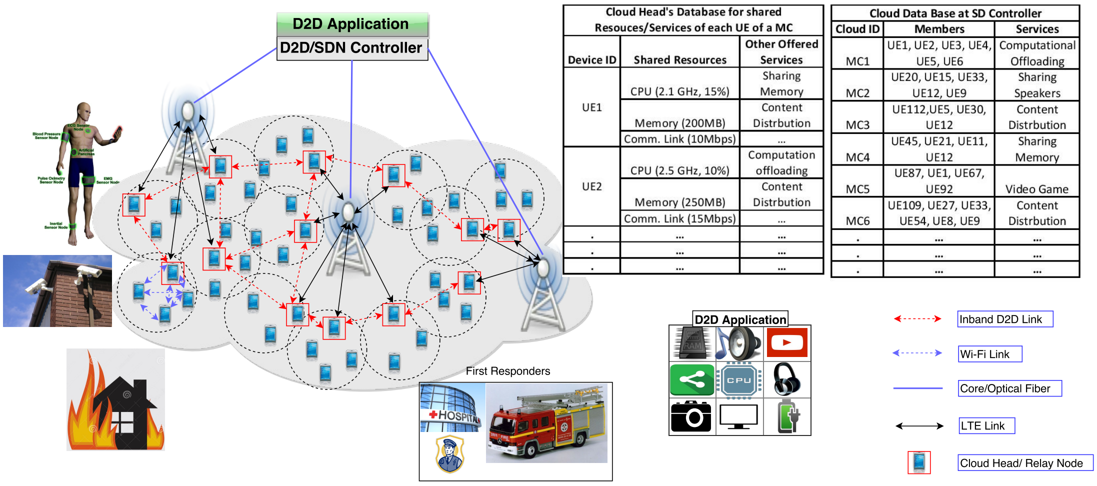
I. INTRODUCTION

The exponential increase in number of cellular devices and traffic volume in combination with the looming spectrum crunch represents undoubtedly the primary challenge for the fifth generation (5G) networks. Therefore, 5G networks intend to combine radical solutions to assure more capacity, lower latency, and higher reliability [1], [2]. Such solutions include several emerging technologies such as Network Function Virtualization (NFV), Software-Defined Networking (SDN), massive MIMO and Device-to-Device (D2D) communication. D2D communication represents one such technology that can potentially solve the capacity bottleneck problem of legacy cellular systems. This new paradigm enables direct interaction between nearby Long Term Evolution (LTE) based devices, minimizing the data transmissions in the radio access network. By doing so, it provides several benefits. First, direct communication can offload data from the treasured spectrum to out-of-band technologies (i.e., WiFi, Bluetooth, etc.), improving spectral efficiency. Second, data rates and coverage can be increased for devices lacking direct access to the cellular infrastructure. Third, higher energy efficiency can be achieved due to close proximity of devices requiring lower transmission powers. To fully realise these benefits in practice, the architecture for D2D communication should be flexible and powerful to meet needs of commercial cellular scenarios as well as public safety applications.

The convergence of public safety applications with the commercial cellular networks poses a major problem in defining the D2D communication architectures. This is due to more stringent requirements of public safety applications, like for example, high service reliability with ultra-low delays. Even when cellular infrastructure becomes overloaded or partially unavailable (e.g., in case of extra-ordinary events such as disasters or terrorist attacks), basic communication services should still be made available to public safety agencies such as police and paramedics. Furthermore, these networks should incorporate mechanisms to seamlessly integrate with emerging technologies designed to further enhance public safety such as Wireless Sensor Networks (WSNs).

In this paper, we propose an SDN architecture for supporting D2D communication, which meets the above-mentioned requirements of public safety applications as well as commercial cellular scenarios. First, we exploit D2D communication to build mobile clouds, a powerful concept that enables diverse services for a wide variety of applications such as proximity-based social networking (e.g., online gaming, video streaming), advertisements for by-passers, public safety (devices provide at least local connectivity in the case of damage to the radio infrastructure), intelligent vehicle communication, and efficient content distribution. Second, we build our architecture on top of public safety enhancements for LTE standardized by the Third Generation Partnership Project (3GPP) as Proximity Services (ProSe) and Group Call System, assuring inter operability across different public saftey applications.

The basic idea behind the proposed architecture is to associate a D2D controller application to a hierarchy of SDN controllers in the network, in such a way to couple the formation and management of the mobile clouds of devices with the centralized control, resource allocation and routing features of SDN. To make our architecture scalable, we design it to be hierarchical in nature, placing SDN controllers locally to the mobile cloud as well as globally in the core network. This choice makes the process of cloud formation scalable and energy efficient and robust to cellular infrastructure failure.



Cloud Head's Database for shared Resouces/Services of each UE of a MC

Device ID	Shared Resources	Other Offered Services
UE1	CPU (2.1 GHz, 15%)	Sharing Memory
	Memory (200MB)	Content Distrbution
	Comm. Link (10Mbps)	...
UE2	CPU (2.5 GHz, 10%)	Computation offloading
	Memory (250MB)	Content Distrbution
	Comm. Link (15Mbps)	...
.	...	...
.	...	...
.	...	...

Cloud Data Base at SD Controller

Cloud ID	Members	Services
MC1	UE1, UE2, UE3, UE4, UE5, UE6	Computational Offloading
MC2	UE20, UE15, UE33, UE12, UE9	Sharing Speakers
MC3	UE112,UE5, UE30, UE12	Content Distrbution
MC4	UE45, UE21, UE11, UE12	Sharing Memory
MC5	UE87, UE1, UE67, UE92	Video Game
MC6	UE109, UE27, UE33, UE54, UE8, UE9	Content Distrbution
.	...	...
.	...	...
.	...	...

Fig. 1. The proposed Software-Defined D2D communication architecture for public safety applications

The cloud formation process is divided in two phases. In the first phase, a UE initiates formation of mobile cloud by broadcasting a request to the nearby devices by using an out-of-band technology e.g., Wi-Fi Direct, Bluetooth etc. Based on the information received from the responding UEs, a mobile cloud is formed and it is registered at a global SDN controller. In the second phase, the central SDN controller will have a global view of all served clouds with the services they offer. At this point, the global controller will be able to setup the clouds upon users requests. The SDN controller has also a visibility of link qualities between UEs/CHs and residual batteries, which it can use to compute routing paths between the CHs.

Moreover, this architecture is applicable to a wide range of scenarios. We highlight its robustness with a public safety scenario presented in Section IV.

The rest of the paper is organized as follows. We provide a short summary of related work in Section II. The system architecture is presented in Section III. Section IV discusses a possible scenario targated by our architecture. Section V concludes the paper highlighting the future directions.

II. RELATED WORK

In literature, various architectures are proposed for D2D communication in cellular networks. In [3], Hassan et al. propose a D2D-based mobile cloud architecture, where mobile cloud coverage area is divided into clusters (logical regions) of UEs and comprises of a primary cluster head (PCH), a secondary cluster head (SCH) and standard UEs. PCH and SCH, which are chosen based on the residual energy and SINR of the UEs as well as multicast information to the UEs of their respective clusters. The architecture provides an energy efficient solution for a single eNB. However it does not allow extension of coverage area beyond a single cell, making it less ideal for public safety applications.

Mass et al. [4] propose a mobile cloud system that implements device discovery based on the audio data obtained from the user environment. This centrally controlled cloud system follows client-server architecture, where clients (UEs) send synchronized time series recordings to the server that runs a clustering algorithm on the time series in order to group them based on their audio similarity. Such a complex algorithm is neither energy-efficient nor scalable, as all clients have to be continuously synchronized with a single server through the cellular interface.

Some of the ideas proposed in the literature are analogous to our work and can also be used in our proposed architecture. Satyanarayanan et al. [5] propose cloudlets to describe resource rich computing environment located at the edge of the network and in the proximity of mobile users. The UEs can use this environment to offload computations and execute virtualized tasks. Wu et al. [6] propose FlashLinQ, a synchronous OFDM based system, to perform device discovery, channel allocation and link scheduling in the licensed spectrum. The distributed channel allocation in licensed spectrum is claimed to provide significant gain over conventional IEEE 802.11 systems.

Our mobile cloud based architecture provides several advantages over state-of-the-art solutions:

- **Scalability:** The mobile clouds and hierarchical controllers make our architecture very scalable. The cloud heads control the nearby UEs and transmit their aggregated information to the central controller, reducing the number of LTE links and improving scalability.
- **Energy and spectral efficiency** Since the number of LTE links is reduced by exploiting the aggregated information of cloud heads, the UEs communicate with each other using Wi-Fi links (shorter range; low transmit power). This improves the overall energy and spectral efficiencies of the network.
- **Robustness:** In case of disaster and traffic hotspot situation, the UEs are still able to communicate with partial support from cellular infrastructure, making the architecture reliable and robust. UEs outside the cellular coverage

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will be served by UEs inside the cellular coverage.

- **Interference reduction:** The central controller has the global view of the network by managing multiple eNBs (as in [8]). Such global view enables the interference reduction between neighboring eNBs and allows UEs to participate in multiple clouds.

III. THE SOFTWARE-DEFINED D2D ARCHITECTURE

Fig. 1 shows a schematic diagram of our D2D architecture for public saftey applications. Each UE runs a D2D application, using a hierarchical approach to create mobile cloud on demand. The central D2D/SDN controller that resides in the Internet has a global view of all mobile clouds in its range, while the local controllers (cloud heads) are aware of UEs only in their neighborhood. Each SDN controller serves a number of eNBs depending on the deployment.

Our architecture also enables a UE to participate in multiple mobile clouds providing different resources/services. This raises two important issues that need to be considered:

- The operations belonging to different mobile clouds should be isolated from each other with no ability whatsoever to affect each other, a primary goal for *virtualization*.
- Given heterogeneity across different applications requiring different Quality of Service (QoS), SDN controller should be able to dynamically *allocate resources*. For example, let us consider that one of the mobile cloud provides services for file transfer and the other one for video conferencing. In such situations, we need to deploy a dynamic resource allocation scheme that will take into account the service requirements with the final goal of achieving an improved network performance in terms of better spectrum utilization and/or a better network throughput.

Signaling for Cloud Formation: Fig. 2 describes the formation and the operation of the mobile clouds. The initiator broadcasts a request of cloud formation over the Wi-Fi interface. The mobile devices in the vicinity, interested in sharing such service, respond with their resources/services. The SDN application in each mobile device maintains a database of all services and resources that a mobile user is willing to share. Once a cloud formation request is received from an initiating UE, all interested UEs share the complete database with the initiator. The initiator shares this database with the central SDN controller. The SDN controller registers the mobile cloud and assigns an authentication key to the cloud. The initiator then unicasts the authentication key to each UE, securing it from any malicious attack. Once the cloud is formed, devices can communicate for the rest of their operation, unless the cloud head sends a termination request.

Energy and Spectral Efficiency: The SDN controller maintains a database of all mobile clouds, saving identities of individual UEs and their sharable services. In case of resource sharing services, the details of resources is also stored in the SDN database. Once the database is fully populated, the central controller can form clouds without involving local controllers and save energy. Inaddition, using outband D2D links in mobile clouds improves the spectal efficiency of the network. Moreover, any service change of a UE will be updated to the SDN controller over the LTE interface.

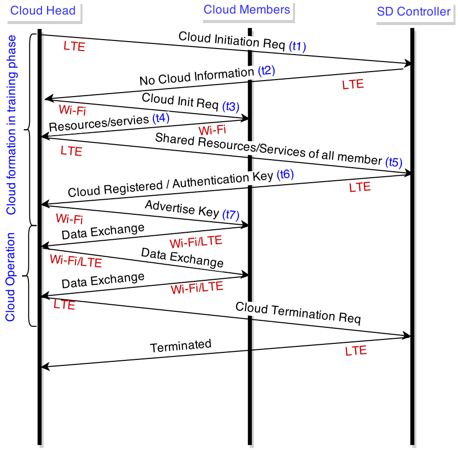


Fig. 2. Description of signaling for cloud formation

Scalability: There are several studies concerning the design and implementation of controllers (e.g., centralized, distributed, hierarchical, etc.), where each has its own advantages and disadvantages. However, the hierarchal architecture better fits our needs in a way that it helps to address the problems of scalability and efficient resource utilization by lowering the communication load with the central controller. The distribution of different functionalities to different levels of the controllers (i.e., local and central) enables to reduce unnecessary communication with the higher-level controllers, which use the scarce radio resources (i.e., LTE spectrum). For example, the local controller (initiator/cloud head) can independently enable and or disable clouds without involving the central-controller.

In addition, the hierarchical architecture is very convenient for scalability. The number of devices participating in a cloud can increase as far as the processing capacity of the Cloud Head (CH) is not reached. The Channel Quality Information (CQI) of the UE determines the selection of the CH, i.e., the UE should be in better signal condition. Moreover, the flexibility of having local decisions carried out by local controller enables each cloud to work in a distributed manner.

Based on the above contributions (i.e., saving resources in terms of spectrum), our architecture is applicable to a wide range of applications that are an integral part of 5G networks, e.g., in public safety.

Coverage and Interoperability: Proximity services [7] include features to discover devices in physical proximity and enable an optimized communication between them. Proximity services offer two functions: the network-assisted discovery of users in a close proximity and the facilitation of direct communication between such users with or without supervision from the network (see Fig. 3). Proximity services also extend normal network coverage area. If a User Equipment

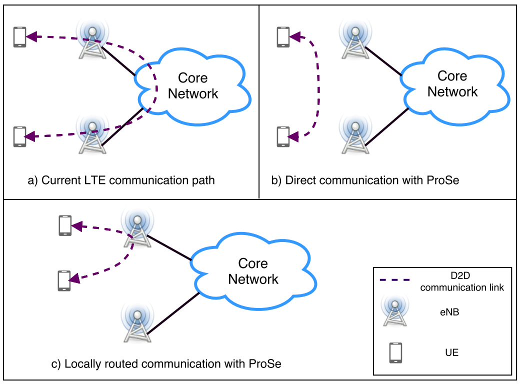


Fig. 3. Examples of Proximity Services

(UE) is outside the cellular coverage, it can, through another UE, relay its traffic to a base station (eNodeB) or to a different UE. The former is termed as User Equipment to Network Relay feature, while the later is called User Equipment to User Equipment Relay feature. Notably, in User Equipment to User Equipment Relay feature, the traffic does not even traverse the cellular network and yet it can reach the intended destination or at least a location closer to it. In addition to the extended network coverage provided by ProSe, public safety devices need to communicate in groups. Therefore, the LTE Group Call System provides and optimizes concurrent communication between multiple groups. In addition, it describes appropriate group management and control facilities.

IV. PUBLIC SAFETY SCENARIO

In future smart cities there will be a dense deployment of WSNs ranging from water reservation to public safety and health care. These WSNs should be seamlessly integrated with future 5G networks. Our architecture for D2D communication in 5G networks makes this integration straightforward and simple. The concept of local and central SDN controllers assists our architecture to work in case of infrastructure collapse also. In a smart city where most of the people have body sensors to frequently check the body health status such as blood pressure, glucose level and heart beat etc. and send this information to the central hospital as a regular update, our architecture helps to maintain the communication between the body area WSNs and first responders to exactly locate the victims that are in critical condition and need immediate aid. This helps the first responder to prioritize their work in terms of health conditions of the disaster victims.

There can be many different kinds of WSNs that can aide first responders. Let us consider the WSN applications deployed in a large building for automation and indoor localization [8] that can report, in case of earthquake, the presence to injured persons under rubble. The first responders do not necessarily need the raw data from the sensors to decide their rescue plan. Instead, intelligence extracted and mined from the raw data is indeed more relevant and can potentially save lives. In our architecture, the processing and storage needs can be conveniently met locally by the mobile clouds without any involvement of the infrastructure, which might have already been damaged by the earthquake. This also allows us to offload most data traffic from the cellular spectrum, thus achieving energy and spectrum efficiency.

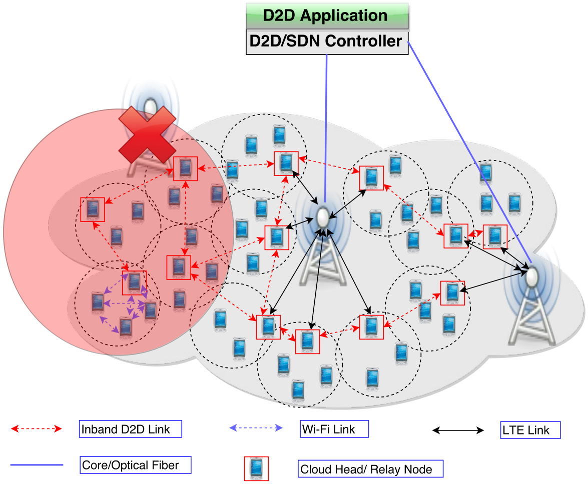
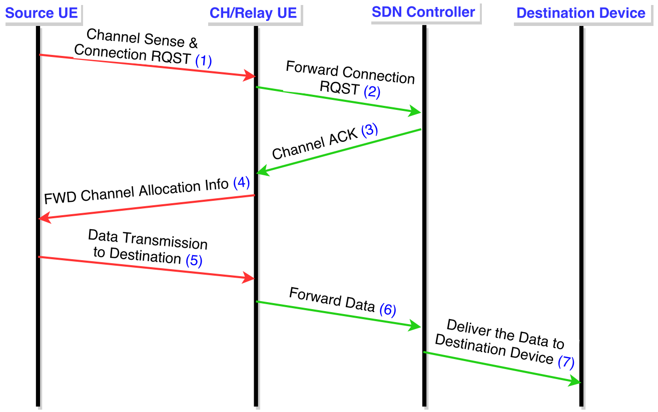


Fig. 4. Extending coverage area in case of disaster and traffic hotspot situation

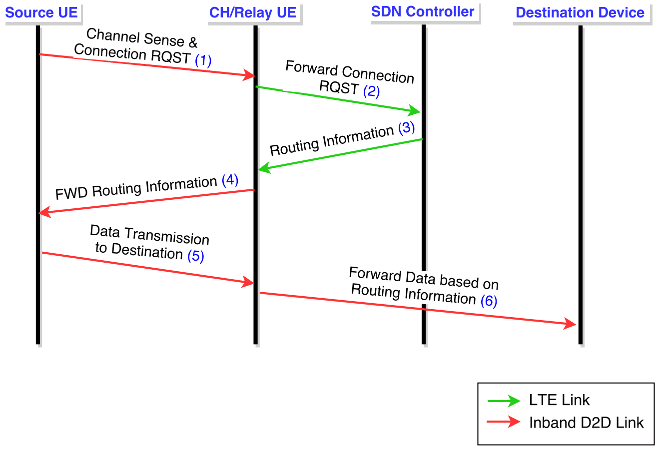
A. Scenario Description

In our architecture, the CH acts as a relay UE and communicates with other CHs using inband (i.e., the cellular and the D2D communications will be carried out in the same frequency band) D2D communication for reaching longer range. Fig. 4 presents a scenario where one of the base stations is collapsed, highlighted in red circle, due to a natural disaster. The mobile devices make a relay network to reach the nearest UEs inside the coverage area (User Equipment to Network Relay). The devices marked with a red boundary in figure act as relay to carry the information of out of coverage devices to the other part of the network. We can consider two cases: i) due to several resource requests from UEs, the network could be congested, ii) due to the disaster several devices try to get connected to the working eNB and result in congestion. In case of disaster all the out-of-coverage UEs try to reach the nearest base station using relay network. This flood of traffic from the out-of-coverage area of the network results in the congestion in the other area of the network due to the scarce resources available at the BS. Our architecture provides an efficient solution to that situation. The central SDN controller, having global information of all the devices in its range, can define a route in the UEs that are inside the coverage area using Dijkstra algorithm. The UEs in the out-of-coverage area can activate a multi-hop route to reach the connected cellular network. There are several studies concerning multi-hop ad-hoc communication in the literature. In this way, our architecture seamlessly integrates the public safety applications to cellular network without overloading it.

Our architecture is capable of integrating multiple smart city applications with 5G networks. For example, the mobile clouds



(a) Adequate resource available in eNB



(b) The eNB is fully loaded, computes a route information

Fig. 5. Signaling for multi-hop routing between cloud heads

in our architecture also meet the needs of processing and storage demands of WSNs, where raw data from sensors can be processed and sent to first responders to decide their rescue plan. WSNs installed for monitoring demand and supply of water tanks in a smart city can be seamlessly connected to water reservation authority to send periodic updates using multi-hop relay network.

B. Route Computation

Fig. 5 shows the possible signaling that could be performed for delivering the information from the source to destination in the cases that were discussed in subsection IV.A. The signaling shown in Fig. 5(a) is for the case when the target eNB have an adequate radio resources to entertain the incoming resource requests, whereby allocates cellular radio resources to the transmission, as shown in the signaling number [(1)-(7)]. Whereas Fig. 5(b) shows the signaling when the cellular network radio resource is completely depleted. In this case, the central SDN controller computes a route from the source (i.e., Relay UE) to the destination device using the inband D2D communication links between CHs and forwards the routing information to the Relay UE (i.e., as depicted by the signaling number (4)) . The computation of the routing information could be done using different routing algorithms, such as the Dijkstra's routing algorithm. Dijkstras algorithm finds the shortest paths between nodes (source and destination) in a graph traversing though the smallest link cost paths.

The link cost function could be defined as a function of device battery life, computational power, and channel quality indicator (CQI) (i.e., contributes to the physical data rate of the channel). Each of these parameters has direct proportionality with respect to the probability of selection of the link, as in (1), as a shortest path. That means, if the battery life of the device is high then the probability of this node being selected as the next hop of the route will be higher.

$$P_n \propto f(P_{comp}, L_{batt}, CQI) \ , \tag{1}$$

where P_n is the probability of selecting a link as a shortest path to the next hop (node), P_{comp} is the computational power of the device and CQI (a fuction of the recieved signal strength indicator (RSSI)) is directly related to the signal-to-noise (SNR) of the channel resulting a direct insite on the channel capacity of the link. Actually the link cost is defined as the inverse of P_n. From (1) we can further describe P_{comp} and L_{batt} in details respectively as shown below:

$$P_{comp} = vf^2 \ , \tag{2}$$

where v is the voltage (in volts) input to the processor of the device and f is the number of instructions executed per second.

$$L_{batt} = \frac{Battery\ capacity\ [mAh]}{Load\ current\ [mA]} \ , \tag{3}$$

The choice of the cost function depends on a predefined *priority*, where the device batter life (L_{batt}) is assumed to have the highest priority then the channel link quality and finally the computational power (P_{comp}) of the device. Based on these priorities the link cost is assigned to every edge that is connecting source node to the next hop such that facilitating the computation of the route information from source to destination.

Fig. 6 shows an example of route selection based on different cost functions. Let us assume that we want to find the shortest path from UE 1 to UE 4. We have two options, though UE 2 or UE 3. Relying on the priority of the cost functions that we defined earlier, the battery life of UE 2 is better than UE 3. Thus *Link 1* will be selected instead of *Link 2*. On the other hand, if both UEs (i.e., UE 2 and UE 3) have equal battery life, then the next parameter to be considered will be the computational power (i.e., CPU voltage and CPU frequency) of the devices.

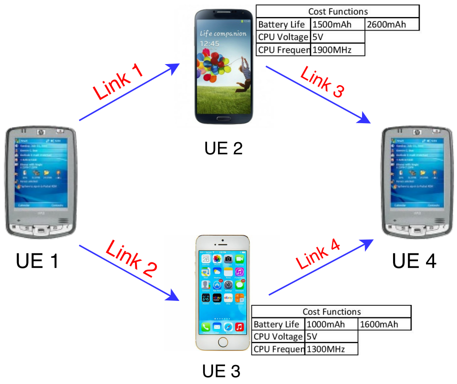


Fig. 6. Example of route selection for different cost functions

V. CONCLUSIONS

In future smart cities there will be a dense deployment of WSNs ranging from water reservation to public safety and the seamless integration of these WSNs with future 5G networks is an open issue. In this paper, we proposed a novel hybrid D2D communication architecture that is applicable to a wide range of applications. The central SDN controller has a global view of the network and consistently handles management of UEs belonging to different clouds. The local SDN controllers help to make our architecture scalable and infrastructure independent. In case of disaster and hotspot situations, the central controller can select multi-hop routing path between the disaster victims and first responder to maintain the communication between them. This helps first responder to exactly locate the victims that are in critical condition and need immediate aid. The mobile clouds in our architecture meet the needs of processing and storage demands of WSNs, where raw data from sensors can be processed and sent to first responders to decide their rescue plan. We are currently working towards simulating the above-mentioned scenario using the NS3 simulator to analyze the computational load incurred by the cloud heads.

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