

Multi-hop Device-to-Device Routing Protocols for Software-Defined Wireless Networks

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STATEMENT OF ORIGINALITY

I, Mahrokh Abdollahi Lorestani declare that this thesis, is submitted in fulfilment of the requirements for the award of the degree of doctor of philosophy, in the faculty of Engineering and Information Technology at the University of Technology Sydney. This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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ABSTRACT

Multi-hop device-to-device (MD2D) communications are an integral part of future wireless networks. Multi-hop communications enable mobile devices in close proximity to communicate directly or through multi-hop connections instead of traversing through a network infrastructure. This provides numerous benefits for cellular networks, such as low-cost communications, enhanced cellular coverage and capacity, reduced total power consumption in devices, and improved spectral efficiency. Consequently, service providers can leverage the advantages of both D2D and cellular networks to enhance the quality of their services. However, tight coupling of control and data functions in cellular equipment and the utilization of proprietary interfaces and protocols in existing cellular infrastructure make integration difficult and rigid. Hence, there is a need for open and reprogrammable frameworks to make the network more flexible and scalable. Software-defined networking (SDN) is a promising technology for future wireless networks that provides an open and reprogrammable framework wherein the control functions are taken from network devices and are logically centralized in a control entity. The open framework of SDN provides an opportunity for service providers to manage networks more intelligently and develop services in a more agile manner.

This thesis introduces an SDN-based framework for cellular networks, referred to as virtual ad hoc routing protocol framework (VARP), capable of developing different types of multi-hop routing protocols. In the proposed framework, an SDN controller determines the mode of communication for mobile devices (i.e., cellular or multi-hop modes). Two different multi-hop routing protocols are designed for the proposed framework: source-based virtual ad hoc routing protocol (VARP-S) and SDN-based multi-hop D2D routing protocol (SMDRP). In both protocols, a source of data packet sends a route request to the controller and receives the forwarding information from the controller in response. This thesis then presents a multi-protocol framework capable of developing multiple routing protocols under a single framework. In the proposed framework, an SDN controller logically divides a cell into multiple clusters based on its knowledge of the entire cell. The controller determines which multi-hop routing protocol can provide the best performance for each cluster. The simulation results show that the proposed multi-protocol framework provides better performance than traditional single-protocol architectures. Finally, the thesis presents a novel software-defined adaptive routing algorithm for multi-hop multi-frequency communications in wireless multi-hop mesh networks. The simulation results indicate that the proposed algorithm improves the end-to-end throughput of multi-hop connections by considering the sur-

rounding WiFi traffic and adaptive selection of frequencies and routes.

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To my lovely parents, Susan and Masoud

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LIST OF ABBREVIATIONS

1G	First Generation
1xEVDO	1x Evolution Data Optimized
1xRTT	1x Radio Transmission Technology
2G	Second Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AAA	Authentication, Authorization, and Accounting
AHP	Analytic Hierarchy Process
ALARM	A Location-Aware Routing Metric
AMPS	Advanced Mobile Phone System
AODV-ST	Ad-hoc On-demand Distance Vector Spanning Tree
AP	Access Point
ARIB	Association of Radio Industries and Businesses
ARS	Ad hoc Relaying Stations
ATIS	Alliance for Telecommunications Industry Solutions
ATSSS	Access Traffic Steering, Switching and Splitting
AUC	Authentication Centre
BATMAN	Better Approach To Mobile Adhoc Networking
BS	Base Station
BSS	Base Station Subsystem
BTS	Base Transceiver Station
CCSA	China Communications Standards Association
CDMA	Code Division Multiple Access
CI	Cellular Indicator
CN	Core Network
COTS	Commercial-Off-The-Shelf
CR-Id	Controller ID
CS	Circuit-switched
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D2D	Device to Device

DCF	Distributed Coordination Function
DIFS	Distributed Inter Frame Space
DRERR	Data Route Error
DRR	Data Route Record
DRREP	Data Route Reply
DRREQ	Data Route Request
DRREQI	DRREQ Intervals
DRREQT	Data Route Request Table
E2E	End-to-End
EDGE	Enhanced Data rates for GSM Evolution
EIR	Equipment Information Register
eNodeB	E-UTRAN Node B
EPC	Evolved Packet Core
ePDG	evolved Packet Data Gateway
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
ETT	Expected Transmission Time
ETX	Expected Transmission Count
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Mobile Telecommunications System Terrestrial Radio Access Network
EWT	Error Waiting Time
ExOR	Extremely Opportunistic Routing
FDMA	Frequency Division Multiple Access
FERR	Flow Error
FERR-WI	Flow Error Waiting Interval
FI-T	Flow Invalid Time period
FREQ	Flow Request
FREQT	Flow Request Table
FT	Flow Table
G-CE	Global Control Entities
GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Switching Centre
GPRS	General Packet Radio Service
GSM	Global System for Mobile communication
HLR	Home Location Register
HRFA	Hybrid Routing Forwarding Algorithm
HSAW	Hybrid SDN Architecture for Wireless distributed networks
HSS	Home Subscriber Server
HWMP	Hybrid Wireless Mesh Protocol
I²C	Inter-Integrated-Circuit

I²S	Inter-Integrated-Chip Sound
IB	Information Base
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronic Engineers
IMEI	International Mobile Equipment Identity
IoT	Internet of Things
L-CE	Local Control Entities
LE-WARP	Linux Enriched Wireless Open Access Research Platform
LLDP	Link Layer Discovery Protocol
LOLS	Localized On-demand Link State
LQSR	Link Quality Source Routing
LSDB	Link State Database
LTE	Long Term Evolution
LTE-A	LTE Advanced
LVAP	Light Virtual Access Point
M2M	Machine-to-Machine
MAC	Media Access Control
MADF	Mobile-Assisted Data Forwarding
MANETs	Mobile Ad-hoc Networks
MC	Mission Critical
MCDM	Multiple-Criteria Decision-Making
MD2D	Multi-hop Device-to-Device
MEC	Mobile Edge Computing
MeshDV	Mesh Distance Vector
MGW	Media Gateway
MIC	Metric of Interference and Channel-Switching
MIMO	Multiple-Input Multiple-Output
ML	Minimum Loss
MME	Mobility Management Entity
MMS	Multimedia Message Services
mmWave	millimeter Wave
MS	Mobile Stations
MSC	Mobile Switching Centre
N_hop	Next Hop
NC	Non-Critical
NFV	Network Functions virtualization
NMS	Network Management Server
NPT	Node Power Threshold
NSS	Network Subsystem
NT	Neighbour Table
ODL	Open Daylight

OFDMA	Orthogonal Frequency Division Multiple Access
OLSR	Optimized Link State Routing Protocol
ONF	Open Networking Foundation
P_hop	Previous Hop
PCEF	Policy Control Enforcement Function
PCRF	Policy and Charging Rules Function
PDN	Packet Data Networks
P-GW	Packet Data Network Gateway
ProSe	Proximity Service
PS	Packet-switched
PSK	Phase Shift Keying
PSTN	Public Switched Telephone Network
QoE	Quality of Experience
QoS	Quality of service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RA-OLSR	Radio-Aware Optimized Link State Routing
REST	Representational state Transfer
RG	Relay Gateways
RMS	Routing Method Selection
RNC	Radio Network Controller
ROMER	Resilient Opportunistic Mesh Routing
RPS	Routing Protocol Selection
RQA	Route Quality Assessment
RQAMS	Route Quality Assessment & Metric Selection
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indication
SAE	System Architecture Evolution
SDK	Software Development Kit
SDN	Software defined networking
SDR	Software Defined Radio
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SMDRP	SDN-based Multi-hop D2D Routing Protocol
SMS	Short Message Services
SNR	Signal to Noise Ratio
SOPRANO	Self-Organizing Packet Radio Ad hoc Network with Overlay
SPF	Shortest Path First
SPI	Serial Peripheral Interface
SPT	Shortest Path Tree
SVD	Singular Value Decomposition

TC	Topology Control
TCREQ	Topology Control Request
TDMA	Time Division Multiple Access
TSDSI	Telecommunications Standards Development Society
TTA	Telecommunications Technology Association
TTC	Telecommunication Technology Committee
UAV	Unmanned Aerial Vehicle
UCAN	Unified Cellular and Ad hoc Networks
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UnF	Unreachable Flag
URI	Uniform Resource Identifier
VANET	Vehicular Ad hoc Network
VARP	Virtual Ad hoc Routing Protocol
VARP	Virtual Ad hoc Routing Protocol
VARP-S	Virtual Adhoc Routing Protocol- Source-based
VLR	Visitor Location Register
VM	Virtual Machine
VN	Validity Number
VoIP	Voice-Over-IP
WARP	Wireless Open-Access Research Platform
WCDMA	Wideband Code Division Multiple Access
WCETT	Weighted Cumulative ETT
WiFi	Wireless Fidelity
WiMAX	Wireless interoperability for Microwave Access
WLAN	Wireless Local Area Networks
WMN	Wireless Mesh Networks
WMSC	WCDMA Mobile Switching Centre
WNS	Wireless Sensor Networks
WPR	Wireless-mesh-network Proactive Routing
WTPs	Wireless Termination Points
WWAN	Wireless Wide Area Networks

