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A Cross-Domain Optimization Scheme for MANET Communications in Heterogeneous Networks

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Abstract

In this paper, we propose a cross-domain optimization (CDO) scheme, which optimizes the MANET topology and enables communication between multiple MANETs via LTE. Particularly, we first deploy a gateway to the center of gravity of all nodes in each MANET so that the network topology is optimized. Thus, the aggregation cost of intra-MANET traffic in the gateway is improved. Likewise, we then deploy an eNodeB in the center of gravity of all gateways to establish communication connections between multiple MANETs via LTE. Then, the aggregation cost of inter-MANET traffic at eNodeBs can be largely reduced because of the minimization of the distances between eNodeBs and gateways, along with a significant performance improvement of inter-MANET communications owing to the superiority of LTE. Vis extensive simulations, we validate the effectiveness of our proposed scheme. Our experimental results demonstrate that the CDO scheme can greatly improve network performance. Finally, we discuss some other issues.

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1. Introduction

The Heterogeneous Network (HetNet), as illustrated in Fig. 1, is a wireless network consisting of various access technologies (LTE, WiFi, Zigbee, Bluetooth, etc.) and diverse wireless devices (smart phones, medical monitors, tablets, garage-door openers, TV remotes, etc.) [26, 32]. It has been widely adopted by network service providers (NSPs) to expand network coverage, boost network capacity, and enhance network performance (throughput, delay, packet loss ratio, etc.) [30]. Although seamless and reliable network service is provided to an extended region by integrating multiple network access technologies together into HetNets, unprecedented challenges, such as mobility management, network infrastructure shortage, etc., are still gradually coming up. This plague is caused by the exponential growth of mobile applications (mobile banking, mobile advertising, mobile inventory management, etc.), especially in a challenging areas (military battlefields, deserts, catastrophe scenes, etc.) where there is little or no communication infrastructure [3].

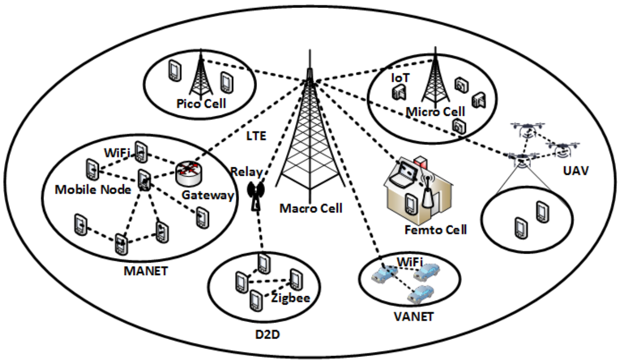

Figure 1. System Model of Typical Heterogeneous Networks

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The Mobile Ad-hoc Network (MANET) is referred to as a self-configured and infrastructure-free network based on ad-hoc communications. In MANET communications, data packet routing and other network functions (computing, storage, caching, etc.) are carried out by each mobile node, which will then support the ability of sending, receiving and forwarding data traffic to other mobile nodes, independently [8, 20]. Thus, all mobile nodes are free to come in or depart from a MANET. This reduces its dependence on the centralized fixed network infrastructure, while at the same time eases wireless network deployment. Therefore, MANET communication plays an essential role in tackling the challenges mentioned above when dynamic network environments are encountered in HetNets.

Nonetheless, wireless connections of mobile nodes might become fragile when intra- and inter-MANET topologies are sparse. This is because the wireless link's health (capacity, stability, path loss, etc.) highly relies on the distance between mobile nodes, and the transmission range of mobile nodes in a MANET is relatively limited compared to networks with centralized fixed infrastructures [13]. Particularly, disconnection between MANET nodes could occur with high likelihood in challenging locations, such as mountaintops and building roofs, due to their long distance from other mobile nodes. If the poor connections between mobile nodes in MANET communications are not properly maintained, it will certainly confine the integrity and popularization (market wise) of HetNets.

To this end, in this paper, we propose a cross-domain optimization (CDO) scheme for MANET communications in HetNets. Our proposed CDO scheme focuses on both intra- and inter-MANET communications. It first optimizes each single MANET topology by appropriately locating its traffic aggregation gateway, and then enables smooth communication between multiple MANETs by setting up LTE connections via eNodeB deployment. When a large amount of in/out data traffic is generated by each MANET, the limited capacity of one single eNodeB might restrict the number of MANETs in HetNets. Nonetheless, our proposed CDO scheme can be extended to large-scale HetNets with a tremendous number of MANETs by deploying multiple eNodeBs.

In intra-MANET communication, a gateway is added by CDO as an access point to aggregate in/out data traffic of a single MANET, in which all mobile nodes connect to each other directly or indirectly through other MANET nodes. Particularly, the gateway position is specified at the center of gravity of all mobile nodes in the MANET, which minimizes the distance between gateway and mobile nodes. Thus, the intra-MANET traffic aggregation cost (transmission power, transmission delay, packet loss, etc.) can be minimized. In inter-MANET communication, CDO likewise deploys an eNodeB at the center of gravity of all gateways in multiple MANETs to minimize the distances between eNodeBs and gateways. Therefore, the performance of inter communication between multiple MANETs is enhanced. With the deployment of the LTE connection, data traffic from mobile nodes in one MANET can be transmitted to the gateway first, and further forwarded to another MANET more effectively via LTE connection, due to its superiority in mobile network environments.

In order to validate the effectiveness of our proposed CDO scheme for MANET communications in HetNets, we designed four simulation scenarios, denoted initial, Topology Optimization (TO), LTE-assisted (LTE), and CDO scenarios, to compare their network performance with respect to throughput, delay, and packet loss ratio in the NS3 network simulation tool. The initial scenario simulates a regular MANET network without gateways or eNodeBs, while the TO scenario deploys a gateway at the center of gravity of all mobile nodes in each MANET. The LTE scenario places an eNodeB at the center of gravity of multiple gateways in diverse MANETs to construct LTE connections, such that low-cost aggregation of communication traffic between multiple MANETs can be enabled. Finally, The CDO scenario combines the TO and LTE scenarios together to represent the full solution of our proposed scheme. The performance of CDO is thoroughly evaluated under three representative MANET routing protocols: AODV (ad-hoc on-demand distance vector), DSDV (destination-sequenced distance-vector), and OLSR (optimized link state routing). Our experimental results demonstrate a significant network performance improvement by our proposed CDO scheme with respect to throughput, delay and packet loss ratio. In addition, we extend our proposed CDO scheme in several aspects, such as mobility, heterogeneity, and security, and discuss several use cases of CDO schemes in M2M communication, D2D communications, and edge computing.

The remainder of this paper is organized as follows: In Section 2, we provide a review of relevant literature. In Section 3, we present our experimental design in detail. In Section 4, we demonstrate our experimental results to validate the effectiveness of our proposed scheme. In Section 5, we discuss extensions and use cases of our proposed scheme. In Section 6, we conclude the paper and give some final remarks.

2. Related Works

In order to improve the network performance of MANET communications in heterogeneous networks (HetNets), a number of research efforts have been conducted [4, 10, 12, 18, 21, 22, 25, 29, 35, 36].

Those efforts can be classified into the following two categories: (i) intra-MANET optimization and (ii) inter-MANET optimization.

Intra-MANET optimization is constrained within a MANET to improve network performance such as throughput, delay, energy consumption, jitter, packet loss ratio, etc., and the optimization could target diverse aspects (network topology, routing protocol, traffic monitoring, etc.) [4, 10, 25, 35, 36]. For example, Zahidi *et al.*. in [35] proposed an improved integer linear programming (ILP) formulation of the clustering problem in MANETs, by implementing multiple enhancements regarding intra-cluster communications, multi-hop connections, and coverage constraints. The improved ILP is proven to be effective in prolonging the lifetime of both small and large MANET networks. Zhang *et al.* in [36] designed an interference-based topology control algorithm for delay-constrained MANET networks with joint consideration of both interference and delay constraints. The proposed scheme provides a significant reduction of transmission delay, contention delay, and queuing delay.

Inter-MANET communication, consisting of communication between MANET and Internet, communication between two different MANETs, and communication between MANET and another type of network, such as PAN (personal area network) and EPN (enterprise private network), is facing enormous challenges (link capacity, network compatibility, network coverage, etc.) due to network heterogeneity and the mobility of MANET nodes. Inter-MANET optimization endeavors to increase MANET traffic capacity, maintain seamless incorporation of diverse MANETs, and extend MANET transmission range through reformed inter-MANET routing protocols, load balance algorithms, and node clustering techniques, among others. [12, 18, 21, 22, 29]. For instance, Toutouh *et al.* in [29] compared a series of representative meta heuristic algorithms to find an optimal set of parameter configurations (i.e., HELLO-INTERVAL, WILLINGNESS, TOP-HOLD-TIME) for the OLSR routing protocol for VANETs (vehicular ad-hoc networks), which are a type of MANET. The authors conducted a thorough experiment with realistic VANET scenarios, and concluded that the optimal configuration could provide a better quality of service (QoS) than the standard request for comment (RFC 3623). In addition, Lee *et al.* in [12] proposed an inter-MANET routing protocol called InterMR to support seamless routing across heterogeneous MANETs, and an Inter-MANET address scheme to enable merging/split of network topologies within one name server. Via packet-level simulation, the authors showed that InterMR could improve the throughput performance of the User Datagram Protocol (UDP) up to 112 % by using the adaptive gateway assignment functionalities within the proposed Inter-MANET address scheme.

Unlike the existing schemes, our proposed CDO (cross-domain optimization) scheme aims to optimize both intra- and inter-MANET communications within the context of HetNets. CDO not only embeds a gateway to the center of gravity of all mobile nodes of an individual MANET, but also puts up LTE connections between multiple MANETs by placing an eNodeB at the center of gravity of gateways that are already optimally initialized. With the combination of both intra- and inter-MANET optimization, CDO significantly improves the overall network performance of MANET communications in HetNets. Notice that we focus on two individual MANETs within one macro cell in this investigation to validate the effectiveness of our CDO scheme. Nonetheless, our proposed CDO scheme can be extended to multiple macro cells, and each macro cell can include as many MANETs as its capacity consents. Also notice that, in a large scale network with crowded macro cells and dense MANETs, the interference between diverse macro cells and the interference between multiple mobile nodes in each MANET need to be considered.

3. Experiment Design

In this section, we introduce our experimental design in detail.

3.1. Overview

In our experiment, we used NS3 to set up our simulation environment consisting of both LTE and MANET networks. Notice that NS3 is a well-known computer network simulator publicly available under the GNU GPLv2 license [31]. It was developed to replace NS2, funded by National Science Foundation (NSF). NS3 contains diverse network modules (LTE, WiFi, WiMAX, etc.) to enable the development and implementation of realistic network environments. In addition, NS3 also provides a Flow Monitor module, which can be used to collect network traffic data statistics (timeFirstTxPacket, timeLastRxPacket, delay sum, txBytes, lostPackets, timeForwarded, and packetDropped, and others) from a list of trace sources (LtePdcp, WifiMac, WimaxNetDevice, and others). Notice that typical network evaluation metrics (throughput, delay, packet loss ratio, jitter, pathloss, etc.) can all be obtained on the basis of the above-mentioned traffic data statistics.

Generally, in our experiment, we adopt the LTE module to construct LTE network infrastructures, and the WiFi module to compose mobile ad-hoc network (MANET) infrastructures. In LTE network simulation, we exploit EpcHelper in NS3 to set up an EPC entity, which forms a core network. In addition, IPv4 static routing is utilized to deliver data packets in the deployed LTE network, and PCAP (packet capture) file is used to analyze traffic details. In MANET network simulation, the mobility module is employed to accurately frame a wireless mobile network environment. Obviously, it is a fundamental feature for data traffic to be sent and forwarded, hop by hop, in the MANET environment. Thus, we include diverse routing modules, consisting of reactive routing: AODV (ad-hoc on-demand distance vector), and proactive routing: DSDV (destination-sequenced distance-vector) and OLSR (optimized link state routing), to thoroughly demonstrate the effectiveness of our proposed CDO (cross-domain optimization) scheme.

To be specific, we elevate one single macro cell with two MANETs in NS3 as the basic network infrastructure. The macro cell comprises one eNodeB and two separate MANETs. Each MANET consists of the same number (11, 21, 31, 41, and 51 for diverse mobile node densities) of UEs, and all the UEs fall into two categories: data traffic aggregation gateway (1 UE) and mobile nodes (the rest of the UEs). In addition, the positions of all the devices (eNodeB and UEs) within the coverage of the constructed macro cell are randomly generated at the beginning of the simulation. In this experiment, we aim to validate the effectiveness of our proposed CDO scheme for MANET communications in heterogeneous networks (HetNets).

To this end, we build up a MANET network with two groups of mobile nodes, and the numbers of mobile nodes in both groups are the same. First, we initialize the distance between the two groups with a relatively large value (a frequently occurring scenario in real-world MANET networks due to node mobility, where the two groups could be actually treated as two individual MANETs), but their connectivity is still guaranteed [7]. Without gateway or eNodeB deployment, the limited network performance with respect to throughput, delay, and packet loss ratio under the fragile connection between two MANETs can be demonstrated.

Then, we properly deploy a gateway to the center of gravity of all mobile nodes in each MANET to aggregate the data traffic, and likewise deploy an eNodeB to the center of gravity of the appropriately located gateways of the MANETs to enable smooth inter-MANET communications via LTE. With the assistance of the suitably arranged gateways and eNodeB, we validate the effectiveness of our proposed CDO scheme with respect to throughput, delay, and packet loss ratio, for MANET communications in HetNets. In our experiment, we consider four scenarios:

- Two fragilely connected MANETs without gateways or eNodeBs,
- Two connected MANETs with appropriately located gateways,
- One macro cell with two MANETs having randomly deployed gateways and a centralized eNodeB,
- One macro cell with two MANETs under properly located gateways and an eNodeB.

In the following, we describe our experiment setup with regards to *MANET Routing Protocols*, *Scope of Experiment*, *Network Simulation Scenarios*, and *System Settings*.

3.2. MANET Routing Protocols

Routing protocols are a necessity in MANETs when a data packet is forwarded from one mobile node to its destination via other mobile nodes. Generally speaking, MANET routing protocols are classified into two categories: reactive routing protocols and proactive routing protocols [28]. In our experiment, we use three representative MANET routing protocols, AODV (ad-hoc on-demand distance vector), DSDV (destination-sequenced distance-vector), and OLSR (optimized link state routing) to evaluate the performance of our proposed CDO (cross-domain optimization) scheme.

Reactive routing protocols are also called on-demand routing protocols. In reactive routing, the route between the source and destination is only created when it is needed, and once the data transmission is finished, the route will no longer exist. In our experiment, we use ad-hoc on-demand distance vector (AODV) [23] as the representative reactive MANET routing protocol. AODV aims to reduce broadcasts in MANET networks. Thus, when a mobile node wants to send data packets to another mobile node, AODV first checks the routing table to see whether the route between source and destination already exists or not. If the route does exist, the data packet will be sent and forwarded to its destination via that route. Otherwise, AODV will discover the updated shortest route between source and destination by using route request (PREQ) and route reply (RREP).

Proactive routing protocols are also referred to as table-driven routing protocols. In proactive routing, the routing table of each mobile node contains the route information from itself to all the other mobile nodes in the MANET, and each mobile node retains and maintains the routing table all the time, in order to be aware of its routes continuously. In our experiment, we select destination-sequenced distance-vector (DSDV) [24] and optimized link state routing (OLSR) [5] as typical examples of proactive MANET routing protocols.

To be specific, DSDV is a single-route routing protocol, in which each mobile node maintains a regularly updated routing table to indicate the routes between itself and all the other mobile nodes in the MANET network. If any changes occur regarding MANET network topology, the altered mobile node will broadcast its updated routing information (new sequence number, new destination address, new number of hops, and others) in the MANET. OLSR is a link-state routing protocol especially designed for MANETs with high mobility. Similar to DSDV, each mobile node in OLSR maintains a routing table with the route information between itself and all the other mobile nodes in the MANET. In addition, OLSR chooses a special set of mobile nodes to work as multi-point relays (MPRs), then routing procedures of all mobile nodes (peer discovery, link sensing, MPR re-selection, etc.) are performed only by the MPRs. Thus, OLSR can significantly reduce the required TC (topology control) message transmission and minimize the possibility of control traffic flooding for the mobile nodes that do not work as MPRs.

3.3. Scope of Experiment

Throughput. Throughput is the data transmission rate within a network. In our simulation, we define throughput as the number of bytes received by the constructed networks (corresponding to the four scenarios illustrated in Section 3.4) per unit time. The outgoing data traffic of mobile nodes maintains a pre-configured stable rate, while the incoming data traffic rate depends on the link quality. Thus, we collect network traffic data from all destination mobile nodes (receiving incoming data packets) via a packet sink application in NS3. The MANET data is collected from the MAC layer by using a flow monitor, while the LTE data is gathered from the packet data convergence protocol (PDCP) layer by using the NS3 tracing system.

Delay. Delay is the time taken for data traffic to transmit from its source to destination within a network. In our experiment, we first obtain the time taken by each flow (source-destination pair) to finish transmitting all its data packets, and the number of received data packets for the destination mobile node in each flow are also counted. Then, we define delay as the ratio between the sum of the consuming times of all flows and the sum of received data packets of all flows. The delay is therefore equivalent to the average transmitting time of a packet from its source to destination. The delay related data (tx bytes, rx bytes, delay sum, etc.) of a MANET is also collected in XML format from the MAC layer using a flow monitor, while the delay-related LTE data comes from the PDCP layer via NS3 trace sources.

Packet Loss Ratio. Packet loss ratio is the fraction of the number of lost data packets over the number of transmitted data packets within a network. In our simulation, we collect the number of lost data packets and the number of transmitted data packets in each flow, obtain the summation regarding the numbers of lost data packets in all flows and the numbers of transmitted data packets in all flows, and define packet loss ratio as the ratio of lost data packets over transmitted data packets in all flows. The data collection is the same as for throughput and delay.

3.4. Network Simulation Scenarios

To understand the performance of MANET communications under low-quality connection links, we set up the initial scenario as a baseline, without assistance from gateways or an eNodeB. In the topology optimization (TO) scenario, we utilize the center of gravity mechanism, described in Section 1 and our previously published paper [20], in each MANET to deploy gateways, which optimizes the MANET topology. This TO scenario is used to investigate MANET network performance improvements by properly adding gateways.

Next, we create an LTE-assisted (LTE) scenario to look into the impact of incorporating gateways and an eNodeB on MANET performance. The LTE scenario adds gateway to each MANET without introducing the center of gravity scheme, but introduces the optimal placement of an eNodeB by applying the center of gravity mechanism between the two MANETs to enable the LTE connection. Combining the network configurations in the TO and LET scenarios, in the cross-domain optimization (CDO) scenario, we apply the center of gravity mechanism for both gateway and eNodeB positions, which is used to show the effectiveness of our proposed CDO scheme for Inter-MANET communications in HetNets. All these scenarios are summarized in Table 1. We now describe them in detail.

Initial Scenario. As shown in Fig. 2, our initial scenario implements a sparse MANET in a large area (1000 m x 500 m) without any deployment of gateways or eNodeBs. In this scenario, the MANET consists of predetermined numbers of mobile nodes (20, 40, 60, 80, and 100) to evaluate diverse node densities of the network. All the mobile nodes in the MANET are evenly grouped into two separate clusters (10, 20, 30, 40, and 50 mobile nodes in each cluster) and a large distance (200 m) between those two clusters (separating the MANET) is also configured. In addition, one pre-selected mobile node is positioned at the edge of each cluster. Thus, two pre-selected mobile nodes in both clusters can establish a communication link with guaranteed connectivity, but limited performance. In fact, those two clusters could actually be treated as two separate MANETs, due to the long distance between them. Mobile nodes in both MANETs are randomly distributed by applying a predefined random function,

Table 1. Network Simulation Scenarios

Scenario	Description
Initial (pure MANET)	A sparse MANET network in a large area without any infrastructure deployment of gateways or an eNodeB, shown in Fig. 2.
TO (MANETs with optimized gateways)	Two MANET networks interconnected by two location optimized gateways in both MANETs via applying the center of gravity mechanism, shown in Fig. 3.
LTE (HetNets with optimized eNodeB)	A heterogeneous network consisting of one macro cell and two MANETs. The eNodeB for the macro cell is appropriately located (utilizing the center of gravity mechanism), while the gateways in both MANETs are randomly dispersed, shown in Fig. 4.
CDO (HetNets with optimized gateways and eNodeB)	A heterogeneous network comprised of one macro cell and two MANETs. Both the eNodeB for the macro cell, and the gateways for the MANETs, are properly deployed (using the center of gravity mechanism), shown in Fig. 5.

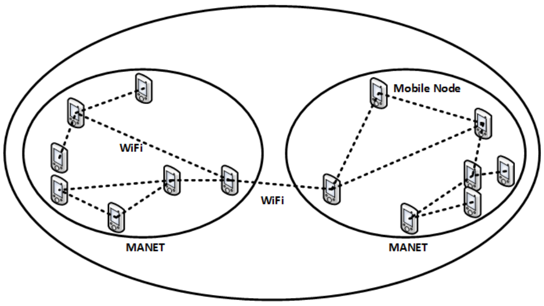

Figure 2. Initial

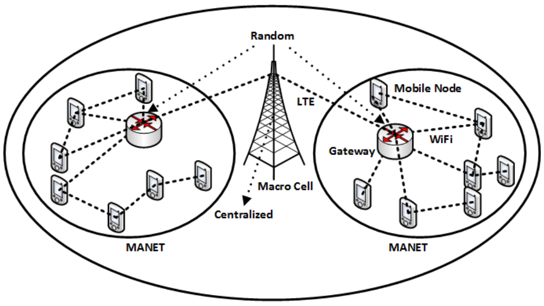

Figure 4. LTE-assisted

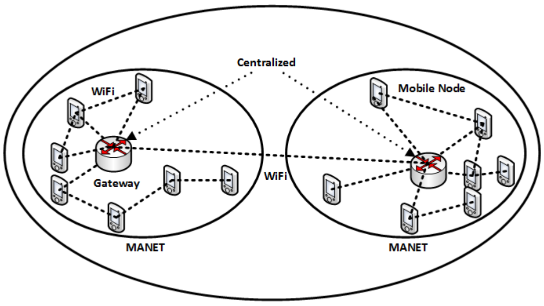

Figure 3. Topology Optimization

and each mobile node in one MANET transmits data packets to another mobile node in the other MANET via the two pre-selected mobile nodes.

TO Scenario. In this scenario, as shown in Fig. 3, we extend our initial scenario with two location-optimized gateways in both MANETs. The gateway is properly located in the center of gravity of all mobile nodes in each MANET to minimize the transmission distance between the gateway and all connected mobile nodes. Notice that all mobile node positions in both MANETs remain the same as those of the mobile nodes in the initial scenario. We compare the performance of MANET communications in the topology optimization scenario with that of initial scenario, regarding the three metrics defined in Section 3.3. In addition, each mobile node in one MANET first sends its data traffic to the optimal gateway, which further delivers the data traffic to the optimal gateway in the other MANET. Then, mobile nodes in the destination MANET receive data packets from their corresponding gateways.

LTE Scenario. As shown in Fig. 4, we deploy a macro-cell base station (eNodeB) and two gateways into our initial scenario to construct the LTE-assisted MANET communications in a heterogeneous network (HetNet) environment. We apply the center of gravity mechanism to properly select the location for the eNodeB in this scenario, and randomly specify the locations of the gateways for both MANETs within the HetNets. It is worth noting that the locations of all mobile nodes and the size of simulation area (1000 m x 500 m) remain the same as those in the initial scenario. Thus, the transmission range (1000 m to 20000 m) of a standard eNodeB is capable of covering the entire simulation area. As it certainly costs a significant amount to install both LTE and WiFi interfaces in all mobile nodes, we instead place both interfaces on the two gateways to enable smooth communications between the LTE network and MANETs. Then, data traffic going through both MANETs is delivered via efficient LTE channel instead of the traditional WiFi connection. To summarize, data traffic sent from mobile nodes in one MANET is first aggregated via gateway, which transfers data traffic to the gateway in the other MANET via LTE link provided by the eNodeB.

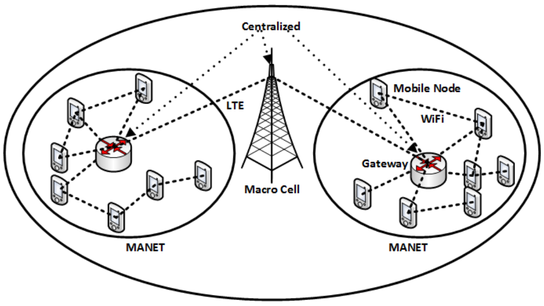

Figure 5. Cross-Domain Optimization

CDO Scenario. In this scenario, as shown in Fig. 5, we apply our proposed cross-domain optimization scheme (CDO) into the initial scenario to validate its effectiveness compared to the scenarios above. However, rather than adopting the random deployment of eNodeB and gateways, we instead assign their positions by leveraging the center of gravity mechanism in this CDO scenario. To be specific, we first move the gateway to the center of gravity of all mobile nodes in each MANET, we then likewise dispose the eNodeB to the center of gravity of both gateways in the HetNets. Still, the locations of all mobile nodes in this scenario stay the same as those in the previous scenarios. By doing so, we evaluate the effectiveness of our proposed CDO scheme in improving the network performance of MANET communications in HetNets, with respect to the metrics defined in Section 3.3. In this scenario, mobile nodes in each MANET generate data traffic and send it hop by hop to the optimized gateway via intra-MANET routing, the optimized gateway then utilizes LTE link to enable inter-MANET transmission of the data packets to the other optimized gateway in this HetNet, and finally the destination mobile nodes can obtain the data traffic from their optimized gateway also via intra-MANET routing.

3.5. System Settings

In the NS3 network simulator, we initialize a 1000 m x 500 m rectangular area. The number of mobile nodes randomly distributed within the area could be 20, 40, 60, 80 and 100, which represent MANETs with node densities. The initial coordinations of all mobile nodes are generated by a predefined random function, and all mobile nodes are grouped into two separate clusters with a distance of 200 m between them, which results in two individual MANETs (corresponding to two clusters), due to the long distance between them. Particularly, one mobile node is deployed on the edge of each MANET to establish an inter-MANET connection. In order to closely simulate a real-world network environment for HetNets, which is comprised of one macro cell with two MANETs for our experiment, we also appropriately set up all the network related parameters, including transmission power and inter-packet interval, among others, for both the LTE network and MANET. Please refer to Table 2 for more detail.

Regarding LTE communication, we set uplink and downlink bandwidths between the eNodeB and gateways as 25 MHz, the transmission power of the eNodeB as 46 dBm, and the transmission power of all mobile nodes as 10 dBm (the same in all four scenarios). The evolved packet core (EPC) module is integrated in our experiment to work as the backbone of the LTE core network, and one eNodeB is attached to the EPC via a point-to-point link with a data transmission rate of 100 Gbps, an MTU (maximum transmission unit) size of 1500 bytes, and a transmission delay of 0.010 s. In addition, the transmission mode of LTE is set as single input single output (SISO), and the inter packet interval is initialized as 0.100 s. We use the trace system of NS3 to collect our experimental data regarding LTE from the PDCP (packet data convergence protocol) layer.

Regarding MANET communication, we use the 802.11b standard as the WiFi model to present a MANET, and the WiFi propagation speed is the same as the traveling speed of light. To be specific, the data packet in MANET is generated from UDP (user datagram protocol) socket factory, the data packet transmission rate is set at a constant value of 10 kbps, and the MANET workload is balanced at 1000 data packets with the same packet size of 1000 bytes. The data traffic in our simulation is equivalent to an 800x600 JPEG picture file at a 50 % image quality or a 10 s voice file. Notice that it is not necessary to apply any congestion control mechanism in the simulation, because MANET routing protocols can automatically handle data flow congestion. We collect the MANET-related experimental data from the MAC (medium access control) layer by using both the NS3 trace system and a flow monitor.

4. Performance Evaluation

In this section, we demonstrate and analyze our network performance evaluation results regarding the three key metrics of throughput, delay, and packet loss ratio, defined in Section 3.3. The experimental results are collected from the designed network simulation scenarios (initial, TO: topology optimization, LTE: LTE-assisted, and CDO: cross-domain optimization) described in Section 3.4. The first two scenarios are implemented in a pure MANET network environment with two MANETs, while the last two scenarios are implemented in a heterogeneous network (HetNet) environment consisting of a macro cell with two MANETs.

Table 2. Simulation Parameters

HetNets Simulation Scale: 1000 m x 500 m	
LTE Network	MANET Network
Up- and Down-link Bandwidths: 25 MHz eNodeB Transmission Power: 46 dBm Point-to-Point Transmission Rate: 100 Gbps Point-to-Point MTU Size: 1500 bytes Point-to-Point Transmission Delay: 0.010 s LTE Transmission Mode: SISO Inter Packet Interval: 0.100 s	Number of Mobile Nodes: 20, 40, 60, 80, 100 Distance between MANETs: 200 m WiFi Model: 802.11b WiFi Propagation Speed: 3 x10^8 m/s Data Packet Transmission Rate: 10 kbps MANETs Workload: 1000 data packets Data Packet Size: 1000 bytes

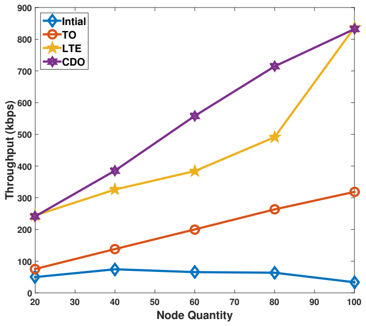

Figure 6. Throughput-AODV

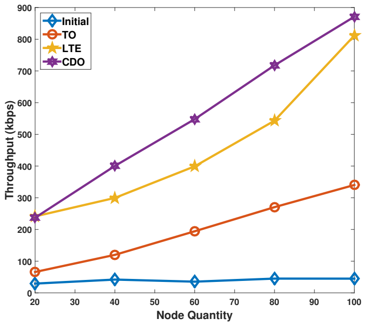

Figure 7. Throughput-DSDV

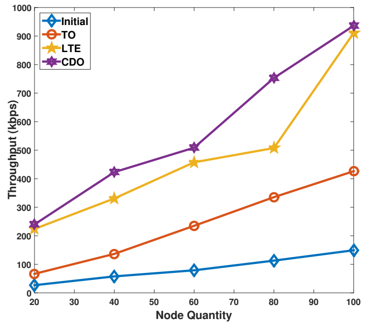

Figure 8. Throughput-OLSR

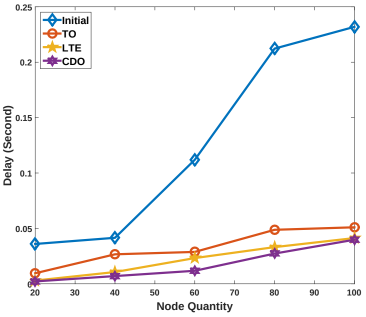

Figure 9. Delay-AODV

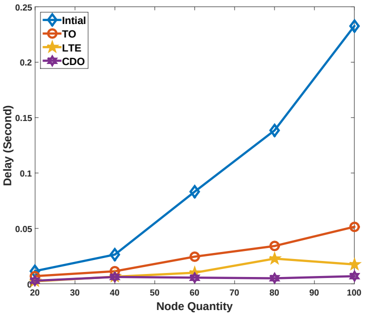

Figure 10. Delay-DSDV

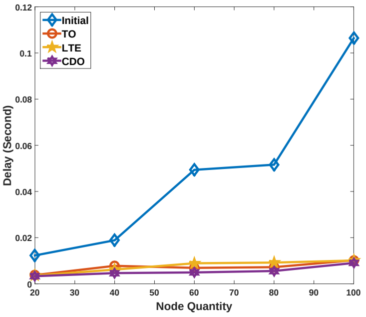

Figure 11. Delay-OLSR

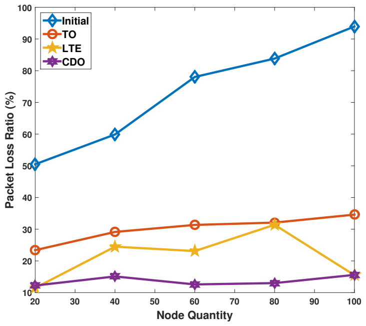

Figure 12. Packet Loss Ratio-AODV

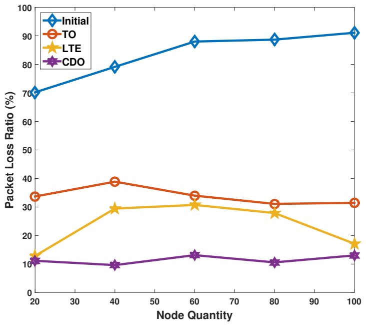

Figure 13. Packet Loss Ratio-DSDV

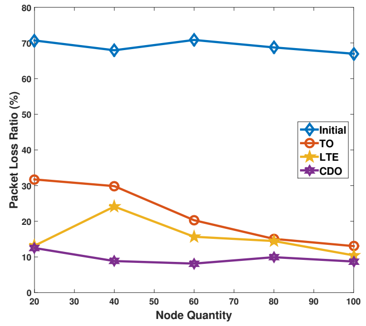

Figure 14. Packet Loss Ratio-OLSR

We thoroughly investigate the effectiveness of our proposed cross-domain optimization (CDO) scheme by exploiting three commonly used MANET routing protocols (AODV: ad-hoc on-demand distance vector, DSDV: destination-sequenced distance-vector, and OLSR: optimized link state routing), introduced in Section 3.2. In the evaluation of our proposed scheme for improving network performance of MANET communications in HetNets, the effectiveness of CDO with respect to throughput, delay, and packet loss ratio can be observed by comparing the network performance of the CDO scenario with that of the three other scenarios (initial, TO, and CDO) in Fig. 6 to Fig. 14. Specifically, Fig. 6, Fig. 9, and Fig. 12 present the comparison results under the AODV MANET routing protocol, while Fig. 7, Fig. 10, and Fig. 13 correspond to DSDV, and Fig. 8, Fig. 11 and Fig. 14 relate to OLSR. We now review all the results in detail.

Throughput Evaluation. Fig. 6, Fig. 7, and Fig. 8 demonstrate the overall throughput of diverse networks (initial: pure MANET, TO: MANET with optimized gateways, LTE: HetNets with optimized eNodeB, and CDO: HetNets with optimized gateways and eNodeB) under AODV, DSDV, and OLSR MANET routing protocols, respectively. The throughput performance of each network type is studied from five different node densities with the number of mobile nodes set to 20, 40, 60, 80, and 100. As shown in these figures, our proposed CDO scheme outperforms the LTE-assisted scheme, topology optimization scheme, and the baseline in every routing protocol. In addition, the LTE-assisted scheme always performs much better than topology optimization scheme, while the performance of the baseline continuously performs the worst. For example, the DSDV throughput of the HetNets running CDO is at least 659.432 kbps larger than that of the HetNets running the LTE-assisted scheme for most node densities in Fig. 7. With respect to the topology optimization scheme and the baseline scheme, the difference with the CDO scheme in Fig. 7 could be as high as 530.739 kbps and 826.102 kbps, respectively.

Delay Evaluation. Fig. 9, Fig. 10, and Fig. 11 illustrate the performance comparison of the CDO scheme, LTE-assisted scheme, topology optimization scheme, and the baseline with respect to average delay performance. As we can see from the figures, the average delays of the HetNets with the CDO scheme, the HetNets with the LTE-assisted scheme, and the MANET with the topology optimization scheme are much lower than that of the baseline with pure MANET in every routing protocol, and this performance difference remains for all the network node densities. Generally speaking, CDO has the best performance in every routing protocol, while the performance of the LTE-assisted scheme, the topology optimization scheme, and the baseline gets worse in that order. We do see a subtle fluctuation in the performance of the LTE-assisted scheme and the topology optimization scheme in Fig. 11 under the OLSR routing protocol, but they both outperform the baseline and are still not as good as the CDO scheme. For example, the delay of CDO scheme could be as low as 0.002157 s in Fig. 9 under AODV, while that of the baseline might reach up to 0.03596 s. The performance increase of the CDO scheme against LTE-assisted scheme and topology optimization scheme is not as great as that of the CDO scheme against the baseline, but it is still very significant.

Packet Loss Ratio Evaluation. Fig. 12, Fig. 13, and Fig. 14 show the performance diversity of the CDO scheme, LTE-assisted scheme, topology optimization scheme, and the baseline, with respect to packet loss ratio. As implied in the figures, the CDO scheme, together with the LTE-assisted scheme and topology optimization scheme, always hold a dominant position against the baseline in every routing protocol. The CDO scheme still performs the best for all network node densities, while the effectiveness of the LTE-assisted scheme and the topology optimization scheme decreases in order. Specifically, the packet loss ratio of CDO, LTE-assisted, and topology optimization is lower than 30% for almost all network node densities, while that of the baseline is at approximately 70%. Notice, the packet loss ratio of CDO remains under 10% for most network node densities.

5. Discussion

In this section, we first discuss how to extend our proposed CDO (cross-domain optimization) scheme from the following perspectives: mobility, heterogeneity, and security, which are the basic network features for MANETs in heterogeneous networks (HetNets) [16]. We then introduce some use cases of CDO in M2M (machine-to-machine) communications, D2D (device-to-device) communications, and edge computing, which are integrated with 5G HetNets to enable the Internet-of-Things (IoT) for smart systems [1, 14, 15].

5.1. Extensions

Mobility. In MANET networks, the self-configuring and infrastructure-less characteristics enable a decentralized environment with a number of mobile nodes [27]. The mobility feature of MANET can significantly improve network capacity with respect to throughput, delay, energy consumption, packet loss ratio, etc., which makes it a viable solution for diverse mobile scenarios, such as disaster relief and battlefield support. Nonetheless, the center of gravity of mobile nodes certainly could change with the varying locations of mobile nodes at different times, and the gateway must be relocated accordingly. Otherwise, the aggregation cost of intra-MANET traffic in the gateway cannot be guaranteed at minimum.

Towards this end, CDO periodically collects the location information of mobile nodes, aggregates the information in the gateway, and acquires the updated center of gravity momentarily based on renewed mobile nodes location information. Notice that the period duration is identified based on the particular MANET network mobility level. In addition, CDO customizes a distance threshold regarding the distance between the original gateway and the relocated gateway, and it is used to leverage the trade-offs between the improvement of network performance (throughput, delay, packet loss ratio) with gateway redeployment and the sacrifice of not moving the gateway. If the threshold is not reached, it is not necessary to relocate the gateway. Otherwise, the gateway must be relocated to the updated center of gravity to further optimize the intra-MANET topology, such that the unaccepted degradation of MANET network QoS (Quality of Service) can be avoided. In addition, the eNodeBs in HetNets could likewise be properly relocated to the center of gravity of updated gateways, if it is deployed on a mobile vehicle, instead of being fixed.

Heterogeneity. The popularity of MANETs in HetNets highly relies on their decentralized characteristics, which allow multiple MANETs to adopt diverse network access technologies (WiFi, Zigbee, WiMAX, etc.) at the same time in one HetNet environment [19]. Nonetheless, this heterogeneity also raises challenges for both gateways in MANETs, and for eNodeBs in HetNets. Regarding gateways in MANETs, the individual gateway for a specified MANET must have a certain network access interface to enable the corresponding network access technology, which consequently results in a different MANET network mobility levels (MANET network access technology is highly related to the mobility of the network [12]). Regarding eNodeBs in HetNets, it is required that they be capable of serving data traffic from diverse network technologies.

In order to address these issues, CDO could first install relevant network access interfaces for gateways in MANETs to appropriately aggregate intra-MANET traffic, and initialize the distance thresholds with diverse values according to the network mobility levels of multiple MANETs (the same as what we have in the mobility extension), which is exploited for mobility management. Then, CDO attaches an LTE air interface for the gateway in each MANET instead of adding diverse interfaces to eNodeBs in HetNets. By doing so, the inter-MANET traffic aggregation is more efficiently processed in the eNodeB only via LTE air interface, which has superior attributes over other network access interfaces in mobile network environments.

Security. HetNets are a mixture of diverse network environments (LTE, WiFi, Zigbee, WiMAX, etc.), which are continuously affected by uncertain network security factors, such as integrity, confidentiality, authentication, etc., due to their profound heterogeneity. With the deep integration of MANETs in HetNets, the security challenges of MANET communications are therefore exponentially increased. By exploiting the vulnerable characteristics of MANET communications, like hop-by-hop transmission, open border, wireless medium, etc., adversaries could launch snooping attacks, routing attacks, resource consumption attacks, denial-of-service attacks, and others [6]. Our proposed CDO scheme shall be able to detect the routing attacks, in which a malicious node modifies or deletes other mobile nodes' routing tables.

To be specific, if the distance threshold maintained by the gateway is not exceeded, there will not be necessity of gateway relocation (illustrated in mobility extension). Then, the gateway remains relatively near to the mobile nodes in the MANET, due to the adoption of the center of gravity mechanism. Thus, the routing table of the gateway should be stable, because diverse MANET routing protocols prefer the shortest route to be the transmission path. If the routing table of the gateway refreshes itself constantly, there shall be malicious nodes tampering other mobile nodes' routing tables. If the distance threshold is surpassed and the gateway is repositioned, the gateway's routing table will keep updating for until a firm state is achieved, and the time of rerouting highly depends on the moving distance from original location to new location. Once the gateway routing table continues to vary momentarily after the period, a routing attack might be inferred. In addition, the routing attack against gateways in MANETs could also be detected by leveraging the routing information related to eNodeBs in HetNets.

5.2. Use Cases

M2M Communications. M2M communication [9], also called machine type communication (MTC), enables universal connectivity between devices with little or no human intervention. It is also specified by the 5GPPP (5G public private partnership) that the requirements of M2M communications must be met in 5G HetNets to support Internet-of-Things applications [15, 34]. Though M2M devices barely move in most use cases, such as data collection in e-Health, remote surveillance in public safety, etc., most M2M devices in intelligent transportation and tracking systems do move. Thus, MANETs are frequently implemented for M2M communications in fleet management, personal tracking, robotic applications, and more, due to their superiority of mobility.

In 5G HetNets, M2M communication is mainly enabled by a core network with EPC (evolved packet core, LTE related), along with multiple networks implemented by diverse network access technologies (WiFi, Zigbee, WiMAX, etc.). Once a MANET is adopted for diverse networks to enable M2M applications, CDO could appropriately locate an M2M gateway to the center of gravity of all M2M devices in each M2M application, such that the aggregation cost of data traffic within the M2M application in gateway is minimized. In addition, the position of eNodeBs in LTE core networks for HetNets can also be optimized by leveraging the positions of relocated M2M gateways in MANETs with the same center of gravity mechanism.

Then, the aggregation costs of data traffic from diverse MANET networks in eNodeBs are minimized.

D2D Communications. D2D communication [2, 11] is defined in cellular networks, enabling direct communication between two mobile devices without passing through eNodeBs. The connection between two mobile devices is established directly via peer discovery in two different ways: inband and outband communications. Regarding inband communications, the D2D link and cellular link are both enabled via licensed cellular spectrum, such as LTE, to improve spectrum efficiency. As to outband communications, the D2D link is established via unlicensed spectrum (WiFi direct, Zigbee, Bluetooth, etc.), while the cellular link is enabled via licensed cellular spectrum. This highly reduces the interference between the D2D link and cellular link. If outband communication is used, the D2D communications in diverse clusters will actually be groups of MANETs. Then, CDO can be used to improve the performance of both D2D communications in MANETs and the cellular network performance in HetNets. Specifically, if one device is selected as the head of the MANET cluster with multiple devices, the selected device will indeed be working as a gateway to aggregate data traffic within the MANET cluster. Therefore, CDO can specify the gateway in the MANET cluster as the center of gravity of all other devices to minimize the distance between them. Then, a minimum aggregation cost of data traffic within the MANET cluster is obtained. Likewise, the aggregation cost of data traffic from diverse MANET clusters is also minimized by exploiting the same center of gravity mechanism to the eNodeBs in HetNets on the basis of all relocated gateways.

Edge Computing. Edge computing [17, 33] is treated as a extension of cloud computing, regarding data transmission delay, shrinking data cost, security, and network scalability. It pushes the computation intensive tasks to the edge of the network near the data sources, such as eNodeBs and even local aggregation points (gateways, access points, etc.) in 5G HetNets. Thus, the transmitted data volume, the data transmission cost, and data information security are highly improved, due to local data processing instead of remote data operation in the centralized cloud owned by large companies (Amazon, Microsoft, etc.).

Particularly, mobile edge computing in 5G HetNets builds its backbone core network via LTE, and favors MANET to construct its local networks, also due to the mobility benefits of MANET networks. If edge clouds are deployed to local aggregation point gateways and eNodeBs in MANETs and HetNets, respectively, CDO will be able to significantly improve mobile edge computing performance in 5G HetNets. To be specific, the distance between the aggregation point gateway and data sources is minimized by applying the center of gravity mechanism to properly locate the gateway, which results in a minimum transmission cost of data exchange in local MANET networks. Similarly, the distance between eNodeBs in HetNets and optimized aggregation point gateways in MANETs is also minimized by CDO, which places eNodeBs to the center of gravity of optimized aggregation points. Thus, mobile edge computing in eNodeBs could save significant time on data traffic convergence from diverse MANETs.

6. Final Remarks

In this paper, we have proposed a Cross-Domain Optimization (CDO) scheme to optimally construct intra-MANET topology and significantly enhance inter-MANET communication via LTE in heterogeneous networks (HetNets). Particularly, CDO first specifies a gateway in the center of gravity of all mobile nodes for each MANET to minimize the transmission distance between the gateway and all mobile nodes. Then, it utilizes the same center of gravity mechanism to deploy an eNodeB for multiple gateways to minimize the transmission distance between the eNodeB and all gateways, along with enabling smooth communication between diverse MANETs due to the superiorities of LTE network performance in mobile network environments. Our proposed scheme is competent to obtain better placement of gateways for intra-MANET networks and strengthen inter-MANET communications via LTE, instead of the traditional wireless connections (WiFi, Zigbee, WiMAX, etc.). The experimental results of our extensive simulation, exploiting three typically adopted MANET routing protocols (AODV, DSDV, and OLSR), validate that CDO can achieve a better network performance, with respect to throughput, delay, and packet loss ratio, for MANET communications in HetNets than all the other configurations. In addition, we have extended our proposed CDO scheme from several aspects, such as mobility, heterogeneity, and security, and discussed several use cases of CDO schemes in M2M communications, D2D communications, and edge computing.

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