CONGESTION CONTROL SCHEME FOR ENERGY EFFICIENCY OF NAMED DATA NETWORKING BASED MOBILE AD HOC NETWORK

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DEDICATION

This thesis work is dedicated to my parents, families and my teachers throughout my education career who have not only loved me unconditionally but whose good examples have taught me to work hard for the things that I aspire to achieve.

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"All praise to Allah, the lord of the worlds, and His Prophet Muhammad (peace be upon him), his family and his companions".

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ABSTRACT

Named Data Networking (NDN) was originally a proposed future Internet Protocol to solve content sharing and distribution problems on the Internet. At the same time, NDN has a lot of advantages as a communication protocol in Mobile Ad hoc Network (MANET). However, network congestion is a major cause of energy wastage in NDN-based MANET like traditional MANET. Therefore, an efficient congestion control scheme is proposed, consisting of three different sub-scheme to tackle three different network congestion problems that resulting energy wastage. First, the Hop-by-Hop Congestion Detection scheme was developed to deal with inaccurate congestion detection due to false positive and false negative errors. Secondly, the Preventive and Reactive Congestion Avoidance scheme was designed to handle intermittent bandwidth limit fluctuation, leading to a high congestion rate. Finally, the Congestion-Aware Load Balancing scheme was established to handle unbalanced shared bandwidth, leading to a high congestion rate. Performance comparison was conducted using testbed between proposed congestion control scheme with two existing congestion control solutions in NDN forwarder daemon (NFD), namely, Practical Congestion Control scheme for NDN (PCON) and Best Effort Link Reliability Protocol (BELRP). The performance of these schemes was measured and analysed using suitable metrics such as congestion detection rate, goodput and energy consumption of consumer nodes. In the baseline topology scenario, the proposed congestion control scheme had a better congestion detection accuracy with a congestion detection rate as low as 42.91%, compared to PCON (69.68%) and BELRP (43.37%). The proposed congestion control scheme also produced a better goodput of 3.39 kbps, compared to PCON (1.17 kbps) and BELRP (0.94 kbps) in the random mobility scenario. More importantly, in the random mobility scenario, the energy consumption of consumer nodes when using the proposed congestion control scheme was lower at 1445.7 joules, compared to PCON (4082.83 joules) and BELRP (5214 joules). In conclusion, the proposed congestion control scheme outperformed the aforementioned existing congestion control solutions.

ABSTRAK

Rangkaian Data Dinamakan (NDN) pada asalnya merupakan Protokol Internet masa hadapan yang dicadangkan untuk menyelesaikan masalah perkongsian dan pengedaran kandungan dalam Internet. Pada masa yang sama, NDN mempunyai banyak kelebihan sebagai protokol komunikasi dalam Rangkaian Ad hoc Mudah Alih (MANET). Walau bagaimanapun, kesesakan rangkaian adalah punca utama pembaziran tenaga dalam MANET berasaskan NDN seperti MANET tradisional. Oleh itu, satu skim kawalan kesesakan yang cekap dicadangkan, yang terdiri daripada tiga sub-skim yang berbeza untuk menangani tiga masalah kesesakan rangkaian yang berbeza yang menyebabkan pembaziran tenaga. Pertama, skim Pengesanan Kesesakan Hop demi Hop dibangunkan untuk menangani pengesanan kesesakan yang tidak tepat akibat daripada ralat positif palsu dan negatif palsu. Kedua, skim Pengelakan Kesesakan Secara Pencegahan dan Reaktif direka untuk mengendalikan masalah had lebar jalur yang berubah-ubah yang mengakibatkan kadar kesesakan yang tinggi. Akhir sekali, skim Pengimbangan Beban Peka Kesesakan diwujudkan untuk mengendalikan lebar jalur kongsi yang tidak seimbang yang membawa kepada kadar kesesakan yang tinggi. Perbandingan prestasi telah dijalankan secara *testbed* antara skim kawalan kesesakan yang dicadangkan dengan dua penyelesaian kawalan kesesakan sedia ada dalam daemon penghantar NDN (NFD) iaitu, Skim Kawalan Kesesakan Praktikal untuk NDN (PCON) dan Protokol Usaha Terbaik Kebolehpercayaan Pautan (BELRP). Prestasi skim ini diukur dan dianalisis menggunakan metrik yang sesuai seperti kadar pengesanan kesesakan, kadar pemindahan data dan penggunaan tenaga nod pengguna. Dalam senario topologi garis dasar, skim kawalan kesesakan yang dicadangkan mempunyai ketepatan mengesan kesesakan yang lebih baik dengan kadar pengesanan kesesakan serendah 42.91%, berbanding PCON (69.68%) dan BELRP (43.37%). Skim kawalan kesesakan yang dicadangkan juga menghasilkan kadar pemindahan data yang lebih baik sebanyak 3.39 kbps, berbanding PCON (1.17 kbps) dan BELRP (0.94 kbps) dalam senario mobiliti rawak. Malahan dalam senario mobiliti rawak, penggunaan tenaga nod pengguna bila menggunakan skim kawalan kesesakan yang dicadangkan adalah lebih rendah pada 1445.7 joule, berbanding PCON (4082.83 joule) dan BELRP (5214 joule). Kesimpulannya, skim kawalan kesesakan yang dicadangkan mengatasi prestasi penyelesaian kawalan kesesakan yang sedia ada yang dinyatakan di atas.

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LIST OF ABBREVIATIONS

2S-LCD	–	Two Stages Local Congestion Detection
3S-HOPTS	–	Three States of Hop-by-Hop Traffic Shaping
ABRA	–	Adaptive Backoff Response Approach
ACK	–	Acknowledgment
ACO	–	Ant Colony Optimisation
ADU	–	Ad Hoc Dynamic Unicast
ASF	–	Adaptive SRTT-based Forwarding Strategy
AddDupacks	–	Additional duplicate acknowledgment
ADV-CC	–	Ad hoc Distance Vector with Congestion Control
AF	–	Adaptive forwarding
AF-BELRP	–	Adaptive forwarding with BELRP
AF-PCON	–	Adaptive forwarding with PCON
AI	–	Artificial intelligence
AIMD	–	Additive-increase/Multiplicative-decrease
AODV	–	Ad hoc On-Demand Distance Vector
AOMDV	–	Ad hoc On-Demand Multipath Distance Vector
API	–	Application programming interface
ARCCR	–	Adaptive reliable and congestion control routing protocol
ARM	–	Advanced RISC Machine
ASRM	–	Adjusting sending rate module
ASU	–	Adaptive Smoothed-RTT Update
ATCP	–	Ad hoc TCP
ATP	–	Ad hoc Transport Protocol

AQM	–	Active queue management
BELRP	–	Best Effort Link Reliability Protocol
BER	–	Bit error rate
BLOOGO	–	BLOOm filter based GOssip algorithm
C3TCP	–	Cross-layer Congestion Control for TCP
CALB	–	Congestion-Aware Load Balancing
CAS	–	Congestion adjacent state
CCF	–	Congestion control framework
CCN	–	Content Centric Networking
CCS	–	Congestion control scheme
CCTCP	–	Content-centric TCP
CDR	–	Content detection rate
CS	–	Content store
CState	–	Congestion state
CSV	–	Comma-separated values
CHoPCoP	–	Chunk-switched Hop Pull Control Protocol
CoDel	–	Controlled delay
CW	–	Congestion warning
cwdDec	–	Number of congestion window size decrement (congestion detected)
DCCP	–	Datagram Congestion Control Protocol
DDLRP	–	Detecting and differentiating the loss of retransmitted packets
E-CHANET	–	Enhanced-content-centric multi-hop wireless network
ECN	–	Explicit Congestion Notification
EELRP	–	Energy Efficient Link Reliability Protocol
EROTT	–	Estimated relative one-way trip time
EWMA	–	Exponentially-weighted moving average

ECI	–	Explicit congestion indication
F-ECN	–	Fuzzy logic-based explicit loss discrimination scheme
FIB	–	Forwarding information base
FMLB	–	Fibonacci Multipath Load Balancing
FRL	–	Fast retransmission loss
FCLCC	–	Fuzzy cross-layer congestion control
HCD	–	Hop-by-hop congestion detection
HCN	–	Host Centric Networking
HIS	–	Hop-by-hop interest shaper
HoBHIS	–	Hop-by-hop interest shaping
HR-ICP	–	Hop-by-hop and receiver-driven interest control protocol
HWCC	–	Hop-by-hop window-based congestion control
IAT	–	Inter arrival time
IBBS	–	Independent Basic Service Set
ICN	–	Information Centric Networking
ICP	–	Interest control protocol
ICTP	–	Information-Centric Transport Protocol
IDE	–	Integrated development environment
IFR	–	Immediate fast recovery
IP	–	Internet Protocol
IRTOR	–	Immediate retransmission timeout recovery
LFBL	–	Listen First Broadcast Later
LDM	–	Loss detection mechanism
LLD	–	Link loss detection
LLFRT	–	Link layer fast retransmit
lostSeg	–	Number of lost or retransmitted segments

MAC	–	Medium access control
MAD-TCP	–	Mobile ad hoc TCP
MADN	–	Multipath ad hoc data network
MANET	–	Mobile Ad hoc Network
MFC	–	Multi-path flow control
MIAIMD	–	Multiplicative-increase/Additive-increase/Multiplicative-decrease
MIRCC	–	Multipath-aware ICN rate-based congestion control
MIMO	–	Multiple-Input and Multiple-Output
MIMD	–	Multiplicative-increase/Multiplicative-decrease
MLBCC	–	Multipath Load Balancing Technique for Congestion Control
NACK	–	Negative acknowledgment
NCE	–	Non-congestion events
NDN	–	Named Data Networking
NFD	–	Named Forwarding Daemon
nMANET	–	Named-based Mobile Ad hoc Network
pCHoPCoP	–	Parallel CHoPCoP
PCC	–	Predictive capacity consumption
PCON	–	Practical Congestion Control Scheme for NDN
PIT	–	Pending Interest Table
PLBCD	–	Packet loss-based congestion detection
PMU	–	Power Management Unit
PMU IC	–	Power Management Unit Integrated Circuit
PRCA	–	Preventive and Reactive Congestion Avoidance
PROCALB	–	Probability based Congestion-Aware Load Balancing
RAAQM	–	Remote adaptive active queue management
RALM	–	Reliable adaptive lightweight multicast

RCA – Reactive Congestion Avoidance
REHOPCON – Reliable Hop-by-Hop Congestion Notification
REM – Random early marking
RIC – Receiver interest control
RLDetection – Retransmission loss detection
ROS – Robot Operating System
ROTT – Relative one-way round-trip time
RTO – Retransmission timeout
RTT – Round-trip time
SELF-FRR – Self Fast Retransmit and Recovery
SBC – Single Board Computer
SCTP – Stream Control Transmission Protocol
SECN – ECN-based control with smart forwarding
SIRC – Self-regulating interest rate control
SNR – Signal-to-noise ratio
SRTT – Smoothed round-trip time
STR – Sustainable packet transmission rate
T- DLRP – Loss of fast retransmitted packets
TCP – Transmission Control Protocol
TCP-BUS – TCP with BUffering capability and Sequence information
TCP-ABSE – TCP adaptive bandwidth share estimation
TCP-ELFN – TCP with explicit link failure notification
TCP-F – TCP-Feedback
TCP-NCE – TCP for Non-Congestion Events
TCP-R – TCP Redirection
TCP-WAM – TCP for wireless asymmetric networks

TCP-Welcome	–	TCP variant for Wireless Environment, Link losses, and COngestion packet loss ModEls
TCP/IP	–	Transmission Control Protocol/Internet Protocol
TDLRP	–	Timestamp based Detection of the Loss of Fast Retransmitted Packets
ToM	–	Testbed on MANET
ToMRobot	–	Testbed on MANET's Mobile Robot
TSEcR	–	TS Echo Reply
UDP	–	User Datagram Protocol
VIP	–	Virtual interest packet
WCCP	–	Wireless congestion control protocol
WOOF	–	Wireless cOngestion Optimized Fallback

LIST OF SYMBOLS

B_l	–	Estimated local link bandwidth at t time.
$Backoff_t$	–	Multiplier of RTO_t based on the changes of $SRTT$
$MAX_i(t)$	–	Maximum limit of interest sending rate at t time.
$p(i)$	–	Probability of each content path, based on ranking.
$R_i(t)$	–	Interest sending rate at t time.
RTO_t	–	Retransmission Timeout at t time.
RTT_t	–	Round-trip Delay Time at t time.
$SRTT_t$	–	Smoothed Round-trip Delay Time at t time.

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CHAPTER 1

INTRODUCTION

1.1 Overview

A Mobile Ad hoc Network (MANET) is a decentralised ad hoc network without network infrastructure such as routers, access points and base stations. Each ad hoc node in the network is connected to the others through a shared wireless channel. At the same time, each node in the network serves as both a user node and a router for network traffic from other nodes. MANET is set apart from other ad hoc networks such as mesh networks by its unique feature which is node mobility.

In choosing communication protocol for MANET, researchers may use Named Data Networking (NDN) instead of Host Centric Networking (HCN) such as TCP/IP. The architecture of NDN was designed and developed by Van Jacobson, who is the same person responsible for introducing congestion control for TCP/IP when the Internet experienced a critical congestion collapse in the mid-80s. Van Jacobson created NDN on his observations that the network's problems have changed, and that it awareness was important for the future needs of the Internet. The problems in current and future Internet do not longer revolve around the issue of connectivity between networks, but it is more about effectiveness in content sharing and content distribution. In fact, TCP/IP is not an efficient communication protocol to handle the problem of content sharing and distribution (Jacobson *et al.*, 2009; Zhang *et al.*, 2014b; Saxena *et al.*, 2016).

NDN has many advantages over TCP/IP as a communication protocol in MANET. For example, NDN eliminates the dedicated link session requirement for communication between source and destination nodes, which corresponds to the dynamic nature of MANET. NDNs also natively support node mobility, multipath routing, in-network caching, content level security and broadcast friendly protocols (Zhu *et al.*, 2013; Zhu, 2013). Furthermore, each mobile node in NDN-based MANET does not need to update network topology information, as practiced in HCN-based MANET (Conti *et al.*, 2015).

NDN-based MANET is also made up of ad hoc networks of mobile devices, similar to HCN-based MANET. Therefore, one of the challenges shared by both types of MANETs is that the mobile devices in the network have limited energy supplies derived from their batteries. The life of each mobile device in MANET is limited by the amount of power the battery can provide, and the life of the mobile device determines the life of the network itself. Since the maximum limit of the energy supply is fixed, the only thing that can be done to extend the life of the mobile device in the network is to lower the energy consumption of the mobile device.

One of the ways to improve energy efficiency in NDN-based MANET is through the effective control of the network congestion that occurs in it. Implementing congestion control in an NDN-based MANET environment is more challenging than with infrastructured NDN. NDN-based MANET does not have a dedicated facility for effectively managing the network congestion. Therefore, the task of managing network congestion is placed on the mobile device. Exploring efficient congestion control strategies to handle network congestion in NDN-based MANET is essential for improving the energy efficiency of NDN-based MANET.

1.2 Problem Background

In the past years, researchers have shown interest in energy efficiency improvements in NDN-based MANET such as Rehman *et al.* (2017), Wu *et al.* (2018), Xie *et al.* (2018), and Tariq *et al.* (2019). In the literature, it is found that most of the previous works on improving energy efficiency were focused on content routing solutions through forwarding strategy optimised for a MANET environment (Rehman and Kim, 2015; Tariq *et al.*, 2019), content-store strategy (Gao *et al.*, 2016; Hahm *et al.*, 2017; Wang *et al.*, 2014) and transport mechanism (Amadeo *et al.*, 2014).

Based on the preliminary studies, there is a lack of prior research focusing on congestion control for NDN-based MANET as shown in Figure 1.1. Meanwhile, network congestion is one of the main causes of energy wastage in MANET, including NDN-based MANET. It is difficult to put energy wastage into context, however, because there are very few references related to congestion control for NDN-based MANET, thus, existing works of congestion control for HCN-based MANET and wired NDN are also considered in this study.

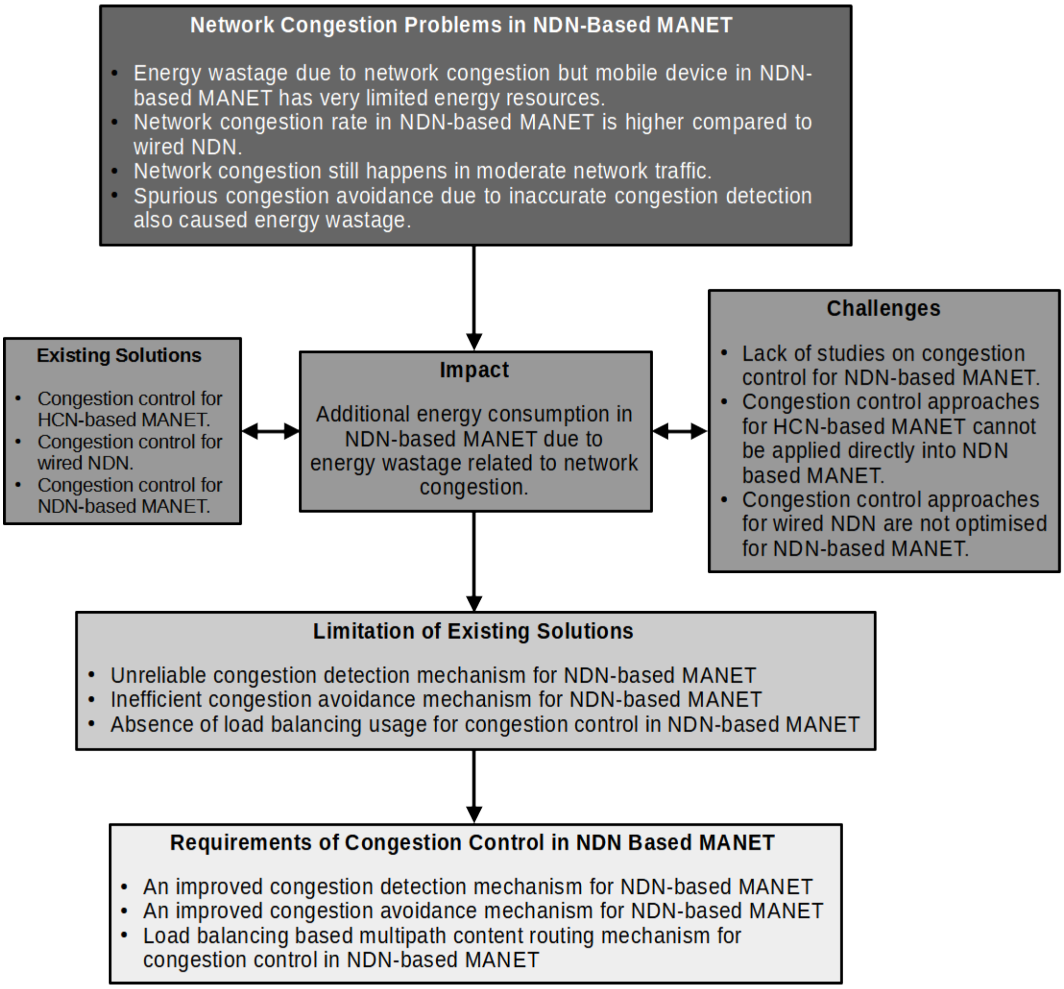

Figure 1.1 Problem leading to the research

Network congestion occurs when network traffic exceeds the available network capacity, which leads to packet loss, round trip delay, drastic reduction in network throughput and energy wastage. Relating to other communication networks, network congestion also occurs in NDN-based MANET. In fact, the network congestion rate in NDN-based MANET is higher than wired NDN.

In addition, the effects of energy wastage due to network congestion have a critical impact on NDN-based MANET because the energy resources in MANET are very limited. Efficient congestion control can conserve the lifespan of mobile devices in the network, which will also extend the lifespan of the network itself. In order to know how to control network congestion in NDN-based MANET efficiently, it is necessary to know how network congestion causes energy wastage.

Energy wastage in NDN-based MANET related to network congestion is due to two different causes. The first cause is that the congestion detection approaches used are less reliable for NDN-based MANET environment, which is true because of two reasons. The first is that the indicators used to determine congestion status are not suitable for MANET environments or NDN architecture. Energy wastage occurs as a result of spurious congestion avoidance such as unnecessary drastic network traffic reduction or packet retransmission even when no congestion occurs. The second reason for the unreliability of the approaches is due to the absence of a congestion detection mechanism, instead only relying on the congestion prevention mechanism. Energy wastage occurs because the congestion is not removed immediately, which lead to failed detection. The reason is that the congestion persists because it is very challenging to completely prevent congestion in MANET environment.

The second cause of energy wastage are due to high network congestion rates in NDN-based MANET. There are two factors that cause network congestion rates is very high in NDN-based MANET.

The first factor is that existing congestion avoidance approaches are not reducing congestion rate in NDN-based MANET. But only remove congestion after it is detected, which is not enough due to fluctuated bandwidth nature in MANET environment. Thus, congestion is still being experienced due to lack of efficient mechanism for preventing congestion. Even when the congestion is proactively prevented, the network congestion is still significantly observed, which is due to the fluctuated bandwidth. Another reason is that in preventive congestion avoidance there are no mechanism to efficiently remove congestion and it will take more times to recover network connection from congestion.

The second factor of high rates congestion in NDN-based MANET is the lack of load balancing mechanism for the purpose of congestion avoidance, although there is native support for multipath content routing in NDN-based MANET. The high rate of network congestion caused by the high network load on a single content path leads to energy wastage. Meanwhile, the shared bandwidth capacity in MANET is very limited.

Thus, energy wastage associated with network congestion in NDN-based MANET occurs due to the inefficiency of existing congestion control approaches. The part that need improvement in energy wastage due to congestion is efficient congestion control for NDN-based MANET that can significantly enhance energy efficiency of NDN-based MANET.

In developing efficient congestion control for NDN-based MANET, the first challenge is to figure out what is the unique properties of NDN-based MANET that needs to be tackle in term of congestion control. The second challenge is to figure out which NDN features that can be exploited for the benefit of improving the efficiency of congestion control for NDN-based MANET. In addition, the third challenge is the congestion control approaches for HCN-based MANET that cannot be applied directly into NDN-based MANET.

There are few existing works on the implementation of congestion control in NDN-based MANET. A further challenging issue is that the approaches used by all of the existing studies are not different from the approaches used in congestion control for wired NDN. In other words, existing congestion control for NDNs use approaches that are less practicable for MANET environments.

Most of the information on congestion control approaches for MANET environments is obtained from existing congestion control for HCN-based MANETs. Considering the architectural and functionalities differences between NDN and HCN, the information may not be directly suitable for NDN-based MANET. Modifications are needed to enable congestion control approaches for HCN-based MANETs to be applicable, but such modifications are not straightforward. From what is discussed in this section, the unaddressed problems in the existing work of NDN-based MANET provides the motivation to venture in this research with the opportunity to explore new approaches for improving energy efficiency by handling congestion problem in NDN-based MANET.

1.3 Problem Statement

The three problems relating to network congestion issues, which causes energy wastage in NDN-based MANET have been selected in this research, namely: (i) false positives and false negatives in congestion detection in NDN-based MANET will cause inefficient congestion control mechanism; (ii) high rate of network congestion in NDN-based MANET, which is caused by wireless network bandwidth limit fluctuation; and (iii) high rate of network congestion caused by limited shared wireless bandwidth because of the limited capabilities of mobile devices as ad hoc wireless routers in NDN-based MANET.

The first problem of network congestion issue in NDN-based MANET refers to the inaccuracy in detecting network congestion due to false positives and false negatives during congestion detection. By definition, false positive during congestion detection is referred to as spurious congestion detection where congestion control is assumed based on indicator that congestion has occurred but in reality it is not. False detection is caused by the use of incompatible congestion detection methods for NDN-based MANET. For instance, in congestion detection based on retransmission timeout (RTO), packet loss-based congestion detection and delay-based congestion detection. These are incompatible congestion detection methods that may result in false positives for congestion detection. In these detection approaches, the system triggers congestion control mechanisms, even though no congestion has occurred. That will lead to the unnecessary retransmission, underutilisation of network bandwidth and energy wastage.

On the other hand, false negative during congestion detection is referred to condition where congestion control failed to detect congestion that has occurred whether it occurred locally or remotely. Most of the existing congestion control solutions for NDN-based MANET do not have a congestion detection mechanism due to the assumption that network congestion can be avoided through adjusting the adaptive interest sending rate. This assumption cannot be adopted for NDN-based MANET, and it could lead to false negatives congestion detection, which cause slow congestion recovery when congestion occurs.

The second problem in network congestion for NDN-based MANET is that network congestion is not only triggered by high network traffic, but also can occur in moderate network traffic due to fluctuation of the wireless network bandwidth. Random changes of wireless bandwidth in MANET is caused by node mobility and unreliable wireless channel for example, wireless signal interference, broadcast storm and hidden terminal. Existing works on congestion avoidance for NDN-based MANET only use either preventive congestion avoidance or reactive congestion avoidance. Congestion rate in NDN-based MANET is high due to fluctuating wireless bandwidth in MANET environment. Therefore, congestion rate is still high when only preventive congestion avoidance methods is used in the MANET environment. When network congestion occur, it may take longer time to be removed due to absence of a congestion removal mechanism. And also whenever only the reactive congestion avoidance approach is used, then the network congestion may still be high, as measures are only taken after the network congestion is detected.

The third problem in network congestion for NDN-based MANET is the high rate of network congestion, which causes energy wastage due to limited shared wireless bandwidth. MANET has very limited shared wireless bandwidth due to limited capabilities of mobile devices that serves as wireless routers. Thus, mobile device cannot provide large wireless bandwidth compared to dedicated wireless router or relay in infrastructure-based network such as a base transceiver station (BTS) of a cellular network or a wireless access point (AP) of a wireless local area network (WLAN). Network congestion may persist in MANET when network traffic is delivered through a single routing path for every transmission. However, there are lack of existing congestion controls for NDN-based MANET that use multipath content routing for congestion control.

1.4 Research Questions

Considering the discussion provided in Sections 1.2 and 1.3, the following research questions are addressed towards achieving the research objectives:

i) Does using combination of link layer hop-by-hop congestion detection, link loss differentiation and reliable congestion notification approaches can minimise false positive and false negatives during congestion detection in NDN-based MANET?

ii) Does using combination of preventive and reactive congestion avoidance approaches can reduce high rates of network congestion in NDN-based MANET due to wireless network bandwidth limit fluctuation?

iii) Does using congestion-aware load balancing approach can reduce high rates of network congestion in NDN-based MANET due to limited shared wireless bandwidth in NDN-based MANET?

1.5 Research Aim

The aim of this research is to propose a congestion control solution that is able to reduce energy wastage in NDN-based MANET by tackling three issues considered in this research. The issues include, minimising false positives and false negatives during congestion detection, reducing high rates of network congestion due to the fluctuation of limited shared wireless network bandwidth and improving the usage of limited shared wireless network bandwidth of mobile devices.

1.6 Research Objectives

To achieve the aim of this research, three objectives have been established:

i) To propose a Hop-by-Hop Congestion Detection scheme that minimises false positives and false negatives during congestion detection in NDN-based MANET.

ii) To propose a Preventive and Reactive Congestion Avoidance scheme that reduces high rates of network congestion due to wireless network bandwidth limit fluctuation in NDN-based MANET.

iii) To propose a Congestion-Aware Load Balancing scheme that decreases network congestion due to limited shared wireless bandwidth in NDN-based MANET.

1.7 Research Scope and Assumption

i) For content routing in NDN-based MANET, this research only focuses on the use of multipath content routing for congestion control purposes, and does not focus on dynamic content routing.

ii) The wireless technology used in this research is IEEE 802.11n.

iii) The mobile device used for the experiment in this research uses a single-board computer (SBC), because it has a similar processor, memory chip, internal storage and Wi-Fi device as a smart phone.

iv) The first assumption in this research is that network congestion is one of the main cause of energy wastage in NDN-based MANET.

v) The second assumption is that congestion control that efficiently reduce and remove network congestion in NDN-based MANET must take into account of all the unique properties of MANET and NDN architecture.

1.8 Research Contributions

The main contributions of this research are presented in accordance to the objectives as follows:

i) A Hop-by-Hop Congestion Detection scheme is proposed to improve the accuracy of network congestion detection in NDN-based MANET by reducing false positives and false negatives during congestion detection through a combination of local congestion detection at the link layer and hop-by-hop congestion notification. Therefore, the accuracy of congestion detection in NDN-based MANET and the energy efficiency of NDN-based MANET is improved.

ii) A Preventive and Reactive Congestion Avoidance scheme is proposed to reduce high rates of network congestion due to the fluctuation of limited wireless network bandwidth through a combination of hop-by-hop traffic shaping and self fast retransmit and recovery. Consequently, the efficiency of congestion control such as the goodput of network communication and the energy efficiency of NDN-based MANET is improved.

iii) A Congestion-Aware Load Balancing scheme is proposed to improve the utilisation of limited shared wireless bandwidth in NDN-based MANET by proactively distributing the network loads through several different paths. Thus, the efficiency of congestion control including goodput of a network communication and the energy efficiency of NDN-based MANET is improved.

1.9 Significance of the Research

Energy resources are very limited in MANET and improving energy efficiency is the only way to extend the life of the network in MANET. Among the main challenges of implementing MANET as a communication technology in the real world, especially for civilians, is the problem of excessive packet loss and the delay of network communication due to high rates of network congestion in MANET and high energy wastage during network communication in MANET. Both challenges were successfully overcome using the proposed congestion control scheme. Therefore, the use of the proposed congestion control scheme for NDN-based MANET can improve the adaptation of the use of NDN-based MANET in the real world.

Finally, the use of the proposed congestion control scheme can also increase the lifespan of the network in NDN-based MANET, because the lifespan of the mobile device is extended through the reduction of energy wastage. At the same time, the goodput of network traffic has also been significantly improved, and this can increase the efficiency of using NDN-based MANET for real world applications, such as peer-to-peer multimedia content sharing and ad hoc video conferencing in MANET environments.

1.10 Organization of the Thesis

The structure and organisation of the rest of the thesis are outlined as follows:

Chapter 2 presents a comprehensive literature review of the three areas; congestion control for HCN-based MANET, congestion control for wired/infrastructure-based NDN and congestion control for NDN-based MANET. In this chapter, there are also a discussion on limitations of existing works from the three areas related to practical congestion control for NDN-based MANET.

Chapter 3 presents the research methodology used in this research. The research framework consists of three main phases. The first phase presents the review and analysis of the literature of previous works, as well as the research plan, which is the problem-solving method chosen for this research. In also includes the research aim, research questions and research objectives to determine how research aim is achieved. The second phase focuses on the design and development of the proposed solution according to the proposed criteria, based on the research objectives of this research. The third phase presents the design and development of the MANET testbed facility and the design of the experiment for evaluation of the proposed solution of this research.

Chapter 4 describes in detail how each research objective is accomplished in a prototype of the proposed congestion control scheme, which is a combination of three different main schemes: Hop-by-Hop Congestion Detection scheme, Preventive and Reactive Congestion Avoidance scheme and Congestion-Aware Load Balancing scheme. Each of these schemes has been described in detail, including the algorithms and techniques developed for each scheme.

Chapter 5 chronicles the experiments and results for all the three proposed schemes. The analysis is presented quantitatively using graphs and statistical data obtained from experiments conducted. Results from the analysis indicate whether or not the suggested solutions performed better in terms of energy consumption when compared to existing congestion control solutions – namely, a practical congestion control scheme for NDN (PCON) and best effort link reliability protocol (BELRP). At the same time, congestion control efficiency is also measured as to ensure that the suggested solution does not sacrifice congestion control efficiency in attempts to achieve energy efficiency in congestion avoidance.

Chapter 6 presents the conclusion, describing the contributions made by this study and suggesting future directions. This chapter also presents the achievements of the set objectives and a conclusion based on performance evaluation.

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Appendix A Terminology in This Research

Several terms need to be defined to facilitate the explanation of the proposed congestion control scheme. This is because the development of congestion control solutions in NDN is considerably new and because the related terminologies are still not being standardized. Therefore, knowledge of several terms that are related to congestion control for NDN and NDN-based MANET is important to fully understand the solution suggested in this thesis.

- **HCN-Based MANET**

  Host-Centric Networking (HCN) based MANET refers to traditional MANET using HCN, especially TCP/IP, as a communication protocol between nodes. Multihop routing is based on a combination of IP addresses for sender nodes and receiver nodes, as practiced on today's infrastructure networks, such as the Internet.

- **NDN-Based MANET**

  Named Data networking (NDN) based MANET refers to a new paradigm of MANET implementation that uses NDN as a communication protocol between nodes. Multihop routing is done based on the content name required by the consumer node, rather than the host identity, such as TCP/IP using the IP address of each end node.

- **Dynamic Content Routing**

  In NDN, the process of updating the information in the routing table for content retrieval purposes is called content routing. This is because the communication in the NDN is based on the content name and not the end nodes' IP addresses. Because the routing table is dynamically updated in NDN-based MANET, the routing mechanism is called "dynamic content routing".

- **Consumer Node**

  Consumer node refers to the component that performs content requests in NDN-based MANET. Sometimes, it is also known as a content consumer or content requester. In TCP/IP, it is usually called a receiver node, however, the use of this term can be somewhat confusing, since network traffic is two-way in nature, including both interest traffic and data traffic. Consumer nodes send interest packets to obtain data packet from content providers. Therefore, the consumer node acts as the sender node for interest packet traffic and as the receiver node for data packet traffic.

- **Producer Node**

  Producer node refers to the node that produces or creates the desired content. Sometimes, it is also called a content producer. The producer node automatically becomes a provider node in the NDN.

- **Provider Node**

  Provider node refers to the node that possesses the content required by the consumer node, but it does not necessarily have to be content producer. This includes content store, content repository and content proxy.

- **Intermediate Node**

  Intermediate node refers to a mobile node that acts as a relay for the network traffic from other mobile nodes in MANET.

- **Congested Node**

  Congested node refers to any mobile nodes in MANET that are affected by network congestion in their local link with their single-hop neighbour nodes. Congested nodes are also known as intermittent nodes, however, this term is less suitable, since it is also used for infiltrated vulnerable nodes.

- **Hop-by-Hop Congestion Control**

  Hop-by-hop congestion control is performed in the network by intermediate nodes. If it is inside an infrastructured network, then hop-by-hop congestion control is performed by a router or switch. Inside MANET, it is performed by intermediate mobile nodes acting as relays for network traffic from other mobile nodes.

- **Consumer-Driven Congestion Control**

  Consumer-driven congestion control, also known as receiver-driven congestion control in other researches, derived from TCP/IP. The term is somehow misleading in terms of its use for NDN, since network traffic in NDN travels in two directions. When interest forwarding is being performed, the consumer node becomes the sender, while the provider node becomes the receiver. Whereas, when data forwarding is being conducted, the consumer node becomes the receiver and the provider node becomes the sender. Therefore, consumer-driven congestion control was chosen as a term in this research to avoid such confusion.

- **Traffic Shaping**

  Traffic shaping is better known as flow-control in several past literatures, such as Byun *et al.* (2013), Amadeo *et al.* (2013), Byun *et al.* (2014), Amadeo *et al.* (2014), Albalawi (2016), and Schneider *et al.* (2016), with the term borrowed from TCP/IP. Several other literatures have used interest shaping as its name, such as Carofiglio *et al.* (2012a), Carofiglio *et al.* (2012b), Carofiglio *et al.* (2013a), Carofiglio *et al.* (2013b), Wang *et al.* (2013), Park *et al.* (2014), Rozhnova and Fdida (2014), Abu *et al.* (2016), Ndikumana *et al.* (2017), Kato and Bandai (2017), Kato and Bandai (2018b), Ahlgren *et al.* (2018), and Mejri *et al.* (2018). The term traffic shaping is more suitable to be used here, since network traffic in NDN has two different opposite flow directions, namely, interest traffic and data traffic. As of the current date, all of the traffic shaping methods proposed in the previously mentioned literature manipulate the interest sending rate to indirectly control the data receiving rate. This suggests that the term traffic shaping is much more suitable and accurate to be used.

- **Congestion Notification**

  Congestion notification refers to the notification of network congestion performed at the network layer, such as the ones used in explicit congestion notification (ECN) inside TCP/IP. Congestion notification is also known as explicit congestion notification (Zhou *et al.*, 2015), congestion notification (Albalawi, 2016; Schneider *et al.*, 2016) and congestion message (Wang *et al.*, 2018) in previous literatures on congestion control for NDN. Congestion notification can be performed using two main methods, which are the use of congestion NACK (negative acknowledgment), as practiced in Stateful Forwarding Plane (Yi *et al.*, 2013), and using it piggybacked with congestion mark inside the data packet, as in PCON (Schneider *et al.*, 2016). Congestion notification is sent by the congested node either directly to the consumer node or in a hop-by-hop method.

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