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Hayder Al-Kashoash

Congestion Control for 6LoWPAN Wireless Sensor Networks: Toward the Internet of Things

Doctoral Thesis accepted by
the University of Leeds, Leeds, UK

Springer

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Supervisor's Foreword

The internet of things (IoT) is rapidly becoming widely accepted and recognized as the communications paradigm of our time. This was not the case when this student was starting his Ph.D. studies but it has rapidly moved forward, at that stage wireless sensor networks (WSNs) were the dominant solution and this migrated to WSNs and 6LoWPAN networks. Indeed in this thesis, the IoT is largely considered to be a combination of WSNs and 6LoWPAN networks. The work contained in this thesis traces the work of a very gifted student who with small encouragement from his supervisor developed a thorough investigation into the control of congestion for IoT applications. Congestion is the overloading of traffic across networks and clearly needs to be avoided. As a result of congestion, routers in a network will find their input and their output buffers will become full and overflow leading to data loss. Fundamentally, it occurs when the aggregate data coming into a network exceeds the total data leaving the network. Methods to avoid congestion are not straightforward but ‘boil down’ to reducing the data entering the network or increasing the rate at which data leaves the network. In the TCP/IP suite, TCP itself deals with congestion control through managing the rate at which nodes transmit data into the network. TCP is not a ready solution for the IoT due to its heavy header overhead; something more lightweight is needed. The lightweight solution is fundamentally UDP but this does not have any provision for congestion control. Consequently, there is a real need in the rapidly expanding IoT for the provision of congestion control. In this thesis, Hayder examines the problem of congestion, how it can be detected, what action can be taken to avoid it and offers suggestions of how best to alleviate it. He details the networks he is dealing with and the propagation mechanisms which will lead to congestion. This work uses the simulation of networks to explore the actions which can be taken and the anticipated results of those actions. He also uses real network experiments to validate his simulation work. In conclusion, I feel that by working through this thesis the reader have their understanding of networking, and of congestion very greatly enhanced.

Leeds, UK Prof. Andrew Kemp

Abstract

The internet of things (IoT) is the next big challenge for the research community. The IPv6 over low-power wireless personal area network (6LoWPAN) protocol stack is considered a key part of the IoT. Due to power, bandwidth, memory, and processing resources limitation, heavy network traffic in 6LoWPAN networks causes congestion which significantly degrades network performance and impacts on the quality of service (QoS) aspects. This thesis addresses the congestion control issue in 6LoWPAN networks. In addition, the related literature is examined to define the set of current issues and to define the set of objectives based upon this.

An analytical model of congestion for 6LoWPAN networks is proposed using Markov chain and queuing theory. The derived model calculates the buffer-loss probability and the number of received packets at the final destination in the presence of congestion. Simulation results show that the analytical modelling of congestion has a good agreement with simulation. Next, the impact of congestion on 6LoWPAN networks is explored through simulations and real experiments where an extensive analysis is carried out with different scenarios and parameters. Analysis results show that when congestion occurs, the majority of packets are lost due to buffer overflow as compared to channel loss. Therefore, it is important to consider buffer occupancy in protocol design to improve network performance.

Based on the analysis concluded, a new IPv6 routing protocol for low-power and lossy network (RPL) routing metric called buffer occupancy is proposed that reduces the number of lost packets due to buffer overflow when congestion occurs. Also, a new RPL objective function called congestion-aware objective function (CA-OF) is presented. The proposed objective function works efficiently and improves the network performance by selecting less congested paths. However, sometimes the non-congested paths are not available and adapting the sending rates of source nodes is important to mitigate the congestion.

Accordingly, the congestion problem is formulated as a non-cooperative game framework where the nodes (players) behave uncooperatively and demand high data rate in a selfish way. Based on this framework, a novel and simple congestion control mechanism called game theory based congestion control framework (GTCCF) is proposed to adopt the sending rates of nodes and therefore, congestion can be solved. The existence and uniqueness of Nash equilibrium in the designed game are proved and the optimal game solution is computed by using Lagrange multipliers and Karush–Kuhn–Tucker (KKT) conditions. GTCCF is aware of node priorities and application priorities to support the IoT application requirements. On the other hand, combining and utilizing the resource control strategy (i.e. finding non-congested paths) and the traffic control strategy (i.e. adapting sending rate of nodes) into a hybrid scheme is important to efficiently utilize the network resources. Based on this, a novel congestion control algorithm called optimization-based hybrid congestion alleviation (OHCA) is proposed. The proposed algorithm combines traffic control and resource control strategies into a hybrid solution by using the network utility maximization (NUM) framework and a multi-attribute optimization methodology, respectively. Also, the proposed algorithm is aware of node priorities and application priorities to support the IoT application requirements.

Declaration

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis, where reference has been made to the work of others. Most materials contained in the chapters of this thesis have been previously published in research articles written by the author of this work (Hayder Ahmed Abdulmohsin Al-Kashoash), who appears as lead (first) author in all of them. The research has been supervised and guided by Prof. Andrew Kemp, and he appears as a co-author on these articles. All the materials included in this document is of the author's entire intellectual ownership.

A. Details of the publications which have been used (e.g. titles, journals, dates, names of authors):

In Chapter 2:

'Congestion Control for Wireless Sensor and 6LoWPAN Networks: Toward the Internet of Things', *Wireless Networks Journal, Springer*, Published. Co-authors: Harith Kharrufa, Yaarob Al-Nidawi and Andrew Kemp.

In Chapter 3:

'Congestion Analysis for Low Power and Lossy Networks', *IEEE 2016 Wireless Telecommunications Symposium (WTS)*, Published. Co-authors: Yaarob Al-Nidawi and Andrew Kemp. (DOI: https://doi.org/10.1109/WTS.2016.748202710.1109/WTS.2016.7482027).

'Analytical Modelling of Congestion for 6LoWPAN Networks', *Elsevier ICT Express Journal*, Published. Co-authors: Fadoua Hassen, Harith Kharrufa and Andrew Kemp.

In Chapter 4:

'Congestion-Aware RPL for 6LoWPAN Networks", *IEEE 2016 Wireless Telecommunications Symposium (WTS)*, Published. Co-authors: Yaarob Al-Nidawi and Andrew Kemp. (DOI: https://doi.org/10.1109/WTS.2016.748202610.1109/WTS.2016.7482026). "***Best Student Paper Award***".

In Chapter 5:

'Congestion Control for 6LoWPAN Networks: A Game Theoretic Framework', *IEEE Internet of Things Journal*, Published. Co-authors: Maryam Hafeez and Andrew Kemp. (DOI: https://doi.org/10.1109/JIOT.2017.266626910.1109/JIOT.2017.2666269).

In Chapter 6:

'Optimization Based Hybrid Congestion Alleviation for 6LoWPAN Networks', *IEEE Internet of Things Journal*, Published. Co-authors: Hayder Amer, Lyudmila Mihaylova and Andrew Kemp.

B. Details of the work contained within these publications which is directly attributable to Hayder A. A. Al-Kashoash:

With the exceptions detailed in section C, the published work is entirely attributable to Hayder A. A. Al-Kashoash: the literature review necessary to construct and originate the ideas behind the published manuscripts, the novel ideas presented in the papers, the implementation of congestion analysis and the proposed algorithms used in the Contiki OS and all the work necessary in the editing process of the manuscripts.

C. Details of the contributions of other authors to the work:

Prof. Andrew Kemp is the co-author for all the publications listed above. These publications have been written under his supervision, benefiting from excellent technical advice and editorial, patient guidance and valuable feedback.

Yaarob Al-Nidawi and Maryam Hafeez contributed with recommendations about how to efficiently structure papers and how to emphasize the originality of the work and to make it more accessible to the reader.

Harith Kharrufa, Fadoua Hassen, Hayder Amer and Lyudmila Mihaylova performed proofreading to the final drafts of the papers to ensure the solidity of the papers.

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Contents

Abbreviations

6LoWPAN	IPv6 over Low-Power Wireless Personal Area Network
ACK	Acknowledgement
ACO	Ant Colony Optimization
AHP	Analytical Hierarchy Process
AIMD	Additive-Increase/Multiplicative-Decrease
AODV	Ad hoc On-Demand Distance Vector
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BLIP	Berkeley Low-power IP stack
CCA	Clear Channel Assessment
CoAP	Constrained Application Protocol
CoRE	Constrained RESTfull Environments
CRC	Cyclic Redundancy Check
CSMA	Carrier-Sense Multiple Access
DAG	Directed Acyclic Graph
DAO	Destination Advertisement Object
DGRM	Directed Graph Radio Medium
DIO	DODAG Information Object
DIS	DODAG Information Solicitation
DODAG	Destination-Oriented DAG
DSDV	Destination-Sequenced Distance Vector
DYMO-low	Dynamic MANET On-Demand for 6LoWPAN
ESB	Embedded Sensor Board
ETX	Expected Transmission Count
FCS	Frame Check Sequence
FFD	Full-Function Device
GRA	Grey Relational Analysis
GTS	Guaranteed Time Slots
HiLow	Hierarchical Routing over 6LoWPAN
HTTP	Hypertext Transfer Protocol

IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
IP	Internet Protocol
IPHC	Improved Header Compression
IS-IS	Intermediate System-to-Intermediate System
KKT	Karush–Kuhn–Tucker
LLN	Low-Power and Lossy Network
LOAD	6LoWPAN Ad hoc On-Demand Distance Vector
LPWAN	Low-Power Wide Area Network
LR-WPAN	Low-Rate Wireless Personal Area Network
LQI	Link Quality Indicator
MAC	Medium Access Control
MADM	Multiple Attribute Decision-Making
MANET	Mobile Ad Hoc NETwork
MTU	Maximum Transmission Unit
Nam	Network animator
NED	NEtwork Description
NesC	Network embedded system C
NFC	Near-Field Communication
NHC	Next Header Compression
NUM	Network Utility Maximization
OF	Objective Function
OF0	Objective Function zero
OLSR	Optimized Link State Routing Protocol
OS	Operating System
OSPF	Open Shortest Path First
PDR	Packet Delivery Ratio
PHY	PHYsical layer
POS	Personal Operating Space
QoD	Quality of Data
QoS	Quality of Service
RDC	Radio Duty Cycle
REST	REpresentational State Transfer
RFC	Request For Comment
RFD	Reduced-Function Device
RFID	Radio-Frequency Identification
RPL	IPv6 Routing Protocol for Low-Power and Lossy Networks
SAW	Simple Additive Weighting
SD	Standard Deviation
TCP	Transmission Control Protocol
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UDGM	Unit Disk Graph Medium
UDP	User Datagram Protocol
UGRM	Objective Function

VANET	Vehicular Ad hoc NETwork
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

Symbols

μ^I	Average departure rate of intermediate node I_l
μ^L	Average departure rate of leaf node L
B	Buffer size
BE	Backoff exponent of CSMA
CC_b	Channel Capacity in bit/s
CC_p	Channel Capacity in packet/s
I_l	Intermediate node
L_{inter}	Average number of lost packets/s at intermedaite node's buffer
L_k	Leaf node L_k
L_{leaf}	Average number of lost packets/s at leaf node's buffer
M	Number of leaf nodes
m	Maximum number of backoffs in CSMA
PL	Data packet length (bit)
n	Maximum number of retransmissions in CSMA
NB	Number of backoffs in CSMA
P_{arr}	Probability of packet arrival to node's buffer
$P_{buffer-loss}$	Probability of packet loss at node's buffer
P^j_{caf}	Probability of packet loss due to channel access failure at node j
$P^j_{ch-loss}$	Probability of channel loss for node j
$P_{coll,j}$	Probability that transmitted packet encounters collision at node j
$P_{dep.}$	Probability of packet departure from node's buffer
P^j_{mrl}	Probability of packet loss due to maximum number of retransmissions limit at node j
S	Sink node
T	Time step of Markov chain state transition
T_{ACK}	Time required to transmit ACK packet
T_{data}	Time required to transmit data packet
$T_{data,coll}$	Actual time required to transmit one data packet with collision
$T_{data,nocoll}$	Actual time required to transmit one data packet without collision
w_{etx}	Weight of ETX metric in CA-OF

w_{bo}	Weight of BO metric in CA-OF
$P_{cca,j}$	Probability that CCA is busy in node j
λ_k^I	Average arrival rate at intermediate node I_l from leaf node L_k
λ_{total}^I	Total arrival rates at intermediate node I_l from all leaf nodes
λ_k	Average data rate of leaf node L_k
λ_S	Average number of received packets at sink node S every second
p_k	Priority of leaf node L_k
N	Number of applications hosted in a leaf node
p_k^j	Priority of application j hosted in leaf node L_k
λ_k^{max}	Maximum sending rate of leaf node L_k
S_k	Strategy space of leaf node L_k
SS	Strategy space of all leaf nodes
Φ_k	Payoff function of leaf node L_k
λ_{-k}	Vector of sending rates of all leaf nodes except leaf node L_k
$U_k(\lambda_k)$	Utility function of leaf node L_k
$C_k(\lambda_k, \lambda_{-k})$	Congestion cost function of leaf node L_k
$P_k(\lambda_k; p_k)$	Priority cost function of leaf node L_k
λ_{out}	Forwarding rate of the parent node
λ_{in}	Incoming rate to the parent node
ω_k	Preference parameter of function $U_k(\lambda_k)$
α_k	Preference parameter of function $C_k(\lambda_k, \lambda_{-k})$
β_k	Preference parameter of function $P_k(\lambda_k; p_k)$
λ_k^*	Optimal sending rate (Nash Equilibrium) of leaf node L_k
s^*	Vector of optimal sending rates (Nash Equilibrium) of all leaf nodes
$H(s)$	Hessian matrix of payoff function $\Phi_k(s)$
$\mathcal{L}_k$	Lagrangian function of leaf node L_k
λ_k^j	Sending rate of application j hosted in leaf node L_k
θ_j	Weight of application j
I_{check}	Congestion check interval time
ψ	Smoothing factor
A	Set of candidate parents
R	Set of routing metrics
G	Weight vector
D	Decision matrix
a_i	Candidate parent i
r_j	Routing metric j
x_{ij}	Normalized value of routing metric r_j for parent a_i
$\gamma(x_{ij}, x_{0j})$	Grey relational coefficient
$\Gamma(a_i)$	Grey relational grade
L	Set of children nodes
N_l	Child node N_l
p_l	Priority of child node N_l
K	Set of hosted applications in child node N_l
app^k	Application k

p_l^k	Priority of application app^k hosted in node N_l
λ_l	Sending rate of child node N_l
$U_l(\lambda_l)$	Utility function of child node N_l
$\boldsymbol{\lambda}$	Vector of sending rates of all children nodes
ϕ_l	Weight of $U_l(\lambda_l)$
λ_l^k	Sending rate of application app^k hosted in child node N_l
$U^k(\lambda_l^k)$	Utility function of application app^k hosted in child node N_l
ϕ^k	Weight of $U^k(\lambda_l^k)$

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