Computer Communications and Networks

Series editor
A.J. Sammes
Centre for Forensic Computing
Cranfield University, Shrivenham campus
Swindon, UK

The **Computer Communications and Networks** series is a range of textbooks, monographs and handbooks. It sets out to provide students, researchers, and non-specialists alike with a sure grounding in current knowledge, together with comprehensible access to the latest developments in computer communications and networking.

Emphasis is placed on clear and explanatory styles that support a tutorial approach, so that even the most complex of topics is presented in a lucid and intelligible manner.

More information about this series at http://www.springer.com/series/4198

Jacek Rak

Resilient Routing in Communication Networks

Springer

Jacek Rak
Faculty of Electronics, Telecommunications,
and Informatics
Gdansk University of Technology
Gdansk, Poland

ISSN 1617-7975 ISSN 2197-8433 (electronic)
Computer Communications and Networks
ISBN 978-3-319-22332-2 ISBN 978-3-319-22333-9 (eBook)
DOI 10.1007/978-3-319-22333-9

Library of Congress Control Number: 2015945628

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

To the memory of
my grandfather Jan Rak

Preface

Since the introduction of the Internet in the 1970s of the past century, the concept of global communications has notably changed our daily activities. Communication networks, providing access to products and services at any time and location, have become the key elements of a critical infrastructure our everyday life depends on. Therefore, they are expected to offer uninterrupted service in the presence of various challenges. However, as their effective capacity is predicted to increase to accommodate the more-or-less exponentially growing demand volumes, the cost of failures of network elements is forecasted to rise as well.

Communication networks resilience is undoubtedly a complex issue. For any network architecture, a proper understanding of network challenges, including natural threats, as well as malicious human activities, is thus a necessity to introduce the appropriate preventive mechanisms related to end-to-end communications resilience – the topic addressed in this book.

The target audience includes researchers and professionals in the area of resilience and dependability of current and emerging communication technologies. The content can be also valuable for advanced-level students interested in this research area.

A significant part of work presented here has been carried out in the Department of Computer Communications of the Faculty of Electronics, Telecommunications, and Informatics of Gdansk University of Technology, Poland, as well as during my visits to a number of research centres over the years 2010–2015. In particular, a remarkable share of the content of this book is the implication of discussions during my scholarships, scientific visits, invited lectures, and seminar talks at: Concordia University, Montreal, Canada (Concordia Research Chair Optimization of Communication Networks lead by Brigitte Jaumard); Osaka University, Japan (Photonic Networks Laboratory lead by Ken-ichi Kitayama); National Institute of Information and Communications Technology (NICT) Tokyo, Japan; Ghent University-iMinds (lead by Piet Demeester); Technical University of Munich (Chair of Communication Networks lead by Wolfgang Kellerer); and Halmstad University, Sweden (CERES centre with the leadership of Magnus Jonsson).

A notable part of my works has been done in co-operation with many great researchers, in particular (without the intention of forgetting anyone): Javier Alonso Lopez (University of Leon, Spain), Piotr Chołda (AGH University of Science and Technology, Poland), Tibor Cinkler (Budapest University of Technology and Economics, Hungary), Egemen K. Çetinkaya (The University of Kansas, US/Missouri University of Science and Technology, US), Georgios Ellinas (University of Cyprus), Teresa Gomes (University of Coimbra, Portugal), Róża Goścień (Wrocław University of Technology, Poland), Janusz Gozdecki (AGH University of Science and Technology, Poland), Matthias Gunkel (Deutsche Telekom, Germany), Brigitte Jaumard (Concordia University, Canada), Mirosław Kantor (AGH University of Science and Technology, Poland/University of Luxembourg), Mirosław Klinkowski (National Institute of Telecommunications, Poland), Arie Koster (RWTH Aachen, Germany), Yevgeni Koucheryavy (Tampere University of Technology, Finland), Wojciech Molisz (Gdansk University of Technology, Poland), Hussein Mouftah (Ottawa University, Canada), Krzysztof Walkowiak (Wrocław University of Technology, Poland), Dimitri Papadimitriou (Alcatel-Lucent Bell Labs, Belgium), Mario Pickavet (Ghent University-iMinds, Belgium), Michał Pióro (Warsaw University of Technology, Poland/Lund University, Sweden), Gangxiang Shen (Soochow University, China), Peter Soproni (Budapest University of Technology and Economics, Hungary), Dimitri Staessens (Ghent University-iMinds, Belgium), James P.G. Sterbenz (The University of Kansas, US/Lancaster University, UK/The Hong Kong Polytechnic University, Hong Kong), David Tipper (Pittsburgh University, US), Kishor Trivedi (Duke University, US), Alexey Vinel (Halmstad University, Sweden), Krzysztof Wajda (AGH University of Science and Technology, Poland), Rolland Wessäly (atesio GmbH, Germany), Jozef Wozniak (Gdansk University of Technology, Poland), and Wen-De Zhong (Nanyang Technological University, Singapore).

Gdansk, Poland Jacek Rak

Contents

List of Symbols

A	Set of directed arcs used to represent the network links
A_{nn}	Node-to-node incidence matrix
a_h	Directed arc
$BC(n)$	Betweenness centrality coefficient for node n
b_h	Amount of capacity to be reserved at arc a_h for backup paths under backup capacity sharing
$b_{h,g}$	Total capacity needed for backup paths at arc a_h in the case of shared protection provided for working paths traversing the failed arc a_g
$b_{r,h,g}$	Binary variable to indicate whether for r-th demand the failed primary path traverses arc a_g and the corresponding backup path traverses arc a_h
c_h	Total capacity of arc a_h
$c_h(t)$	Capacity of arc a_h available at time t
$\overline{c_h}$	Unused capacity of arc a_h
$\breve{c}_{m,h}$	The lower bound on capacity required at arc a_h for m-th instance of Parallel Internet
c_r	Minimal residual capacity along links of the calculated path of r-th demand
$\overline{c_r}$	Capacity to be reserved for r-th demand along links traversed by the respective path
D	Set of demands
D_m	Set of demands for m-th instance of Parallel Internet
D^{AN}	Set of anycast demands
D^{DS}	Set of anycast downstream demands
D_{nn}	Node-to-node matrix of demanded capacities (for end-to-end flows)
D^{UN}	Set of unicast demands
D^{US}	Set of anycast upstream demands
d_r	Volume of the r-th demand
$d_{r,m}$	Volume of r-th demand from m-th instance of Parallel Internet

$EPFD\left(\hat{\hat{r}}\right)$	Expected percentage of total flow delivered after a failure
$F[\psi]$	Auxiliary function providing information on the frequency a given percentage ψ of flows ($\psi \in \{0,1,\ldots, 100\}$) is successfully delivered after region failures
f	Total flow transported before occurrence of a failure (in a normal state)
$\hat{f}$	The aggregate flow restored after a region failure
G	Arbitrarily chosen large value
(i, J)	VANET hyperlink between vehicle i and the set of forwarding vehicles J
J	Set of forwarding vehicles in VANET anypath communications
k	Degree of a network node
L	Set of transmission channels
N	Set of network nodes
n	Network node
$N\backslash T$	Set of edge nodes
$PFRS(p)$	p-fractile region survivability
$P\left(\hat{\hat{r}}_n\right)$	Probability of node n failure in a region failure scenario
$P(\delta)$	Probability of occurrence of a failure scenario δ
p	Probability of successful delivery of flows after a region failure
p_h	The upper bound on transmission delay along arc a_h
$p_{i,J}$	Probability of delivering the packet from vehicle i to at least one node from forwarding vehicles J
$p_{i,j}$	Layer 2 probability of packet delivery via VANET link (i, j)
$p_{m,r}$	The upper bound on end-to-end transmission delay for r-th demand from m-th instance of Parallel Internet
$p(r_{i,j})$	Probability density function of inter-vehicle distance
$p_{\Psi}(\psi)$	Probability density function of percentage ψ of flows surviving the region failure
$p_{\Psi}\left(\psi, \hat{\hat{r}}\right)$	Probability density function of Ψ defined for region failures of radius $\hat{\hat{r}}$
$P_i(t)$	Probability that a system is in state i at time t
$RFS(\psi)$	Region failure survivability function
R_p	Rain rate in mm/h
r	Index of a demand
$r_{i,j}$	Distance between nodes i and j
$\hat{\hat{r}}$	Radius of a failure region
$\hat{\hat{r}}_{\max}$	Maximum analyzed radius of a failure region
$\hat{\hat{r}}_n$	Distance between node n and the failure epicentre
s_h	Length of arc a_h
$sh_h^{(r)}$	Capacity reserved so far at a_h that may be shared with respect to backup path of r-th demand (continuous)
$S_{\boldsymbol{i}}(t_0, \Delta t)$	Movement vector of vehicle i in time interval $(t_0, t_0+\Delta t)$
$s_i^x(t_0, \Delta t)$	Movement of vehicle i in time interval $(t_0, t_0+\Delta t)$ along X axis

$s_i^y(t_0, \Delta t)$	Movement of vehicle i in time interval (t_0, $t_0+\Delta t$) along Y axis
$s_{i,j}$	Stability index of a VANET link (i, j)
$sp(p, q)$	Number of the shortest paths between nodes p and q (of the same minimal length)
$sp_n(p, q)$	Number of the shortest paths between nodes p and q (of the same minimal length) traversing node n
s_r	Source node of r-th demand
$s_{r,m}$	Source node of r-th demand from m-th instance of Parallel Internet
T	Set of transit nodes
$\breve{T}$	Lifetime of a network
t_r	Destination node of r-th demand
$t_{r,m}$	Destination node of r-th demand from m-th instance of Parallel Internet
u_n	Binary variable to indicate that node n is a replica node
$\boldsymbol{v_i}(t)$	Velocity vector of vehicle i at time t
$v_i^x(t)$	Velocity of vehicle i at time t along X axis
$v_i^y(t)$	Velocity of vehicle i at time t along Y axis
$v_{r,m,h}$	Binary variable used to indicate whether arc a_h is forwarding the traffic referring to r-th demand of m-th instance of Parallel Internet
$v_{r,n}$	Binary variable to indicate whether a replica server located at node n is selected as a backup replica of r-th anycast demand
$w_{i,j}$	Probability of node j being the forwarding node of a packet received from vehicle i
W	Set of states in which the system is considered as available
$x^l_{r,h}$	Binary variable to determine if l-th channel is assigned for r-th demand path at arc $a_h = (i, j)$; 0 otherwise
$x_{r,h}$	Binary variable indicating utilization of arc a_h by a working path of r-th demand
$(\overline{x}_n, \overline{y}_n)$	X and Y axis coordinates of node n
$\left(\hat{\hat{x}}, \hat{\hat{y}}\right)$	X and Y axis coordinates of the failure epicentre
$x_{m,h}$	Capacity assigned for m-th instance of Parallel Internet at arc a_h (in MFlops)
$y_{r,h}$	Binary variable indicating utilization of arc a_h by a backup path of r-th demand
$z_{r,m,h}$	Capacity assigned at arc a_h for r-th demand of m-th instance of Parallel Internet
$\Gamma(N, A)$	Graph representing a directed network
γ	Exponent in power law distribution of node degrees
$\gamma\left(\breve{T}\right)$	Link cost function based on signal attenuation ratio at time $t \in \breve{T}$
δ	Region failure scenario given by the set of non-operational nodes after the outage
ζ_h	Cost per unit flow of each commodity on arc a_h for backup paths (if different from ξ_h)

η_i	i-th disjoint path
Θ	Length of the path over which the rain is observed
$\theta_{m,h}$	Consumption of node processing power measured per unit capacity for m-th instance of Parallel Internet defined for outgoing arc a_h
$\kappa_{r,n}$	Binary variable to indicate if a replica server located at node n is selected as a working replica of r-th anycast demand
Ξ	Matrix of arc costs
ξ_h	Cost per unit flow of each commodity at arc a_h
$\widetilde{\pi}_n$	Probability of existence of a VANET path consisting of k_n links
ρ_h	Probability that two vehicles are connected by a wireless link a_h at any time
$\rho_{m,h}$	Consumption of node processing power measured per unit capacity for m-th instance of Parallel Internet defined for incoming arc a_h
σ_J	Cost of a VANET anypath from set J to the destination node
$\sigma_{i,J}$	Cost of a VANET hyperlink (i, J)
$\sigma_{i,t}$	Cost of a VANET path between nodes i and t
τ	Time interval between two consecutive updates of a WMN topology
$\tau(r)$	Index of a demand associated with r-th demand
$\Phi_i(t)$	Position vector of vehicle i at time t
$\vartheta\left(\breve{T}\right)$	Function determining existence of links at time $t \in \breve{T}$
$\varphi(\boldsymbol{x})$	Objective function
ϕ_n	Aggregate processing power at node n
$\chi_{r,n}$	Binary variable to indicate that node n is the closest replica for anycast r-th demand
$\Psi(\delta)$	Random variable referring to the percentage ψ of flows delivered in scenario δ
$\widetilde{\Psi}_m$	Probability of multipath VANET transmission availability (by means of m paths)
ψ	Percentage of flows surviving the region failures
Ω	Signal attenuation in dB
ω_h	Estimated signal attenuation for arc a_h
$\omega_h(t)$	Estimated signal attenuation for arc a_h at time t
$\wp_{m,n}$	Amount of resources reserved to process flows from m-th instance of Parallel Internet at node n

Acronyms

3G	Third generation
4G	Fourth generation
ADM	Add-Drop Multiplexer
AODV	Ad-hoc On demand Distance Vector
APF	Active Path First
APS	Automatic Protection Switching
ATM	Asynchronous Transfer Mode
BC	Betweenness centrality
BER	Bit Error Rate
BLSR	Bi-directional Line Switched Ring
C2C-CC	Car-to-Car Communications Consortium
CAM	Cooperative Awareness Message
CAN	Content-Aware Networking
CCH	Control Channel
CCN	Content-Centric Networking
CDN	Content Delivery Network
CoS	Class of Service
CON	Content-Oriented Networking
CPU	Central Processing Unit
DDoS	Distributed Denial of Service
DNS	Domain Name System
DSRC	Dedicated Short Range Communications
DSS	Data Stream Switching
DWDM	Dense Wavelength Division Multiplexing
EMP	Electromagnetic Pulse (attack)
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FI	Future Internet
FIA	Future Internet Assembly

FIT	Failures in time
Gb/s	Gigabit per second
GHz	Gigahertz
GMPLS	Generalized Multiprotocol Label Switching
GPS	Global Positioning System
HTTP	Hypertext Transfer Protocol
ICN	Information-Centric Networking
IETF	Internet Engineering Task Force
IFIP	International Federation for Information Processing
ILP	Integer Linear Programming
InP	Infrastructure Provider
IoT	Internet of Things
IP	Internet Protocol
IPDV	IP packet Delay Variation
IPER	IP packet Error Ratio
IPLR	IP packet Loss Ratio
IPTD	IP packet Transfer Delay
IPv6	Internet Protocol version 6
ISP	Internet Service Provider
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
IVC	Inter-Vehicular Communications
LOS	Line of Sight
LP	Linear Programming
LSA	Link State Advertisement
LSP	Label Switched Path
MAC	Media Access Control
Mb/s	Megabit per second
MDT	Mean Downtime
MFlop	Mega Floating-point operations
MIMO	Multiple-input multiple-output
MIVC	Multi-hop Inter-Vehicular Communications
MPLS	Multiprotocol Label Switching
MTBF	Mean Time Between Failures
MTBI	Mean Time Between Interruptions
MTFF	Mean Time to First Failure
MTRS	Mean Time to Restore Service
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair/Recovery
MUT	Mean Uptime
NDO	Named Data Object
NNI	Network-Network Interface
NVE	Network Virtualization Environment
OBU	On-Board Unit
OSPF	Open Shortest Path First

OXC	Optical Cross Connect
P2P	Peer-to-peer
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PHY	Physical Layer
PIA	Percent of IP service Availability
PIU	Percent of IP service Unavailability
PLR	Packet Loss Ratio
POI	Point of Interest
PWCE	Protected Working Capacity Envelope
QoR	Quality of Resilience
QoS	Quality of Service
RFC	Request for Comments
RREP	Route Response
RREQ	Route Request
RSU	Road-Side Unit
SCH	Service Channel
SDH	Synchronous Digital Hierarchy
SDN	Software-Defined Networking
SIVC	Single-hop Inter-Vehicular Communications
SLA	Service Level Agreement
SLB	Service Loss Block
SNR	Signal-to-Noise Ratio
SONET	Synchronous Optical Network
SP	Service Provider
SRLG	Shared Risk Link Group
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
UNI	User-Network Interface
UPSR	Unidirectional Path-Switched Ring
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad-hoc NETwork
VLAN	Virtual Local Area Network
VN	Virtual Network
VoIP	Voice over IP
VPN	Virtual Private Network
VRU	Vulnerable Road User
VSCC	Vehicle Safety Communications Consortium
WDM	Wavelength Division Multiplexing
WMD	Weapons of Mass Destruction
WMN	Wireless Mesh Network
WSN	Wireless Sensor Network