# QoS Enabled IP Based Wireless Networking: Design, Modelling and Performance Analysis

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# Errata/Addenda

1) **IP micromobility management techniques**
The network architecture presented in chapter 3 of this thesis is based on the candidate's published work [34]. As [34] was published while most work on IP micromobility protocols management was still in their infancy, these are not referenced in the thesis and hence this addendum. Differentiated by operational scope, there are two basic types of mobility in Internet Protocol (IP) based wide-area wireless networks (W2ANs): macromobility and micromobility. Macromobility protocols manage mobility of mobile wireless users across domains (i.e. inter-domain mobility) or networks (i.e. inter-network mobility). Micromobility, on the other hand, deals with user mobility across subnetworks belonging to a single domain or network, and hence also referred to as intra-network or intra-domain mobility. The large-scale mobility (i.e. macromobility) is supported by the Mobile IP (MIP) protocol. The MIP protocol cannot support micromobility due the following reasons: (i) transferring large MIP control overhead over a wireless link each time a mobile user moves from one subnet to another is inefficient; (ii) long handoff delay inherent in MIP causes packet losses which can destabilise TCP operation; (iii) re-establishment of QoS reservations between FA and HA after every move of a QoS-enabled mobile host. Techniques proposed in the literature to support micromobility in IP based W2ANs fall into two categories: (a) exploitation of link layer signalling of the radio-networking standard used or (b) the application of autonomous micromobility protocol. The networking architecture (referred to as MOWINTA) proposed in Chapter 3 of this thesis adopts the former approach by exploiting wireless link layer signalling to reduce mobile IP handoff delay and saving TCP instability caused by packet losses during long handoff. Several micromobility architectures falling into the latter category are proposed, such as HAWAII [a], Cellular IP (CIP) [b] and Hierarchical Mobile IP (HMIP) [c].

2) (a) Page 76, Sect. 3.2.2, 1st paragraph: all "minimum" should be replaced by "average" and the average movement detection delay should be $t_{ECS} = t/2$ (b) Page 76, Sect. 3.2.2, 2nd paragraph: Should read " ... in contrast to the 1 sec Mobile IP inter-agent advertisement time. Therefore ... can be reduced by a factor of 10 (i.e. 1sec/100 ms)."

3) Contradiction between Sections 3.2.1 and 3.2.2: It should be modified as "The designed network architecture protects modification of TCP by moving the protocol modifications via intercommunication down one layer, i.e. intercommunication between layer 3 and layer 2 as this seems easier and cheaper. The reason being that TCP is in wider use than any given wireless link layer, as both wired and wireless networks can use TCP."

4) The architecture, MOWINTA, is actually designed to run any application-oriented QoS mechanism, such as IntServ or DiffServ. Table 3.2 in page 93 shows how one can be mapped onto the other. Hence, page 84 should have stated, "although the presented architecture can use either IntServ or DiffServ, most part of the presentation is based on IntServ with Table 3.2 aiding mapping."

5) Page 86: It is assumed that the features of the wireless standard (here IEEE 802.11) are exploited to support the necessary QoS of internal sessions. The IEEE 802.11 has inbuilt mechanisms such as priority schemes to support QoS. How efficient this approach works is still a research topic.

6) Figure 3.5: the transport protocol can also be UDP instead of TCP. Hence, should read TCP/UDP.

7) Page 96, 7th line from top: Replace Figure 10 by Figure 3.6.

8) Section 3.5.2: The database aspect and paging format of location management are outside the scope of the thesis. However, implications for location databases are potential areas for further studies.

9) Page 107, Sect. 4.2.2: The functions $f_1(/cdots)$ and $f_2(/cdots)$ are objective functions which are defined in Equations (4.4) and (4.5). Figure 4.2 illustrates the cumulative service (bottom figure) received by two mobiles undergoing difference instantaneous channel qualities (top figure). This figure assumes that mobile 1 is backlogged with traffic of higher QoS class $\mathrm{GeS}_1$ than mobile 2 that is backlogged with traffic belonging to $\mathrm{GeS}_2$. By normal priority scheduling mobile 2's traffic would never be scheduled until all packets belonging to mobile 1 are scheduled. However, the proposed channel-aware scheduler schedules packets of mobile 2 if its channel quality is much better than that of mobile 1 at the scheduling instant, although mobile 1 is still backlogged. Hence, the scheduler inherently protects both active mobiles from complete service starvation.

10) Equation 5.12 is derived assuming that ACK/NACK never gets corrupted. This seems a reasonable assumption given the low information rate of ACK/NACK feedback channel and the high error immunity. Such assumption is reflected in the literature.

11) Page 112: The discussion in Page 112 assumes the existence of a feedback wireless channel. Feedback of estimated wireless channel state is commonly used in many radio communications standards for purposes such as power control, load control and handoff decisions. The mobile terminal usually communicates such feedback information using the uplink pilot channel. However, a pilot signal need not be transmitted on a dedicated channel. Hence, the designed scheduling scheme does not increase the system complexity by requiring link quality feedback, as it can use the feedback channel of the respective wireless standard. Hence, the complexity associated with the feedback mechanism is not expected to have considerable additional implementation and cost implications to the entire communication system.

**Additional References**

[a] R. Ramjee, K. Varadhan, L. Salgarelli, S.R. Thuel, S-Y Wang and T. La Porta, "HAWAII: A domain-based approach for supporting mobility in wide-area wireless networks," *IEEE/ACM Trans. Netw,* vol 10, no. 3, June 2002, pp. 396–410.

[b] A Valko, "Cellular IP: a new approach to Internet host mobility," *ACM SIGCOMM Comp. Commun. Rev.,* vol. 29, no. 1, Jan 1999, pp. 50-65.

[c] E. Gustafsson, A. Jonsson and C. Perkins, "Mobile IP Regional Registration Registration," Internet draft, July 2000.

[d] A. T. Campbell, J Gomez, S Kim, and C-Y Wan, "Comparison of IP micromobility protocols," *IEEE Wir. Commun,* Feb 2002, pp. 72–82.

**Supervisor:** **Date:** June 13, 2003

Professor Reginald P. Coutts

In memory of my late dad, Mr Kofi Gyasi-Agyei

# Declaration of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university and that, to the best of the candidate's knowledge and belief, the thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

The author consents to the thesis being made available for loan and photocopying.

**Signed:** **Date:** February 21, 2003 **Place:** Adelaide, SA

# Acknowledgments

I am greatly indebted to the Almighty God and His Son Jesus Christ and the Holy Spirit—The Creator of Heaven & Earth and everything in it, The Omniscience & The Omnipresence, The Alpha & The Omega—for His unfathomable mercy, grace and love to me throughout my life, especially during the period of my PhD candidature at Adelaide University. I will forever praise Him so long as He gives me breath.

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A/Prof. S. -L. Kim of RAMO Lab, Information and Communications University (ICU), South Korea, hosted me in his laboratory for 6 weeks in mid-2002. Some academics I met right from the beginning of my career merit acknowledgement. Notable amongst them are Prof. Timo Laakso of Helsinki University of Technology (HUT), Finland, through whom I learnt the "hows" of basic research; Prof. Seppo Halme, also of HUT, provided the opportunity to develop my research career. Dr Hochhaus, Prof. Ackermann and Prof. Schuneman, all of Hamburg-Harburg University of Technology (TUHH), Germany, employed me as Engineering Asssistant (HIWI) throughout my undergraduate degree at TUHH. This enabled me

finance my education without a formal scholarship, as well as giving me insights into practical engineering right from undergraduate level.

I am grateful to the administrative support of the Head of the EEE Department, Mr Michael Liebelt, and the Postgraduate Coordinator, A/Prof Bruce Davies, for providing information related to the format of PhD Research Proposal, as well as the Postgraduate Committee. Supportive role of the EEE Dept's Computing Support Group led by Mr David Bowler is well appraised. I sincerely thank my fellow postgraduate scholars at The Centre for Internet Technology Research (CITR)—Priyadarshana, I Ketut Prihadi Kresna, Van Khanh and Wang Hai and Ching Yoong—for keeping company and for making the centre conducive enough for a successful PhD research though we were many students with diverse backgrounds sharing a facility. I enjoyed the company of my fellow CRC SIT scholars during the CRC SIT student professional training programs in Sydney. SIT CRC staff in Sydney (incl. Ms Lisette Lamb, Ms Terri McLachlan and the CEO) have been very instrumental and welcoming. The former CRC SIT research director, Prof Joe Chicharo, presented very motivating approaches to research during a CRC SIT training program in Sydney.

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Thanks, Merci, Danke Schöne, Tack, Kiitos, Aseda: Amoakoh

# Abstract

Quality of service differentiation has never achieved much attention and relevance until the advent of the convergence of mobile wireless network and the fixed Internet, that is, Internet Protocol (IP) based mobile wireless networks, or wireless Internet. These networks are poised to support multimedia applications' traffic with diverse QoS sensitivities. To date, most traffic transferred over the Internet still undergo best-effort forwarding, which does not guarantee whether or not traffic sent by a source gets to the intended destination, let alone loss and timing bounds. The major contribution of this thesis is three-fold.

First, the thesis proposes a QoS-enabled wireless Internet access architecture, which leverages the micromobility in wireless standards to reduce mobile IP weaknesses, such as long handoff delay, to achieve effective interworking between mobile wireless networks and the global, fixed Internet. Although the idea here is applicable to any wireless standard, the design examples in this thesis are based on the IEEE 802.11b wireless local area network (WLAN) standard.

Second, it proposes a framework for a class of wireless channel state dependent packet scheduling schemes, which consider the QoS requirements of the applications' traffic; the wireless channel state (reflected in instantaneous data rate or noise level); and optimises the usage of the expensive wireless resource. The operation of the QoS-enabled, channel state-dependent packet scheduler is analysed using optimisation theory, eigenanalysis and stochastic modelling.

Third, the thesis analyses the effects of wireless channel properties on differentiated QoS (DQoS) schemes, using two-dimensional, channel-state-dependent queuing theory, matrix analytic methods to stochastic modelling and eigenanalysis. The analytical model of DQoS schemes, especially models accounting for user scenarios such as speed of motion and wireless channel properties, such as fading, spatio-temporarily varying quality and low rate, is not properly covered in the open literature, and hence was a motivation for this part of the thesis. The wireless channel is discretized into discrete-time Markovian states based on the received signal-to-noise plus interference ratio (SNIR), which also reflects on the instantaneous link quality. The link quality, in turn, influences the QoS experienced by the transported applications sitting on top of the ISO/OSI protocol hierarchy. The parameters of the Markovian states are evaluated using realistic physical channel noise models and transceiver characteris-

tics, such as modem. [Different modems (modulator/demodulator) yields different transceiver properties such as sensitivity. The analysis in the thesis adopts QPSK and BPSK modulation.] Source traffic models are used in the analysis.

Lastly, the thesis provides an extensive introduction to, and provides a detailed background material for the new area of mobile wireless Internet systems, upon which considerable future research can be based.

# Publications

The following are some of the publications of the candidate which are related to the theme of this thesis.

1. A. Gyasi-Agyei, "Mobile IP-DECT Internetworking architecture supporting IMT-2000 applications," *IEEE Network*, vol. 15, no. 6, Nov/Dec 2001, pp. 10-22.
2. A. Gyasi-Agyei and R. Coutts, "Analytical model of a Differentiated Service scheme over Wireless IP Links," In *Proceed. IEEE Int. Conf. on Networks (ICON'02)*, Singapore, 27 - 30 August 2002, pp. 223-228.
3. A. Gyasi-Agyei, "Service differentiation in wireless Internet using multi-class RED with drop threshold proportional scheduling," In *Proceed. IEEE Int. Conf. on Networks (ICON'02)*, Singapore, 27 - 30 August 2002, pp. 175-180.
4. A. Gyasi-Agyei, "Performance Analysis of a Differentiated Services over Wireless Links," In *Proceed. 5th IEEE Int. Conf. on High-Speed Networks and Multimedia Commun. (HSNMC)*, Jeju Island, Korea, July 2002, pp. 86-90.
5. Amoakoh Gyasi-Agyei, "A Differentiated Services Scheme for Wireless IP Networks," In *Proceed. IEEE Int Conf. on Telecom (ICT'02)*, vol. 2, Beijing, China, 23-26 June 2002, pp. 361-366.
6. Amoakoh Gyasi-Agyei, "Performance Analysis of a Differentiated Services Scheme over Fading Channels," In *Proceed. IEEE Int Conf. on Telecom (ICT'02)*, vol. 1, Beijing, China, 23-26 June 2002, pp. 1155-1160.
7. A. Gyasi-Agyei, "EGPRS/EDGE random access performance using M-PSK in AWGN and Nakagami-m fading channel," In *Proceed. Int. Conf. on Inform., Commun. & Signal Proc. (ICICS)*, Singapore, Oct. 2001, 5 pp.
8. A. Gyasi-Agyei, "QoS guarantees in IP based wireless/mobile networks," Research Proposal, EEE Dept, Adelaide University, Australia, 5th October 2001, 9 pp.

9. A. Gyasi-Agyei and S. J. Halme (eds), *Network and telecommunications signaling architectures for contemporary and future broadband intelligent networks*, ISBN 951-22-4982-0, ISSN 1456-3835.
10. A. Gyasi-Agyei and S. J. Halme, "A novel planning of 3G all-wireless access network," in *Proc. IEEE Int. Conf. on Inform., Commun. & Sig. Proc. (ICICS)*, Singapore, Dec. 1999, 5 pps.
11. A. Gyasi-Agyei, S. J. Halme and Sarker J, "GPRS–Features and Packet Random Access Channel Performance Analysis," in *Proc. IEEE Int. Conf. on Networks (ICON'00)*, Singapore, Sept. 2000, pp. 13–17.
12. A. Gyasi-Agyei and S. J. Halme, "Mobile IP based DECT multimedia architectures for IMT-2000," in *Proc. IEEE Veh. Techn. Conf. (VTC'00)*, vol. 2, Boston, MA, Sept. 2000, pp. 963–970.

# Papers in Review

1. A. Gyasi-Agyei, "Performance analysis of differentiated services QoS model over multi-state wireless Links," submitted to *Wiley Wireless Communications & Mobile Computing J.*, Dec. 2001, 20 pps.
2. A. Gyasi-Agyei, "Fluid Analysis of a Channel State Dependent Packet Scheduler over Fading Wireless Channels," submitted to *Kluwer Wireless Networks J.*, March 2002.
3. A. Gyasi-Agyei, "MOWINTA—A QoS enabled wireless Internet access architecture based on Mobile IP/IEEE 802.11 interworking," submitted to *special issue* on QoS in next-generation multimedia communications systems *IEEE Wireless Commmun. Mag.*, Dec. 19, 2002.
4. A. Gyasi-Agyei, "Some wireless effects on QoS provisioning in IP based networks," submitted to *IEEE/ACM Trans. on Netw.*, Jan. 21, 2003.

# Notable Seminars and Workshops

The following is a list of some of the lectures, seminars and workshops I presented during my PhD candidature besides presentation at international conferences.

1. Gyasi-Agyei, A., "Performance analysis of the packet random access channel of GPRS," Seminar, Institute for Communications Research (ICR), National University of Singapore (NUS), 2 Feb. 2001.
2. A. Gyasi-Agyei, "QoS guarantees in IP based wireless/mobile networks," Research Proposal Seminar, EEE Dept, Adelaide University, 5 Oct. 2001.
3. A. Gyasi-Agyei, "Performance analysis of DiffServ QoS model over multi-state wireless links," 6th Annual Melbourne-Adelaide Teletraffic Workshop, 12-14 Dec. 2001, Grampians, Vic, Australia.
4. A. Gyasi-Agyei, "Differentiated QoS schemes for wireless internet," 1st Workshop for CRC Smart Internet Technology scholars, Sydney, 8-10 May 2002.
5. A. Gyasi-Agyei, "BL$^4$DF – Wireless Channel State Dependent Packet Scheduling for QoS Provisioning in Multiservice Wireless Networks," Seminar, Computer Science & Eng (CSE) Dept, UNSW, Sydney, 18 Sept. 2002.
6. A. Gyasi-Agyei, "The Innovative Utilisation of Communications/Electronic Engineering in the Development and Growth of Central Queensland Industry and Education," Lecture, Central Queensland University (CQU), Rockhampton, 11 Dec. 2002.

Other publications of the candidate can be found at the bibliographic section.

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Nothing tends so much to the advancement of knowledge as the application of a new instrument.The native intellectual powers of men in different times are not so much the causes of the different success of their labours, as the peculiar nature of the means and artificial resources in their possession – Sir Humphrey Davy.

# Contents

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When I was still a rather precocious young man, I already realized most vividly the futility of the hopes and aspirations that most men pursue throughout their lives – Albert Einstein.

# List of Figures

# List of Tables

# List of Symbols

| | |
|---|---|
| $B_c$ | Coherence bandwidth |
| $B_s$ | Signal bandwidth |
| $\beta_n$ | Bandwidth efficiency in link state $n$ |
| $C$ | Cluster size |
| $c$ | Number of traffic classes/generic streams differentiated |
| $D_i,\ d_i$ | Delay parameter of GeS$_i$ |
| $d_i^*$ | Optimum value of $d_i$ |
| $f_c$ (Hz) | Operating radio frequency (carrier) |
| $f_\gamma(\gamma)$ | Probability density function |
| $\gamma$ | Signal-to-noise ratio |
| $\mathbf{I}$ | An identity matrix of a given order |
| $\mathbf{I}(n)$ | An identity matrix of order $n$ |
| $K,\ N_s$ | Number of traffic sources |
| $\kappa$ | Information part of L2 codeword |
| $\lambda$ | Average packet arrival rate |
| $L_i,\ l_i$ | Loss parameter of GeS$_i$ |
| $L_p$ | Layer 3 (IP) packet size |
| $L2hdr$ | Layer 2 frame header field for error control |
| $m,\ m \geq 1/2$ | Nakagami$-m$ fading figure |
| $\mu$ (dB) | Mean of $10 \log_{10} \gamma$ |
| $N,\ N_c$ | Number of discrete wireless channel states |
| $\nu$ | L2 codeword size |
| $N_0/2$ (W/Hz) | Two-sided power spectral density of AWGN |
| $\mathbf{P}$ | Transition probability matrix |
| $\mathbf{p}$ | A vector of probabilities |
| $P_{b,e}$ | Bit error probability |

| | |
|---|---|
| $P_e$ | Error probability |
| $p_i$ | Service cost (premium) for traffic belonging to $\mathrm{GeS}_i$ |
| $p_{ij}$ | Elements of $\mathbf{P}$ |
| $\hat{r}_{arq},\ \hat{r}$ | Maximum number of ARQ retransmissions |
| $R_b,\ R_p$ | Interface transmission rate |
| $r_m(t)$ | Link rate of mobile $m$ at time $t$ |
| $\rho$ | $E[\gamma]$, i.e. mean of $\gamma$ |
| $\sigma$ (dB) | Standard deviation of $10\log_{10}\gamma$ |
| $s_n$ | Wireless channel state (condition) |
| $\mathbf{T}$ | Infinitesimal generator (state transition rate matrix) |
| $t_{ij}$ | Elements of $\mathbf{T}$ |
| $\tau$ | # number of bit errors per L2 frame correctable by an FEC code |
| $v,\ v_m$ | Mobile user velocity of motion |
| $v_0$ | Speed of light in vacuum ($\approx 3\cdot 10^8$ m/s) |

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It is often stated that of all the theories proposed in this century, the silliest is quantum theory. In fact, some say that the only thing that quantum theory has going for it is that it is unquestionably correct – Michio Kaku.

# List of Acronyms

| | |
|---|---|
| AFD | Average Fade Duration |
| AF | Assured Forwarding PHB |
| AP | Access Port |
| API | Application Programming Interface |
| ARQ | Automatic Repeat reQuest |
| ATM | Asynchronous Transfer Mode |
| AWGN | Additive White Gaussian Noise |
| BEF | Best Effort Forwarding |
| BER | Bit Error Rate |
| BL$^2$DF | Best Link Lowest Delay First scheduler |
| BL$^4$DF | Best Link Lowest Loss Lowest Delay First scheduler |
| BL$^2$PF | Best Link Largest Premium First scheduler |
| BM | Buffer Manager |
| BPSK | Binary Phase-Shift Keying |
| BS | Base Station |
| BSS | Basic Service Set |
| CBB | Class Based Buffering |
| CDMA | Code Division Multiple Access |
| CIDR | Classless Inter-Domain Routing |
| CL | Controlled Load service of IntServ |
| CN/CH | Corresponding Node/Host |
| CO | Connection-Oriented (service of 802.11's LLC) |
| CS | Circuit Switching |
| CSDPS | Channel State Dependent Packet Scheduling |
| DB (dBase) | Database (Register) |
| DECT | Digital Enhanced Cordless Telecommunications |
| DiffServ | Differentiated Services architecture |
| DQoS | Differentiated QoS |
| DS | Same as DiffServ |
| DT-FSMM | Discrete-Time Finite State Markov Model |
| EF | Expedited Forwarding PHB |

| | |
|---|---|
| FCFS | First Come First Served scheduling |
| FDMA | Frequency Division Multiple Access |
| FEC | Forward Error Correction |
| FWR | Fixed Wireless Router (= IBS) |
| GEC | Two state Gilbert-Elliot Channel model |
| GeS | Generic Stream |
| GPRS | General Packet Radio Service |
| GPS | Generalized Processor Sharing scheduling |
| GoS | Grade of Service |
| GS | Guaranteed Service of IntServ |
| GW | Gateway |
| HM | Handoff Management |
| HLC | Home Location Register |
| IBS | IP enabled Base Station |
| IEEE | The Institute of Electrical & Electronic Engineers |
| IMS | IP enabled Mobile Station |
| IntServ | Integrated Services architecture |
| IP | Internet Protocol |
| IP-RAN | IP based RAN |
| IS | Same as IntServ |
| ISO | International Standards Organization |
| L$k$ | ISO/OSI protocol layer $k$ |
| LCR | Level Crossing Rate |
| LLC | Logical Link Control |
| LM | Location Management |
| MA | Mobility Agent |
| MAC | Medium Access Control |
| MH/MN | Mobile Host/Node |
| MIP | Mobile IP |
| MM | Mobility Management |
| MMPP | Markov-Modulated Poisson Process |
| MODEM | Modulator/Demodulator |
| MOWINT | Mobile Wireless Internet |
| MOWINTA | Mobile Wireless Internet Access Architecture(s) |
| MPLS | Multi-Protocol Label Switching |

| | |
|---|---|
| MRSVP | Mobile RSVP |
| MS | Mobile Station |
| MWR | Mobile Wireless Router |
| NAT | Network Address Translation |
| NLN | Nakagami Lognormal channel impairment |
| $NP^3A$ | Non-Pre-emptive Priority with Partial Assurance scheduling |
| OSI | Open Systems Interconnection |
| PBSP | Proportional Buffer Sharing with Pushout |
| pdf | Probability Density Function |
| PHB | Per-Hop Behavior |
| POA | Point of Attachment |
| PS | Packet Scheduler / Packet Switching |
| QDS | QoS enabled Distribution System |
| QoS | Quality of Service |
| QPSK | Quadrature Phase-Shift Keying |
| RAN | Radio Access Network |
| RED | Random Early Detection/Discard |
| RLC | Radio Link Control |
| RSIP | Real Specific Internet Protocol |
| RSSI | Received Signal Strength Indicator |
| RSVP | Resource ReSerVation Protocol |
| SNIR | Signal-to-Noise plus Interference Ratio |
| SNR | Signal-to-Noise Ratio |
| STA | Station (i.e. handset) |
| TC | Traffic Class/Classifier |
| TCP | Transmission Control Protocol |
| TD | Tail/Threshold Dropping |
| TDMA | Time Division Multiple Access |
| 3G | Third Generation Wireless Networks |
| UC | Unacknowledged Connectionless service of 802.11's LLC |
| VLR | Visitor Location Register |
| WLAN | Wireless Local Area Network |
| WR | Wireless Router |