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Research for Communication Control of IEEE 802.11 Ad Hoc Networks

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Research for Communication Control of IEEE 802.11 Ad Hoc Networks

A thesis submitted for the degree of Doctor of Information Science

by

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Abstract (Japanese)

無線 LAN は今現在最も普及している無線データ通信技術であり、標準規格の IEEE 802.11 も 2009 年に 11n, 2013 年に 11ac が策定され高速化、大容量化を遂げている。タブレットやモバイル PC などでは無線 LAN 以外にデータ通信手段を持たない機器も増えており、スマートフォンでも省電力やモバイルネットワークのオフロードの観点から無線 LAN が使える状況では無線 LAN の使用が推奨されている。今後はイーサネットによる有線ネットワークを代替していく可能性がある。また現時点ではこれまでの歴史的な経緯から有線ネットワークの拡張を目的としたアクセスポイントを使うインフラストラクチャ型の無線 LAN の導入が主流である。しかし今後は自動車のような移動体や家電製品にも標準的に搭載されることが期待され、端末同士が直接通信を行ない有線インフラストラクチャに依存しないアドホック型やその発展系であるメッシュ型の無線 LAN も重要な適用領域となる。

このような流れの中で無線 LAN の通信制御のメカニズムは 1997 年に策定された最初規格 IEEE 802.11-1997 から基本的に変更されていない。このため最近や今後の用途や通信環境を考えた場合、最適化されているとは言えない状況が生じている。広く普及し、今後も重要性を増す無線 LAN であるが通信制御の仕組みは完成されたものではなく、改善の余地を残している。

無線 LAN において利便性を損なわず、増大しているスループットに対する要求を満たす技術の開発は重要である。特に通信制御はマルチレート化など最新の物理層の改良に対して最適化されていない。通信制御を最適化することでスループットを向上し、限られた電波資源を有効活用することが一つの重要な課題となる。本研究の目的は、最新の物理層の技術の進展にも対応した通信制御の仕組みを提案することにある。通信制御は広範囲にわたる課題であるが、まずマルチレート化への対応と QoS から検討を行う。具体的にはアドホック型の無線 LAN について、マルチレート化へ対応したさらし端末対策、及びスループット実績を反映した QoS 割り当て技術の二つの研究目標を設定した。各目標と研究の結果、得られた知見についての概要を以下に示す。

マルチレート化へ対応したさらし端末対策について説明する。マルチレートによる送信を前提とした場合、データフレームと制御フレームでの送信速度に差異が生じる。送信速度の差異は到達距離の差異としても表れるため、送信速度を意図的に変更することで到達距離を制御する事が可能になる。まず、この技術をさらし端末の解消に適用する。提案した RTS と CTS の送信速度を非対称とする方式 (ARMRC)がシミュレーションを通して、さらし端末を削減してネットワークのスループットを向上させる効果があることを確認した。シミュレーションした条件では標準方式に比べ 20%から 50%のスループット向上が見られた。また提案方式は個々の端末のスループットを平準化させる効果があり、標準方式でスループットが低い端末ほど、向上率が高くなるという結果が得られた。提案方式のスループット向上率を簡易に見積もる方法を考案したが、シミュレーション結果とよく合致し、見積方法として有効であることが確認できた。

スループット実績を反映した QoS 割り当て技術について説明する。標準方式(DCF/EDCA)では衝突ウィンドウ(CW)の大きさは衝突の発生や送信成功によってのみ増減す

るが、提案方式では端末の要求スループットと実績スループットに応じて増減する。標準方式ではトラフィックが飽和状態になると各端末のスループットの達成率について公平性が損なわれる。標準規方式の場合、全ての端末がほぼ同じ実スループットになるため、端末毎に異なる要求スループットが反映されず端末間で達成率に大きな差が出るためである。提案方式では個々の端末の達成率が標準方式よりも公平になり、シミュレーションでは Jain's Fairness Index にておよそ 0.9 から1．0 へ向上するという結果が得られた。また提案方式ではネットワーク全体の総スループットについても標準方式と比べて10%前後の向上が見られ、達成率の公平化に伴うトレードオフが見られなかった。

本研究では無線 LAN の通信制御方式の改良策として、制御フレームとデータフレームの送信速度の乖離に注目し RTS/CTS から生じるさらし端末の低減または排除方法を考案した。マルチレートを活用し RTS と CTS の送信速度を非対称とする方式 ARMRC (Asymmetric Range by Multi-Rate Control) を提案し、その効果、有効性をシミュレーションにより検証した。またもう一つの改良策として現行の QoS の仕組みである EDCA が優先順位の割り当てのみを提供する点に着目し、それとは異なるスループット実績を反映した QoS 割り当て技術を考案した。シミュレーションにより検証しその効果、有効性が確認できた。これらの状況を踏まえ、今後はより広いパラメータや前提条件を検証し、本方式の改良、発展を目指したい。またこれらに加えて他の改良方法も考案しより包括的な通信制御方式の確立を目指したい。

Abstract

WLAN is the most dominant wireless data communication technology of today, and its standard IEEE 802.11 has been enhanced to support very fast and high capacity with ratification of 11n in 2009 and 11ac in 2013. Devices such as tablets and mobile PC which do not have other communication options are increasing, and even with mobile phones it is recommended that WLAN should be used as much as possible for traffic offload and power saving points of view. WLAN has possibility to completely replace wired connection via Ethernet. Today infrastructure mode with access point is commonly deployed because WLAN has been considered to be an extension of wired network infrastructure. From now on any mobile entities such as automobile and home electronics appliances are expected to be equipped with WLAN. Ad-hoc mode and even mesh type WLAN which allow direct communication among terminals and do not rely on wired infrastructure will be important application.

In this movement communication control mechanism of WLAN has not been updated since it was ratified at IEEE 802.11-1997. Therefore it is can be said that it is no longer well optimized for recent and future usage and environment. Though WLAN is widely spread and has increasing importance, its communication control is not completed mechanism and still it has room for improvements.

It is important to develop technology to support increasing required throughput without losing convenience of WLAN. Communication control has not caught up with the latest physical layer advancement. By optimizing it to increase throughput and to utilize limited radio resource can be an important research object. The object in this research is to propose appropriate communication control mechanism for the latest physical layer development. Communication control covers broad range of subjects, and we decided to focus on to multirate and QoS support in this research. We defined two concrete research objects with WLAN ad-hoc mode, exposed node mitigation by multirate support and QoS allocation based on achieved throughput. Brief summary of these research and their outcomes are explained below.

Regarding exposed node mitigation by multirate support, assuming multirate transmission there is substantial difference of transmission rate between data frame and control frame. This difference is observed as difference of transmission range, therefore we can utilize transmission rate to intentionally control transmission range. First application of this mechanism is mitigation of exposed node. We proposed asymmetric transmission rate for RTS and CTS and named this proposed method as ARMRC. We could confirm the effect of exposed node reduction and improvement of throughput by simulation. With the simulated condition we observed 20 to 50% better throughput than the standard method. Also the proposed method has effect to level throughputs among nodes. Low throughput nodes with standard method have higher improvement ratio. We figured out simple estimation model of throughput improvement by the proposed method, and this fits to the simulation result well and is confirmed as effective estimation model.

Regarding QoS allocation based on achieved throughput, standard method (DCF/EDCA) increases/decreases size of Contention Window (CW) only when collision occurs or transmission succeeds. Our proposed method increases/decreases size of CW based on required/achieved

throughput. When traffic is saturated standard method cannot provide fairness of throughput achievement because all nodes achieve almost the same throughput even if each node has different required throughput. Thus the achievement ratio of each node may differ largely.   We had simulation and the result showed that the proposed method improved from 0.9 to 1.0 with Jain's Fairness Index for throughput achievement among each node compared to standard method. Also the proposed method has several to over 10% better entire network throughput. There is no trade-off between the better fairness of achievement ratio and better throughput.

As an improvement of WLAN communication control, we devised mitigation or elimination of exposed node caused by RTS/CTS focusing difference of transmission rate between data and control frames. We utilize multirate and make transmission rate of RTS and CTS asymmetric. We named this method as ARMRC (Asymmetric Range by Multi-Rate Control), and conducted simulation and confirmed its effect and validity. As another improvement, we devised QoS allocation mechanism based on throughput achievement considering that standard QoS mechanism EDCA uses only fixed priority. We conducted simulation and confirmed its effect and validity. Following up these outcomes, I would like to expand simulation to cover more extensive parameters and conditions, and enhance these proposed methods. Also I would like to devise other improvements of communication control in addition to these, and aim to establish more comprehensive communication control mechanism.

Acknowledgement

I would like to especially thank my research supervisor and thesis advisor Dr. Moo Wan Kim for his guidance, support and encouragement throughout the course of the entire research. His suggestion to project direction and objective has been valuable in ensuring progression in the project. I would also like to thank my research co-supervisor Dr. Masaki Hanada for his valuable advises, particularly about technical and theoretical aspect of simulations in my research. Special thanks also go out to Dr. Hidehiro Kanemitsu of Global Education Center, Waseda University, for his unfailing support to mathematical and theoretical analysis. I appreciate my thesis co-advisors, prof. Masanori Hirano, prof. Fumikazu Izeki and prof. Shintaro Uno who reviewed and gave me valuable comments and suggestions to improve this thesis through the public hearing and the final assessment.

I have also been fortunate to have talented undergraduate students, Takashi Sasagawa and Takato Bannai. They helped me a lot and actually they wrote simulation programs with C++ for my research under my guidance and tutorial of WLAN mechanism. Without their programming skills, my research has never been completed.

I appreciate my family for their constant support and encouragement when it was most required. I owe everything to them and could not have come this far. I am indebted to them as I could have not taken my responsibilities of father and husband well enough for almost three years. I should have taken out them for trips or other family events. By coincidence, my research period was one of my toughest periods in my life. Just before the research started I had to move to new company. This made my days difficult to spare time for research, and after two years of employment, again I had to move to another company. Haruka, my first daughter was born just before I enrolled the University doctorial course and Minori, my second daughter was born in the middle of doctoral course. So the research term was also really amazing period in my life. My final and most heartfelt acknowledgement goes to my lovely wife, Mihoko. Her continual patience, support and encouragement offered are more than anyone could ask for.

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List of Acronyms

AC	Access Category
ACK	Acknowledgement
AEDCF	Adaptive EDCF
AIFS	Arbitration Inter Frame Space
AP	Access Point
ARMRC	Asymmetric Range by Multi-Rate Control
BSS	Basic Service Set
CAP	Control Access Period
CCA	Clear Channel Assessment
CCK	Complementary Code Keying
CFP	Contention-free Period
CP	Contention Period
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access/Collision Detection
CTS	Clear To Send
CW	Contention Window
CWmax	CW maximum
Cwmin	CW minimum
DCF	Distributed Coordination Function
DIFS	DCF Inter Frame Space
DLS	Direct Link Setup
DPCF	Distributed Point Coordination Function
DSSS	Direct Sequence Spread Spectrum
EBA	Early Back off Announcement
ED	Energy Detection
EDCA	Enhanced Distributed Channel Access
GCS	Groupcast with Retries
GPS	Global Positioning System
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
IBSS	Independent BSS
IEEE	Institute of Electrical and Electronics Engineers
LTE	Long Term Evolution
MANET	Mobile Ad hoc Network
MBSS	Mesh Basic Service Set
MCA	Multi Channel Architecture
MIMO	Multiple Input Multiple Output
NAV	Network Allocation Vector
NFC	Near Field Communication
OBSS	Overlapping Basic Service Set
OFDM	Orthogonal Frequency Division Multiplexing
PCF	Point Coordination Function
PLCP	Physical Layer Convergence Protocol
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
ReB	Reservation-based Back off
RR	Resource Reservation
RTS	Request To Send
SCS	Stream Classification Service

SIFS	Short Inter Frame Space
STA	Station
VHT	Very High Throughput
WLAN	Wireless LAN

1 Introduction

1.1 IEEE 802.11 and Background of Research

Now wireless communication already became commodity in our daily life. Several wireless technologies are available to support our communication needs from long to very short distance. Mobile phone is a good example of how we depend on wireless technologies. It often has mobile data communication (3G/LTE), WLAN, Bluetooth, GPS, NFC and even wireless charging feature. Among these technologies, we would say wireless LAN, WLAN or officially IEEE 802.11 is one of the most flourishing technologies with extensive and even expanding its applications. In thesis, we use terminology WLAN and Wi-Fi are interchangeable, and they mean Wireless LAN based on IEEE 802.11 standard.

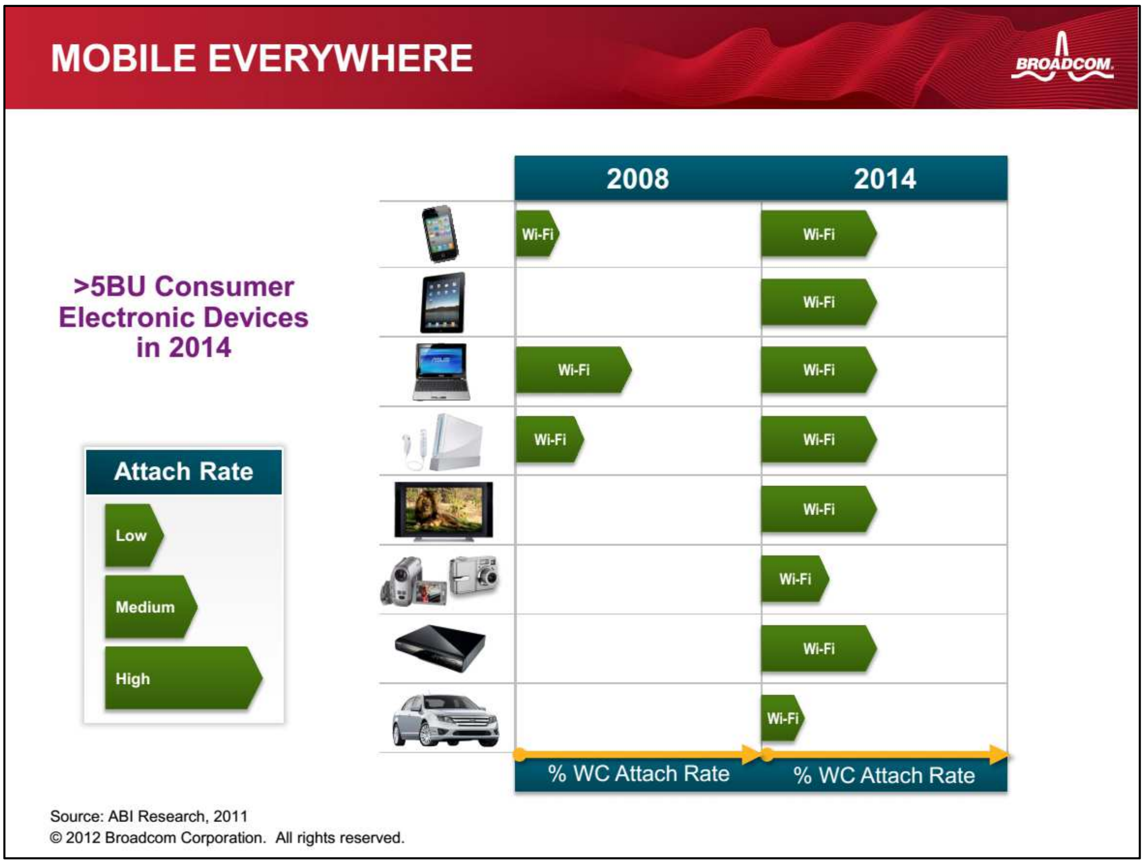

Figure 1: Mobile Everywhere (presentation from Broadcom Corp)

As you see in the Figure 1 from the presentation material for WLAN manufacturer [1], in 2008 WLAN was mostly with laptop PC, mobile phone and home WLAN routers in consumer electronics industry. But by 2014, it has been widely spread to mobile and stationary entities including HDTV, media player and automobile. We already have many devices which have no alternative communication options other than Wi-Fi. Tablet is a good example. Another research report from [2] shows the similar estimation in the Figure 2. The Total WLAN chipset shipment volume exceeded 2 billion in 2013 and will reach near 4 billion by 2018. We would say this is quite amazing volume as human population is expected to be 7.7 billion by 2020 [3]. It is critically important to improve or enhance WLAN technology.

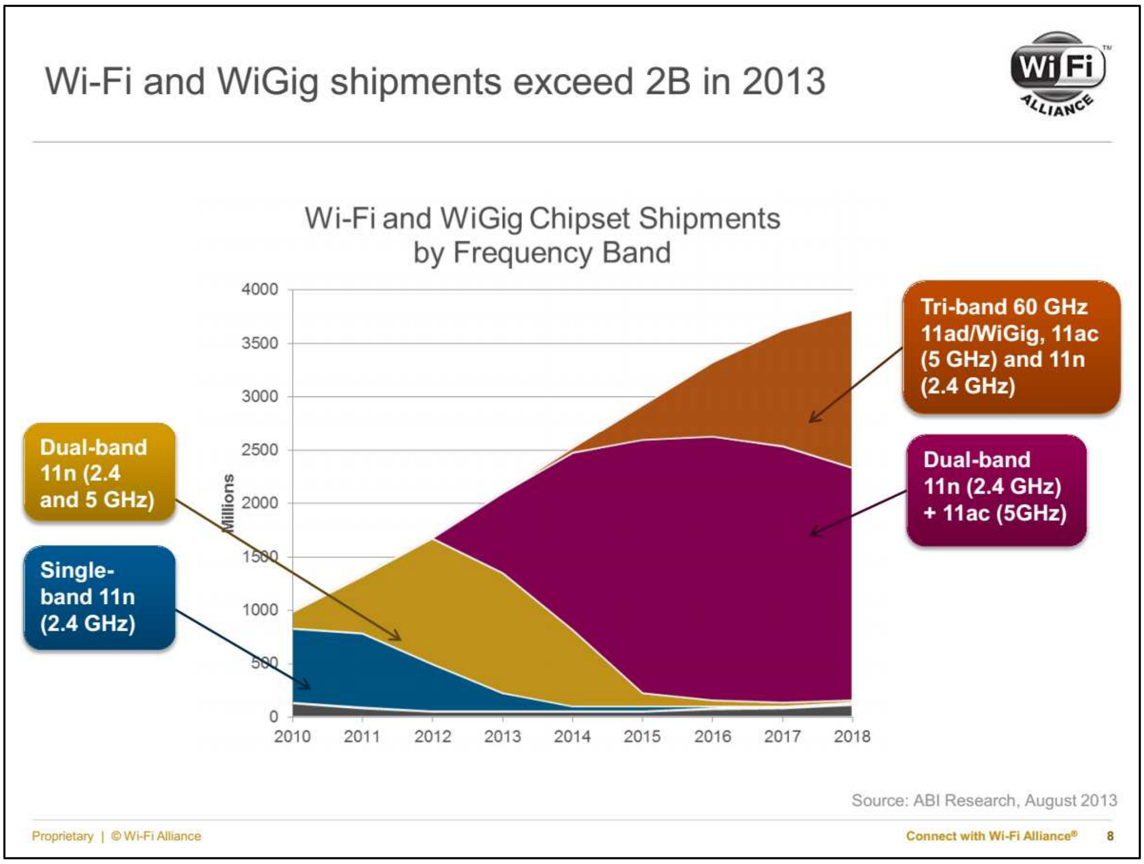

Figure 2: WLAN Chipset Shipments

The first IEEE 802.11 standard was ratified on July 1997 and the maximum speed was 2Mbps. In the standard there were only two data rates, 1 and 2Mbps. Since then, the standard has been evolved smoothly and with the lasted 802.11ac ratified on 2013 its total maximum speed reached 6.9Gbps as shown in the Table 1. Because the first 802.11 had only one spatial stream with 22MHz channel, we should use 86.7Mbps of 802.11ac at 20MHz channel for equivalent comparison. 802.11ac offers 9 different data rates with various modulations up to 246-QAM and coding. It also has several options. Those options are number of spatial streams, width of channel or channel bonding, short grad interval and frame aggregation. The standard developed the speed or throughput more than 40 times in 16 years. If we would take those 11ac options into account, the increase of the speed is about 3,500 times. Substantial efforts have been devoted to improve the speed.

Table 1: Development of IEEE 802.11 Standards

IEEE Standard	**802.11**	**802.11b**	**802.11a**	**802.11g**	**802.11n**	**802.11ac**
Ratification Date	1997/07	1999/07	1999/07	2003/06	2009/09	2013/12
PHY	DSSS	CCK	OFDM	OFDM	OFDM	OFDM
Frequency Band (GHz)	2.4	2.4	5	2.4	2.4/5	5
Channel Width (MHz)	22	22	20	20	20/40	80/160
Max. MIMO Spatial Stream	1	1	1	1	4	8
Max. Throughput (Mbps)*	2	11	54	54	65	86.7
Max. Throughput (Gbps)	0.002	0.011	0.054	0.054	0.6	6.9

*Maximum throughput per Spatial Stream, per standard channel width (22 or 20MHz), with long guard interval.

The ratified and ongoing IEEE 802.11 standards are shown in the Table 2. This table is based on the table 3 of [4] with some updates. In the fourth column "Update", PHY and MAC mean enhancement of physical layer and medium access control layer respectively. "QoS" means enhancement or addition of Quality of Service feature. Speed or throughput is one of the most demanded features in both commercial and research fields and substantial efforts were made to this area. As a result many enhancements have been introduced in 802.11, only a few enhancements were made to basic communication control mechanism including QoS and MAC layer.

The speed has been gradually enhanced with 802.11b, 11g and 11a, and these enhancements were for PHY layer only. When 802.11n was released, totally new features were introduced in PHY. MIMO, channel bonding and short guard interval are examples of these PHY layer features, and these have contributed to the speed drastically. These PHY layer technologies are further enhanced with 802.11ac. With 802.11e QoS introduction, MAC layer was enhanced partially. With 802.11n, MAC layer has been enhanced substantially with frame aggregation and enhanced block ACK in order to increase the throughput.

But still much functionality remains the same as they were first released in 1997. For example, physical carrier sense or CCA (Clear Channel Assessment) and vertical carrier sense (RTS/CTS) have not been enhanced yet. MAC layer access method has been enhanced from DCF to EDCA, but still its principal of operation remains the same. It offers priority based on statistic or probability and it cannot guarantee priority and fairness. It should be the time to focus on to these untouched, basic communication control mechanism of WLAN.

Table 2: IEEE 802.11 Standard Family

IEEE Std	Purpose	Date	Update
802.11	Originally 1 Mbps and 2 Mbps, 2.4 GHz RF and IR standard	1997	PHY
802.11a	54 Mbps, 5 GHz PHY layer standard	1999	PHY
802.11b	Enhancements to 802.11 to support 5.5 and 11 Mbps	1999	
802.11c	Bridge operation procedures [now included in the IEEE 802.1D]	2001	
802.11d	Country-to-country roaming extensions	2001	
802.11e	Enhancements: QoS, including packet bursting	2005	QoS
802.11f	Inter-Access Point Protocol [Stands Cancelled]	2003	
802.11g	54 Mbps, 2.4 GHz standard (backwards compatible with b)	2003	PHY
802.11h	Spectrum Managed 802.11a (5 GHz) for European compatibility	2004	
802.11i	Enhanced security	2004	
802.11j	Extensions for Japan	2004	PHY
802.11k	Radio resource measurement enhancements	2007	
802.11m	IEEE 802.11 Standard Maintenance and Revision	2012	
802.11n	Higher throughput improvements using MIMO	2009	PHY/MAC
802.11p	WAVE—Wireless Access for the Vehicular Environment	2010	
802.11r	Fast BSS transition (FT)	2008	
802.11s	Mesh Networking, Extended Service Set (ESS)	2011	
802.11t	Wireless Performance Prediction (WPP)—test methods and metrics Recommendation [Stands Cancelled]		
802.11u	Improvements related to Hot Spots and 3rd party authorization of clients.	2011	
802.11v	Wireless network management	2011	
802.11w	Protected Management Frames	2009	
802.11y	3650–3700 MHz Operation in the U.S.	2008	
802.11z	Extensions to Direct Link Setup	2010	QoS
802.11aa	Robust streaming of Audio Video Transport Streams	2012	QoS
802.11ad	Very High Throughput 60 GHz	2012	PHY/MAC
802.11ae	Prioritization of Management Frames	2012	QoS
802.11ac	Very High Throughput <6 GHz; potential improvements over 802.11n	2013	PHY/MAC
802.11af	TV Whitespace	2013	PHY
802.11ah	Sub 1 GHz sensor network, smart metering.	2017?	
802.11ai	Fast Initial Link Setup	2016?	
802.11aj	China Millimeter Wave	2016?	
802.11ak	Enhancements for Transit Links Within Bridged Networks	2017?	
802.11aq	Pre-association Discovery	2016?	PHY
802.11ax	High-efficiency Wireless LAN	2019?	PHY

1.2 The Scope of the Thesis Research

In this thesis I addressed to some of those basic communication control mechanism of WLAN. I use terms node, station and STA interchangeably. These terms mean WLAN devices which can connect each other via WLAN technology. Sometimes these terms include access point and client device which also have access point capability. I assumed WLAN network architecture as IBSS or Ad-hoc in the Figure 3 and Mobile Ad-hoc or MANET in the Figure 4. Today most of WLAN deployments are Infrastructure mode with access points as in the Figure 3. But as it is shown in the Figure 1, from now on mobile entities such as automobile will be one of dominant applications. Another rationale is that infrastructure mode is not effective from bandwidth utilization viewpoint. If two stations or STA's associated to the same access point communicate, all the traffic go to the AP first then are forwarded to the destination STA. One radio frame must occupy the channel twice, and consumes valuable air time twice than necessary. This is the motivation of 802.11z Direct Link Setup. Though 802.11z has not been widely implemented, direct communication scheme among STA's would be inevitable. Actually Wi-Fi alliance has developed similar technology called Wi-Fi Direct [5] [6]. 802.11z still needs an AP to establish direct communication between devices which need to associate to the same AP while Wi-Fi Direct does not need AP anymore. These new technologies definitely would contribute to build ad-hoc network.

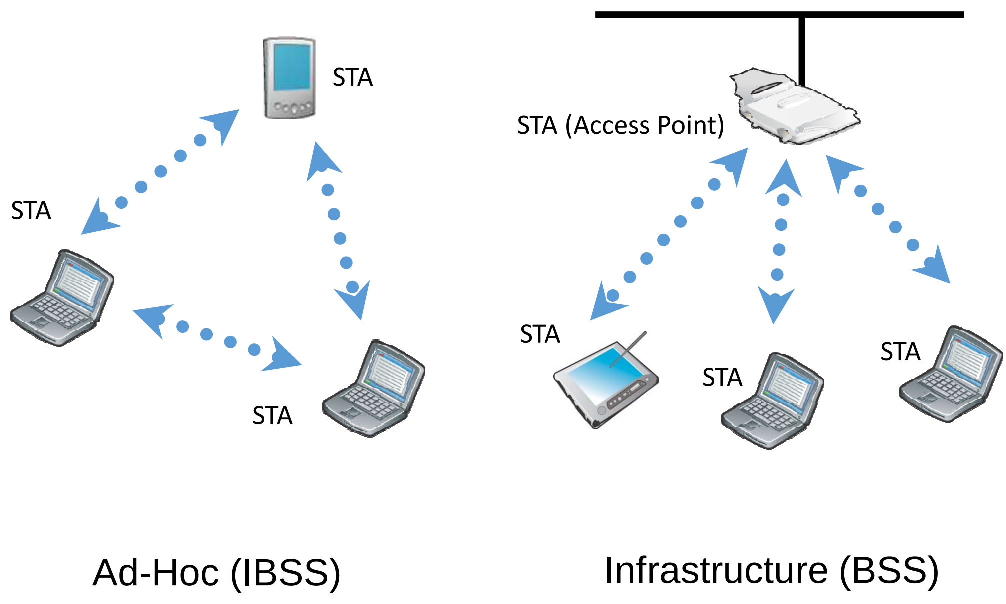

Figure 3: WLAN Network Architecture

In IBSS, all STA's are in radio range of all other STA's, so any STA can communicate to any other STA directly. In MANET, it is not necessary that any STA is within radio range of all other STA's and each STA can forward or route frames toward the destination. As a WLAN standard similar to MANET, 802.11s Mesh Network has been ratified since 2011 [7] [8]. 802.11s is built on top of the existing 802.11 PHY and MAC layer. This introduced MBSS or Mesh Basic Service Set as the third architecture of 802.11 WLAN in addition to BSS and IBSS. 802.11s allows modular implementation of various features. MANET assumes mobility of devices while 802.11s assumes Mesh nodes are stationary most of the time. Due to the nature of the research I did not consider the features of 802.11s or MANET this time because the proposed mechanism was to improve data throughput and fairness between two adjacent nodes and it is not directly relevant to mesh network establishment or traffic routing among multiple nodes.

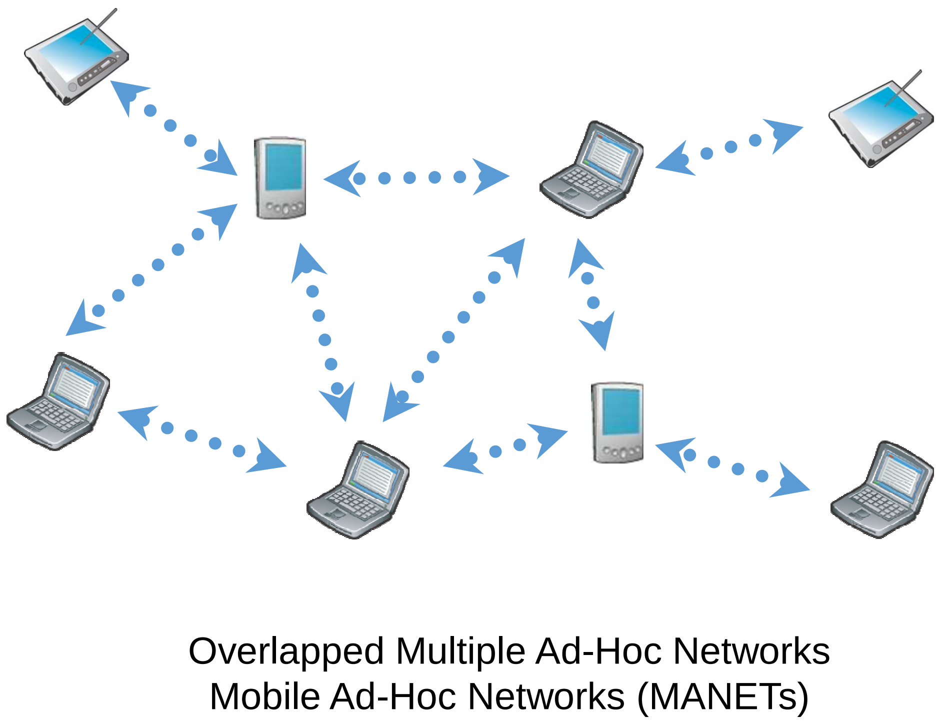

Figure 4: Mobile Ad-Hoc Networks (MANETs)

I also consider only single channel communication in this thesis. It is technically feasible that a device communicates using multiple channels simultaneously, maybe one channel for data and the other channel for signaling purpose, or maybe one channel for transmission and the other channel for receipt. 802.11 WLAN is intended to use one channel between two devices while in infrastructure mode neighboring access points should use different channels each other in order to avoid interferences. This type of deployment is sometimes called Multi Channel Architecture or MCA, but still only one channel is used to communicate between any two devices. Some of WLAN researches exploited to introduce multiple channels simultaneously in communication between two devices. I do not investigate this strategy in this thesis.

1.3 Thesis Contribution

Communication control mechanism covers broad range of functionality, and I decided to start the research with following two subjects;

1) Due to development of high throughput operation, the latest WLAN offers multirate transmission. For example, 802.11a/g offers 7 transmission rates from 6 to 54Mbps. But control frames such as beacon, RTS and CTS are considered to be sent with the lowest transmission rate as these frames should be received by as many STA's as possible. I believe this practice should be no longer optimal strategy.

2) The original 802.11-1997 did not include QoS feature and it was added later in 2003 as 802.11e. But still transmission mechanism is based on statistically given opportunity. Even with QoS, priority is allocated by probability and there are no mechanisms to provide fairness. Access method of the original 802.11 was DCF and the throughput of DCF is known to collapse when the network is saturated. 802.11e introduced revised access method EDCA, but this takes over the same weakness.

Regarding the first subject, I propose new RTC/CTS method which proactively creates difference of transmission rate between RTS and CTS frames, and uses that difference to mitigate exposed nodes. This strategy to utilize intentionally created difference of transmission rate and radio range is named Asymmetric Range by Multi-Rate Control or ARMRC. The second subject is addressed with the new method to adjust contention window or CW based on required and achieved throughput. In both DCF and EDCA, CW is fixed per access category and only collisions expand CW and only successful transmissions shrink CW. I changed this scheme and adjust CW automatically reflecting achievement and requirement of throughput.

In this thesis, mostly I assumed WLAN to be 802.11a. Because this is the first research of proposed MAC layer mechanisms, in order to evaluate its validity I believed I should start with configuration as simple as possible. After 802.11a, 11n and 11ac introduced various new features in PHY layer such as Spatial Multiplexing and transmission beamforming, and in MAC layer such as frame aggregation and block ACK. It was reasonable to add these features later and measure effect of these features after the proposed mechanism was well proven. With the same reason I can expand the scope of research to include MANET or Mesh related control mechanism.

I summarized the contribution of this thesis in the Figure 5. As in the figure there are four domains of functionality which are important for throughput and efficient operation. These four are 1) Modulation and 2) Physical carrier sense in physical layer, 3) Virtual carrier sense and 4) Access method in MAC layer. These are critical functions of media access. There are other domains which are not in the figure such as security and management, and they are not covered in this thesis. Our proposed methods are both in MAC layer and to improve 3) Virtual carrier sense and 4) Access method. Our proposed ARMRC utilizes enhancement of 1) Modulation.

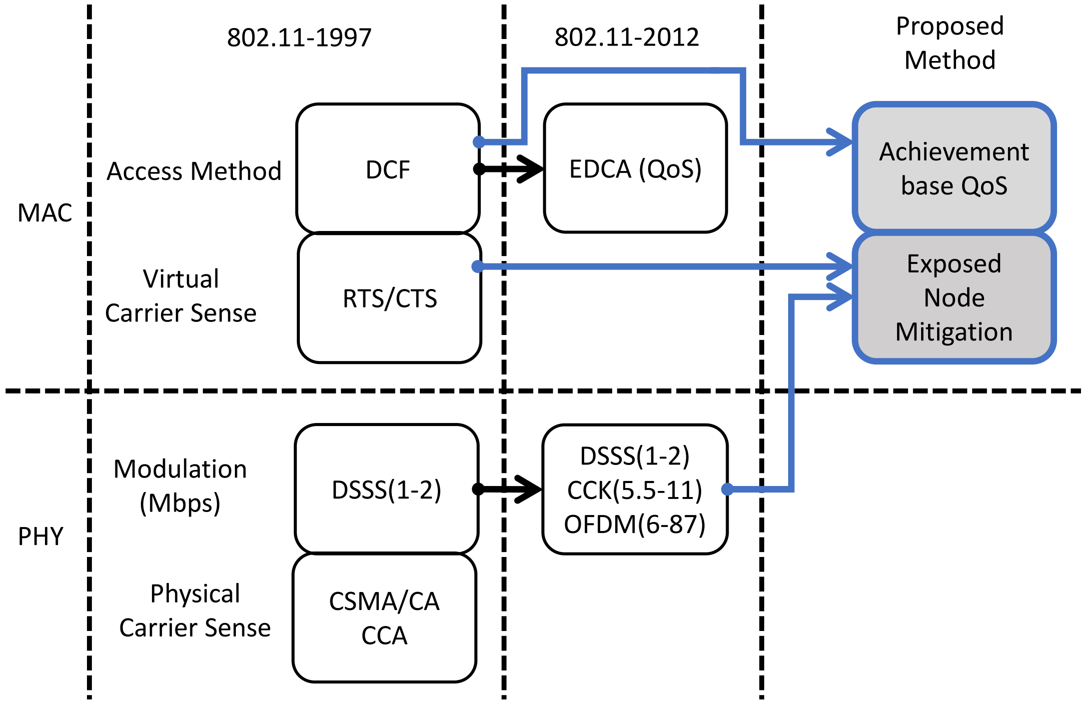

Figure 5: Contribution of this thesis

1.4 Organization

The remaining chapters of this thesis are organized as described below.

Chapter 2 "Asymmetric RTS/CTS for Exposed Node Reduction" describes our first project to utilize multirate transmission frame work. Exposed node mitigation is one application of our proposed mechanism ARMRC.

Chapter 3 "QoS Media Access Control with Automatic Contention Window Adjustment" describes our second projects to introduce fairness to throughput distribution by adjusting CW automatically with required/achieved throughput. This is new alternative strategy of QoS mechanism compared to standard based QoS, DCF and EDCA.

Chapter 4 "Conclusion" concludes the thesis and offers a number of possible areas for future research.

2 Asymmetric RTS/CTS for Exposed Node Reduction

2.1 Introduction

Nowadays mobile devices with wireless communication capability are becoming widespread; thereby ad-hoc networks that allow direct communication between devices without access points or base stations is of great interest. Wireless local area network (WLAN) standard IEEE 802.11 [7] defines carrier sense multiple access with collision avoidance (CSMA/CA) as an access method for autonomous decentralized control. As CSMA protocol implements autonomous transmission control, a sender node first performs carrier sense (clear channel assessment [CCA]), then it starts transmission if the channel is idle for a certain period of time, i.e., the DCF interframe space (DIFS) period. If any other nodes are using the channel, it waits until the channel becomes idle, and then waits another DIFS period plus a random back off period before it starts transmission. With this autonomous decentralized control, frame collisions can be avoided. However, there is a problem in that the sender node cannot know the channel usage condition of nodes outside its reception range. If the sender node happens to start trans-mission when one of those nodes outside the reception range is also in transmission, a collision occurs at the receiver node. This is the hidden node problem and degrades the network throughput [9].

The request to send/clear to send (RTS/CTS) method was introduced in the 802.11 standard to solve this hidden node problem. However, the RTS/CTS method causes a new problem called the exposed node problem. Figure 1 shows an example of hidden and exposed nodes. In Figure 1, the Hidden Node is defined as a node located within the receive range of the Receiver Node but outside the transmission range of the Sender Node. In Figure 1, we assume that transmission range and receive range are equal. The Exposed Node is defined as a node located within the transmission range of the Sender Node but outside the transmission range of the Receiver Node.

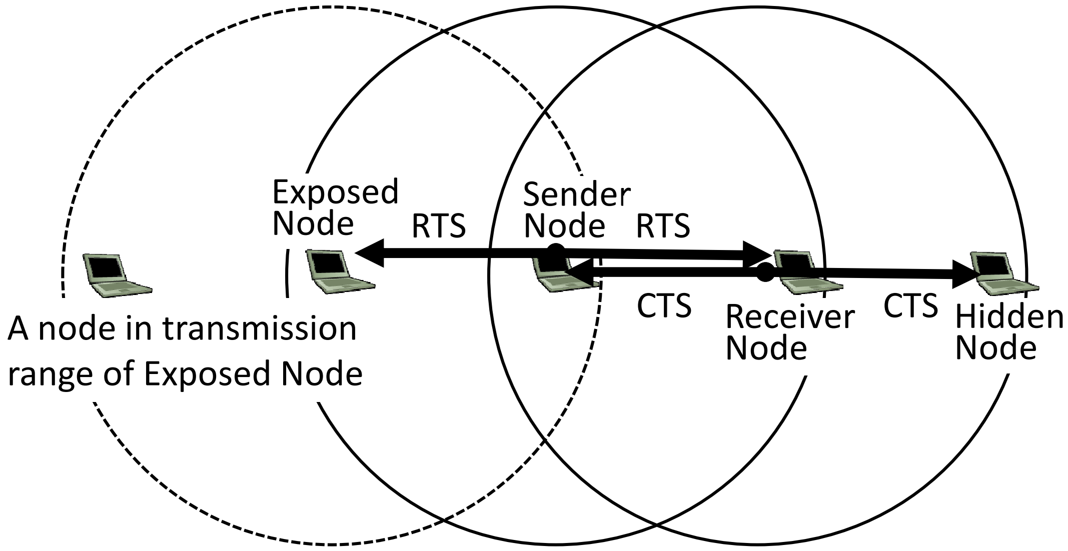

Figure 6: **Example of Hidden Node and Exposed Node**

CTS solves the hidden node problem while RTS causes the exposed node problem as follows. As the exposed nodes receive RTS from the sender, they must hold their transmissions. This allows the sender to receive CTS and ACK from the receiver without collisions, during this time the exposed nodes cannot transmit to any other nodes during that network allocation vector (NAV) period defined in the RTS frame, and their throughput degrades substantially [10] [11]. Holding transmission for the entire NAV period is an unnecessarily large penalty because when the sender is in transmission mode it cannot receive anything from the exposed nodes. Thereby the exposed node should be allowed to transmit when the sender node is sending data frames. The exposed nodes need to hold their transmission only when the sender receives the CTS and ACK frames, and these take a relatively short period compared to the data frame transmission period. In Figure 6, the Exposed Node should be able to send frames to a node in its transmission range when the Sender Node is sending a data frame to the Receiver Node. In this paper we propose an asymmetric RTS/CTS method to reduce the number of exposed nodes. The asymmetric RTS/CTS method assigns asymmetric transmission rates to the RTS and CTS. This method controls the transmission range of RTS and reduces the number of exposed nodes to prevent throughput degradation. Experimental results by simulation shows that the proposed method improves the entire network throughput compared to the standard RTS/CTS method, and also helps to equalize variation of the throughput among each node.

This paper is organized as follows. In the section 2.2, existing research related to exposed nodes and their drawbacks are reviewed. In the section 2.3, the standard RTS/CTS method is explained. In the section 2.4, our proposed asymmetric RTS/CTS method is explained. In the section 2.5, the computer simulation and its result are used to show the effectiveness of the proposed method. In the section 2.6, we summarize this paper and future research directions are discussed.

2.2 Related Works

In this section, we review related research of exposed nodes and mention their drawbacks. In [11], the following method is proposed. A node can recognize itself as an exposed node by receiving RTS not destined for it, not receiving the corresponding CTS, and receiving DATA from the RTS sender. Then the exposed node can send its data frame in parallel during the data frame transmission period of the sender node. This method is improved and named P-MAC in [12]. P-MAC involves a more sophisticated way to avoid collision by introducing 'interference range'. These are interesting approaches to utilize the fact that transmission of an exposed node does not cause collisions or interference as long as the sender node is in transmission state. In these methods, transmissions of exposed nodes must be carefully synchronized to DATA from the sender node, and it must complete the transmission before the DATA transmission is complete. P-MAC has also been modified to send ACK at random intervals, which is a deviation from the standard protocol. Our proposed method exploits this same fact without modifying protocol and maintains complete compatibility with the standard method.

In [13] [14], the following method is proposed. Each node in the network knows the locations of all other nodes in a database beforehand and knows which nodes are exposed nodes. A sender node notifies the exposed nodes which can send data frames in parallel, the same as in [11] [12], and lets them send data frames. This method may not work well on a large scale and with mobile nodes.

In [15], to eliminate exposed nodes, selective disregard of NAVs (SDN) is proposed. This selectively ignores certain physical carrier sense and NAVs. Modification to physical layer and CTS frame is required to perform this operation. This method needs additional functionalities to be implemented in all nodes and lacks compatibility with the IEEE standard.

There are some studies [16] [17] [18] which assume different transmission rate for the RTS/CTS frame and data frame, but no studies assume different transmission rate for the RTS and CTS frames. Our proposed method does not need exposed nodes to adjust their transmissions. We only need to adjust the transmission rate of the RTS and CTS in an asymmetric fashion.

Our first research of the proposed method was reported in [19].

2.3 RTS/CTS Method

In this section we explain the RTS/CTS method defined by the WLAN standard IEEE 802.11. Figure 7 shows the standard RTS/CTS method in the case of four nodes, i.e., the Exposed Node, Sender Node, Receiver Node, and Hidden Node. The standard RTS/CTS method is called 'four-way handshaking' and is outlined below.

1) A sender node performs carrier sense and sends RTS. If the cannel is busy the sender node waits until the channel becomes idle, it waits a further DIFS period plus a random

back off period before its transmission. At this moment, the exposed nodes also receive RTS. The exposed nodes must hold their transmissions for the NAV period as must all other nodes which received the RTS frame.

2) The receiver node receives the RTS and sends CTS to the sender node after the short interframe space (SIFS) period. At this moment, hidden nodes also receive the CTS. The hidden nodes must hold their transmissions for the NAV period as must all other nodes which received the CTS.

3) The sender node receives the CTS and sends the data frame to the receiver node after the SIFS period.

4) The receiver node receives the data frame and sends ACK (Acknowledgement) back to the sender node after the SIFS period.

This mechanism was introduced with the first version of the IEEE 802.11 standard in 1997. At that time, available transmission rates were only 1 Mbps and 2 Mbps. The standard defines that control frames, such as the RTS/CTS/ACK, should be sent at one of the basic data rates in order to be received by as many nodes as possible.

Though it mitigates the hidden node problem, RTS/CTS itself can be an overhead. In [20], it is reported that in a multi-rate environment with an auto rate fallback, such as in the 802.11a infrastructure mode network, RTS/CTS should be always enabled for highly loaded networks. Even if there are no hidden nodes, aggregate throughput is better with RTS/CTS when the data frame size is larger than 640 bytes (aggregate throughput is roughly 40% better at 1000 bytes). This is due to fewer collisions as the channel is reserved by a small RTS frame and occasional collision of RTS frames does not cause auto rate fallback. Therefore reducing the exposed node problem helps to extend RTS/CTS usage.

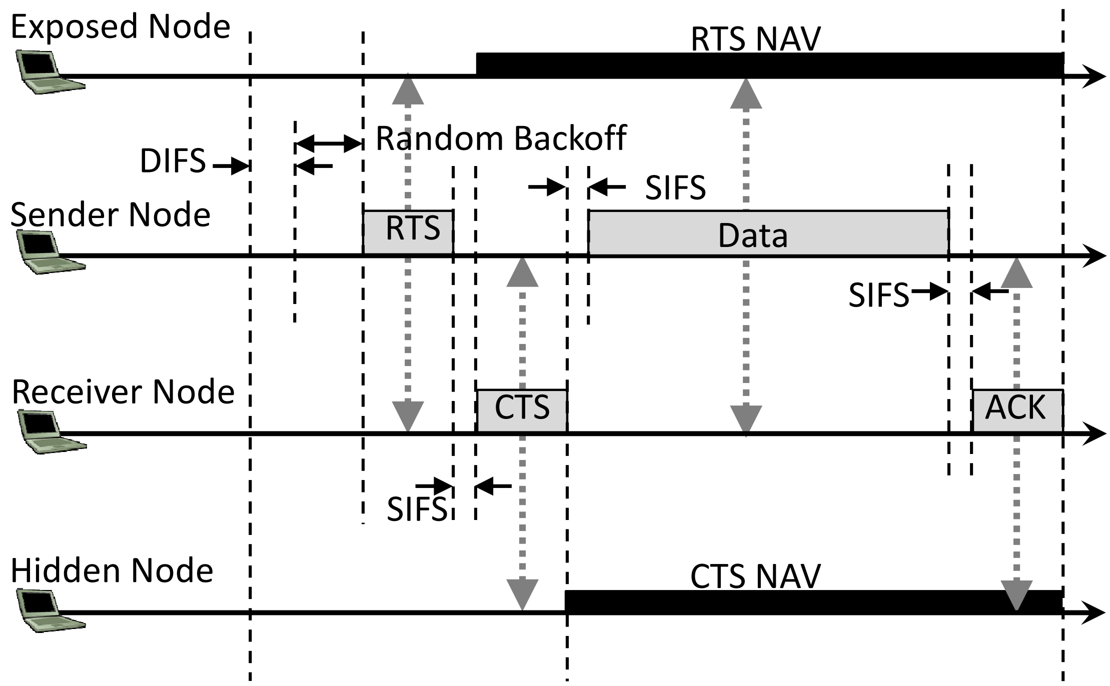

Figure 7: Standard RTS/CTS Mechanism

2.4 Proposed Method

2.4.1 Overview

Using the standard RTS/CTS method we can avoid collisions at the receiver node by eliminating hidden nodes. However, RTS induces exposed nodes and their transmissions are held for unnecessarily long periods, thereby degrading the entire network throughput. Our proposed method configures RTS and CTS transmission rates asymmetrically and controls the range of these frames in order to reduce the number of exposed nodes.

2.4.2 Consideration about RTS and CTS Rate

As in Figure 7, the Receiver Node is provoked to send CTS by receiving RTS. If the RTS range is set to the minimum distance, only reaching the receiver node, this is enough to provoke CTS from the receiver node.

The RTS transmission rate need not be the basic rate and it can be the same as the transmission rate for the data frame, i.e., this transmission rate should be the maximum rate which the sender and the receiver nodes have agreed to. From Table 3, it can be said that the effective transmission range becomes shorter with higher transmission rates. This means that we can make the effective range the smallest by adjusting the RTS transmission rate to the maximum. CTS should reach to all possible nodes that can cause collisions at the receiver node; thereby data frame reception at the receiver node can be protected. Those possible interfering nodes may transmit at the basic rate or the lowest transmission rate, thus CTS should be sent at the lowest transmission rate as well.

Transmission range is not the same as radio range. By transmission range we mean the range at which NAV is correctly interpreted and observed by any receiver node. All IEEE 802.11 frames have PHY layer convergence procedure (PLCP) preamble and header, and these are always transmitted at 6 Mbps (for 802.11a) and this transmission rate cannot be changed. The following parts of the frame, including the duration field that contains the NAV value can be modulated at a higher rate. Even if a sender node sends RTS with the high transmission rate to make the range of NAV reception short, still the range of the PLCP preamble and header is not changed. The PLCP preamble and header can provoke the CCA mechanism of any receiving node and this may spoil the effect of the proposed method. This transmission suspension period by CCA is limited to the RTS, DIFS and random back off period, and is substantially smaller than the NAV period.

Table 3: Relationship between Transmission Rate and Distance

Rate (Mbps)	Receiver Sensitivity (dBm)	Distance Ratio	Free Space Distance (m)	Distance in Cisco document, indoor-outdoor (m)	Distance in this paper (m)
6	-89	7.0	630	50 - 304	140
9	-89	7.0	630	NA	140
12	-89	7.0	630	NA	140
18	-85	5.5	400	33 - 183	88
24	-82	3.1	280	NA	64
36	-79	2.2	200	NA	44
48	-74	1.2	110	NA	24
54	-72	1.0	90	13 - 30	20

If a receiving node fails to listen to or decode the PLCP preamble and header (total 16 µs) it does not recognize the transmission at all. That transmitted frame is just handled as noise; however, noise can still provoke the CCA mechanism by energy detection (ED). The IEEE 802.11 standard defines the ED threshold as 20 dBm higher than the carrier sense (CS) threshold. The minimum modulation and coding rate sensitivity of OFDM is -82 dBm in the standard, therefore ED needs -62 dBm or higher [21] to be invoked. We do not employ power control this time and the effect of ED does not need to be considered. With these assumptions we can say that the effect of the CCA is negligible. We confirmed these assumptions are valid with a supplemental simulation and explain this in the section 2.5.2.3 in detail.

2.4.3 Effect of Asymmetric Range and Adjustment Policy

Based on the strategy mentioned in the section 2.4.2, the RTS and CTS transmission ranges should be asymmetric. Figure 8 shows the concept of our proposed method. First we assumed an environment where every node can communicate with its adjacent nodes with a certain transmission rate. In other words, any one node and its adjacent nodes are located within the range of a certain transmission rate. We also assume that RTS is sent at that certain transmission rate or lower and there are some exposed nodes, as in Figure 8. We name our proposed method Asymmetric Range by Multi-Rate Control (ARMRC) as explained below.

If the range of RTS becomes shorter as the RTS transmission rate becomes higher, some of those exposed nodes begin to fall outside the RTS range and they do not need to hold their transmissions. If the RTS range is completely included in the CTS range, all of them are no longer exposed nodes. Regarding ACK, it only needs to be received by the sender node, so it should be sent at the maximum data rate. Here, we define the Sender Node as S, the Receiver Node as R and Hidden Nodes as H in Figure 8. Assuming there are n nodes, they are defined as N = {N1, N2, …, Nn}. The distance between nodes S and R is defined as a function d, i.e., d(S, R). The radius of the RTS range and CTS range by the standard method are defined as Rrts and Rcts, respectively. Each relationship is expressed as follows.

$$d(S,R) \leq R_{rts},$$

$$d(S,R) \leq R_{cts},$$

$$d(R,H) \leq R_{cts},$$

$$d(E_i,S) \leq R_{rts},$$

$$d(N_i,R) \geq R_{cts},\ for \forall N_i \in N$$ **Equation 1**

We define radius of RTS transmission range by proposed method which we are going to configure as R'_{rts}. The condition that RTS transmission range is included in CTS transmission range completely is expressed as follow;

$$d(S,R) + R'_{rts} \leq R_{cts} \Leftrightarrow R'_{rts} \leq R_{cts} - d(S,R)$$ **Equation 2**

If the **Equation 2** is satisfied, no Exposed Node exists. Also the condition that a node is an Exposed Node is expressed as follow;

$$R'_{rts} \leq d(N_i,S)$$ **Equation 3**

If the formula **Equation** 2 is not satisfied, satisfying **Equation** 3 is an Exposed Node. We can define Exposed Node as follow.

$$E_i = \{\forall N_i, R'_{rts} \leq d(N_i,S)\}$$ **Equation 4**

Now we can briefly estimate the effect of Exposed Node reduction by ARMRC. With the standard method, any nodes included in and/or should hold transmission (this excludes the intended sender and the receiver). With our ARMRC, nodes do not need to hold their transmission and they contribute to throughput of the entire network. We defined the indicative value in terms of the throughput improvement as follow.

$$\text{Improvement Ratio} = \frac{\left|N_{RTS,\overline{RTS'},\overline{CTS}}\right|}{\left|N_{RTS,RTS',CTS}\right|}$$ **Equation 5**

Where

$$N_{RTS,\overline{RTS'},\overline{CTS}} = \left\{N_i \middle| N_i \subset R_{rts,} \, N_i \not\subset R'_{rts,} \, N_i \not\subset R_{cts}\right\}$$

$$N_{RTS,RTS',CTS} = \left\{N_i \middle| N_i \subset R_{rts,} \, N_i \subset R'_{rts,} \, N_i \subset R_{cts}\right\}$$

The shaded area of Figure 8 contains the eliminated exposed nodes by ARMRC and this corresponds to the numerator of the **Equation 5**. The total area of both and/or in Figure 8 contains all exposed nodes and hidden nodes caused by standard RTS/CTS and this corresponds to the denominator of the **Equation 5**. If nodes are distributed homogeneously or randomly, these areas could be used instead of number of nodes in the **Equation 5**.

We show behaviors of above described ARMRC as following steps.

STEP 1 The sender node sends RTS to the receiver node with possible highest transmission rate. This is to minimize the RTS coverage area and reduces exposed nodes. This means that the number of can be reduced.

STEP 2 The receiver node receives the RTS and sends back CTS with the lowest or basic transmission rate. This is to ensure all potential hidden nodes to receive CTS and to suspend their transmission.

STEP 3 The sender node receives the CTS and sends data frame to the receive node with maximum transmission rate. Some nodes around the sender receive both the RTS and the CTS. Some nodes receive the RTS only, and these are exposed node. If the RTS range is completely included in the CTS range, there are no exposed nodes. This case corresponds to (2).

STEP 4 The receiver node receives the data frame and sends back ACK with the highest transmission rate.

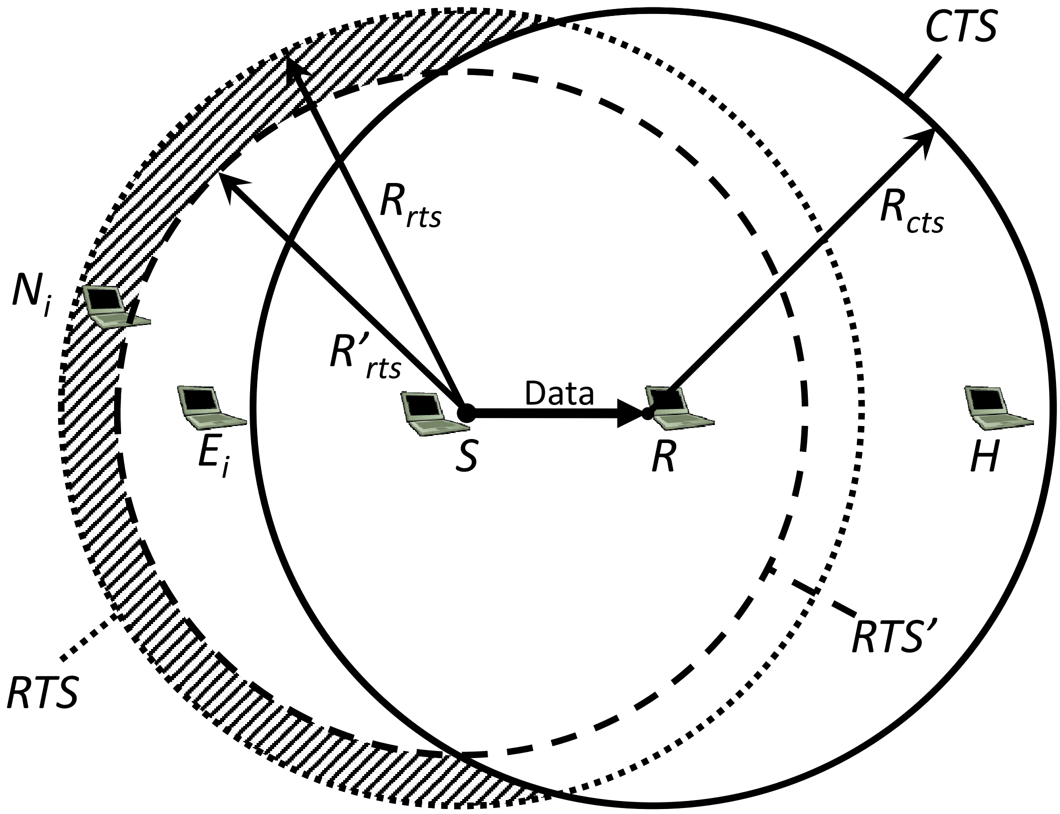

Figure 8: Concept of Asymmetric RTS/CTS

2.5 Simulation

In this section the computer simulation is explained and the proposed method is evaluated.

2.5.1 Simulation Condition

2.5.1.1 System Parameters

We assumed the WLAN standard of the 5 GHz band, IEEE 802.11a for our simulation. The system parameters of our simulation are shown in Table 4.

In IEEE 802.11a, the eight transmission rates are 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. As we mentioned in the section 2.4, the transmission rates of RTS and CTS are configured to be asymmetric. In this simulation, RTS is sent at 18 Mbps and CTS is sent at the minimum basic rate of 6 Mbps. DATA and ACK are sent at the same rate as RTS, i.e., 18 Mbps. We used 18 Mbps for RTS transmission rate to show the effectiveness of the proposed method ARMRC. If we used 54 Mbps, the sender and receiver nodes must be located very close to each other compared to the range of RTS/CTS with the basic transmission rate, and this would cause a relatively small number of exposed node. Other data rates could be configured, and these variations will be the subject of our future research as well as theoretical analysis.

2.5.1.2 Network Topology and Traffic Pattern

In this simulation, as an ad-hoc network topology all nodes are located in a grid with 70 m intervals. Seven cases are assumed with grid sizes of 3 × 3 with 9 nodes, 4 × 4 with 16 nodes, 5

× 5 with 25 nodes, 6 × 6 with 36 nodes, 8 × 8 with 64 nodes, 11 × 11 with 121 nodes, and 15 × 15 with 255 nodes. Nodes can be randomly distributed, but in practical deployment distribution of nodes is often governed by artificial objects, such as walls, furniture, partitions, and the structure of building, and as such follow a geometric arrangement. Many structures or objects in our daily life tend to be in a grid arrangement. Roads and buildings in well-developed areas are good examples of this. Another rationale of the grid layout is that we consulted a couple of deployment guidelines from outdoor Wi-Fi mesh vendors [22] [23] and found that those guidelines often start with a grid topology as a grid that is easy to design and often fits well to real world environments. Thereby we assumed a grid distribution for our research. We will definitely exploit other topologies (e.g., random distribution) and mobility of nodes in our future research.

These RTS and CTS distances are based on the 'distance in this paper' category in Table 3. Table 3 is compiled based on data in [24] [25] and the free space path loss, LOS, is calculated with the following formula;

$$\mathrm{LOS} = \left(\frac{4\pi r}{r}\right)^2$$

or

$$\mathrm{LOS(dB)} = 20\log\left(\frac{4\pi r}{r}\right)$$ **Equation 6**

where λ is wavelength and r is distance from the sender. Table 3 assumes 14 dBm or 25 mW for 5 GHz transmission, a Cisco CB-21 a/b/g client card is used and this card has a -89 dBm receiver sensitivity at 6/9/12 Mbps at 5250 to 5350 MHz. In case λ is 0.0572 m (5260 MHz) and if we solve the above formula in terms of distance r, we obtain 630 m. In practical environments path loss is larger than in free space. Table 3 also does not consider noise and fading. The CB-21 card document from Cisco [25] mentions a typical range at 54 Mbs is 13 m indoors and 30 m outdoors. Then the simple average distance of the Cisco card for 54 Mbps is about 20 m and we extrapolated distances of other transmission rates using the distance ratio in the column 'distance in this paper' in Table 3. The RTS range becomes 88 m at 18 Mbps by referring to Table 3 and RTS can reach to only the next node at the one hop distance. DATA and ACK are also sent at 18 Mbps; hence these frames also can reach the next node only. As locations of all nodes are quantized by a unit of 70 m or the 1 hop distance, an RTS range of 88 m also can be quantized to 70 m and this quantization does not change the simulation results. For simplicity from now on we use 70 m as the RTS, DATA and ACK range, as in Table 4. CTS is 6 Mbps and its range becomes 140 m from Table 3 and it can reach to a node at a two hop distance of 140 m. For comparison purposes we conducted a simulation with RTS and CTS at the same basic rate, 6 Mbps, with the same range, two hops or 140 m. We refer to this comparison simulation as the standard method.

Table 4: System Parameters for the Simulation (ARMRC)

Frame	Type	Transmission Rate	Range	
	RTS	18Mbps	88m	1 hop (70m)
	CTS	6Mbps	140m	2 hops (140m)
	Data	18Mbps	88m	1 hop (70m)
	ACK	18Mbps	88m	1 hop (70m)
Load	3Mbps per node with exponential distribution			
Data Size	1,000 bytes			
Distance	Nodes are located at 70m interval in a grid.			
Other	DIFS=34µs, SIFS=16µs and Slot time=9µs. Other parameters follow 802.11a standard.			

We assumed the following traffic pattern to simulate various data communication in an ad-hoc network. Each node generates 3 Mbps throughput traffic on average with exponentially distributed data frames, and the destination of each data frame is selected at random from four nodes with a one hop distance. We conducted some trial simulations and found out that 3 Mbps is enough to maximize the entire throughput but not saturate the network. Nodes at the boundary of the network do not have four adjacent nodes and select their destination from fewer candidate nodes at random. In practical deployment adhoc networks may not consist of a large number of nodes and a substantial portion of the nodes can be located on the network boundary. We evaluated the effect of a boundary in our simulation. The simulation continued for five seconds.

2.5.1.3 Simulation Examples

The 5 × 5 grid of 25 nodes is shown in Figure 9. In this figure node 13 is the sender and the receiver is selected from nodes 8, 12, 14, and 18 at random. In Figure 9, node 14 is selected as the receiver. An RTS with the standard method reaches up to a node at a two-hop distance and a total of 12 nodes excluding the sender node are in the transmission range. An RTS with the proposed method ARMRC reaches only the nodes at a one-hop distance and a total of four nodes are in the transmission range. As the CTS transmission range has a two-hop distance, the RTS range of the proposed method is completely included in the CTS range and there are no Exposed Nodes. This is the case in formula (2). In this case = 70, d(S, R) = 70 then ≤ d(S, R) and this satisfies **Equation 2**.

In Figure 9, black nodes are in the CTS transmission range and white nodes have no influence on the transmission from node 13 to node 14. Gray nodes would be Exposed Nodes if the standard method is applied. These are no longer Exposed Node with the proposed method. This is the case of formula (3). Rrts = 140, Rrts = 70, E = {3,7,11,17,23} and d(3,13), d(7,13), d(11,13), d(17,13), and d(23,13) are all longer than = 70. These satisfy the formula (3). As we see in Figure 9, in the case of the standard method with a 5 × 5 grid, gray nodes, i.e., exposed nodes, are very often located at the boundary of the network. It is anticipated that boundary conditions should strongly affect the throughput improvement ratio, especially for small grid sizes. Considering this situation, we conducted the simulation up to a 15 × 15 grid of 255 nodes.

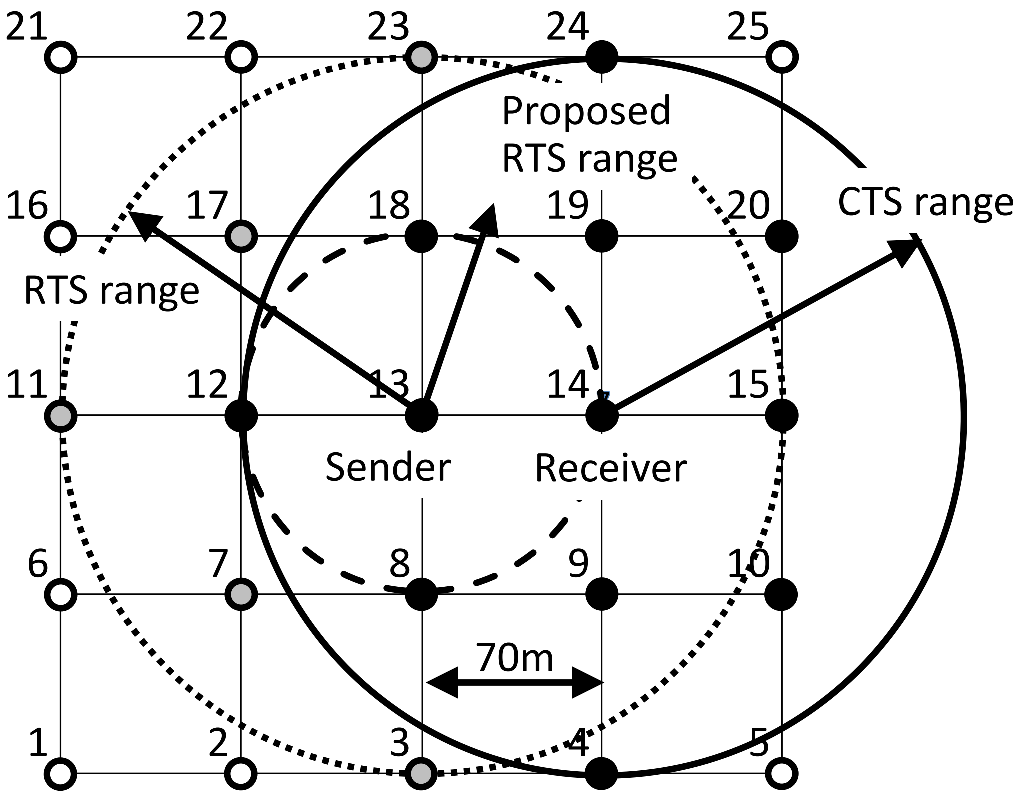

Figure 9: 5 x 5 Grid of 25 Nodes Example

2.5.2 Simulation Results

2.5.2.1 Throughput Comparison with Network Size

In Table 5, average throughput of a node is shown for grid from 3 × 3 with 9 nodes to 15 × 15 with 255 nodes. Figure 10 shows a graph of the throughput improvement ratio between the standard method and the proposed method. Figure 11 is the graph of these average throughputs. All these results were obtained with 3 Mbps traffic generation at each node.

Table 5: Average Throughput per Node by Grid

Grid (No of Nodes)	Average Throughput (Mbps)		Improvement Ratio
	Standard	Proposed	
9	1.71	2.21	1.29
16	1.60	2.04	1.27
25	1.49	1.97	1.32
36	1.40	1.91	1.36
64	1.29	1.84	1.42
121	1.22	1.77	1.46
225	1.16	1.73	1.49

As shown in Figure 10, for all sizes of grid, the proposed method has improved throughput and the improvement ratio is 27% to 49%. As shown in Figure 11, throughput per node descends as the size of the grid ascends for both the standard and the proposed method. However, the entire network throughput increases. Compared to the standard method, the proposed method always has higher throughput and the reason is the reduction of Exposed Nodes.

Next we evaluated the effect of RTS collision. The RTS frame is smaller than the data frame and has a lower possibility of causing a collision. When RTS is received safely the NAV's in RTS and the following CTS guarantee the successful transmission of the data frame by suppressing transmission of other nodes around the receiver node [20].

Figure 12 shows the average number of RTS transmissions per data frame for each grid size. If the number is greater than 1.0, it implies the occurrence of RTS retransmission. Originally RTS/CTS were introduced to mitigate the hidden node problem, but they are also known to have reduced collisions in highly loaded networks [20]. With the standard method, 11% to 13% of RTS were retransmitted due to collisions, and the retransmission ratio becomes higher as the size of the grid becomes bigger. With the proposed method, the average retransmission ratio is lower at 5% to 6%. This does not change when the size of the grid changes. The proposed method can reduce RTS collisions compared to the standard method, and increases throughput.

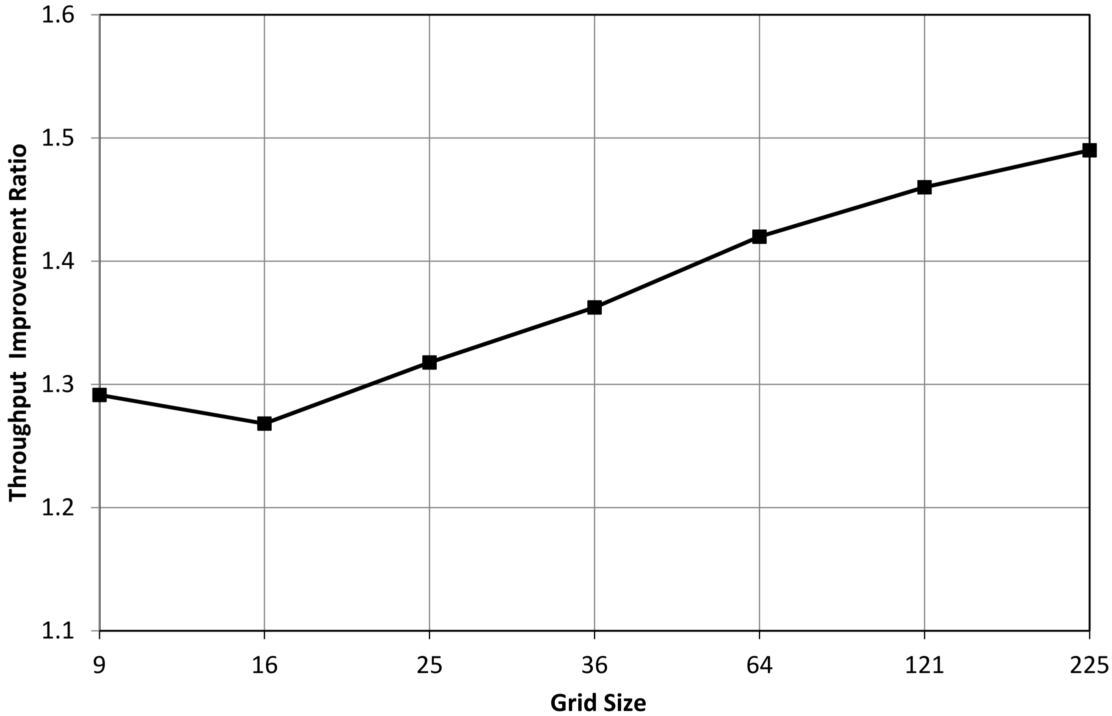

Figure 10: Throughput Improvement Ratio

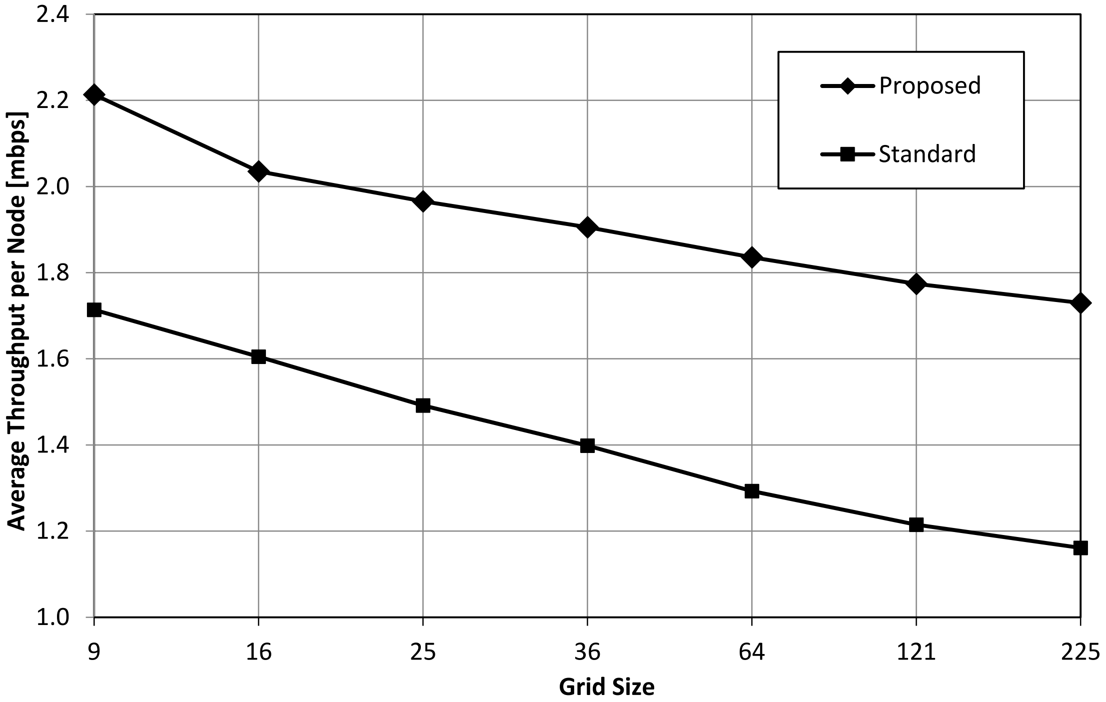

Figure 11: Average Throughout per Node

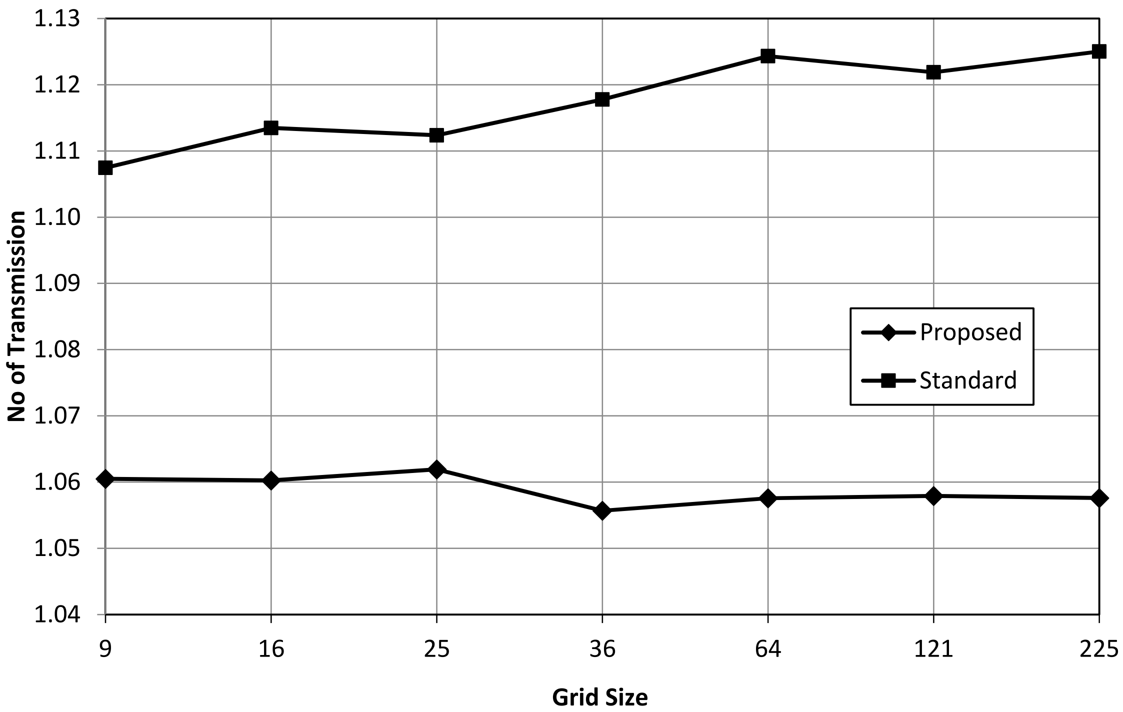

Figure 12: Average Number of RTS Transmission

2.5.2.2 Comparison of Throughput of each node within a Network

Throughput of each node in a network is evaluated in this section. Table 6 shows the improvement ratio in order of improvement. In this table, the network is a 15 × 15 grid with 255 nodes and the improvement ratios of all nodes are sorted in descending order and grouped by every 15 nodes into 15 groups. Both the standard and the proposed method are compiled into Table 6 and each group shows its average throughput for 15 nodes.

Table 6: Throughput of 15 x 15with 255 Nodes Grid

Order of Improve	Average Throughput (Mbps)		Improvement Ratio
	Standard	Proposed	
1-15	0.91	1.61	1.77
16-30	0.96	1.62	1.69
31-45	0.98	1.63	1.65
46-60	0.93	1.51	1.63
61-75	1.01	1.63	1.61
76-90	0.98	1.55	1.59
91-105	1.04	1.63	1.56
106-120	0.98	1.50	1.54
121-135	1.10	1.66	1.51
136-150	1.14	1.69	1.49
151-165	1.19	1.74	1.45
166-180	1.21	1.73	1.43
181-195	1.52	2.11	1.39
196-210	1.54	2.07	1.34
211-225	1.94	2.28	1.18
Average	1.16	1.73	1.49

As shown in Table 6, we can see substantial variations among the throughputs of all groups. We found that the group which has the highest improvement ratio (1.77) also has the lowest throughput (0.91 Mbps) with the standard method, and the group which has the lowest improvement ratio (1.18) has the highest throughput (1.94 Mbps) with the standard method. This tendency is seen for all sizes of grids, and the proposed method has a stronger improvement effect on lower throughput nodes. The 4 × 4 grid with 16 nodes network in Table 7 has the same tendency.

Table 7: Throughput of 4 x 4 with 16 Nodes Grid

Order of Improve	Average Throughput (Mbps)		Improvement Ratio
	Standard	Proposed	
1-4	0.68	1.24	1.82
5-8	1.55	2.11	1.37
9-12	1.80	2.22	1.23
13-16	2.39	2.57	1.07
Average	1.61	2.04	1.27

Figure 13 shows the graph of average throughput dispersion. The proposed method has smaller dispersion than the standard method, and this tendency is more ostensible for smaller grid sizes. We have confirmed that the proposed method levels variation of throughput. For the 15 × 15 grid with 225 nodes there are no differences in dispersion between the standard and the proposed method. We see a tendency that dispersion is converged to a single value as the network size becomes bigger. To the best of our knowledge and experience, there are some commercial ad-hoc network deployments and the size of those deployed networks is small. It is usual to have fewer than 10 nodes, and we would say it is rare to have 100 nodes or more. Therefore this characteristic can be important.

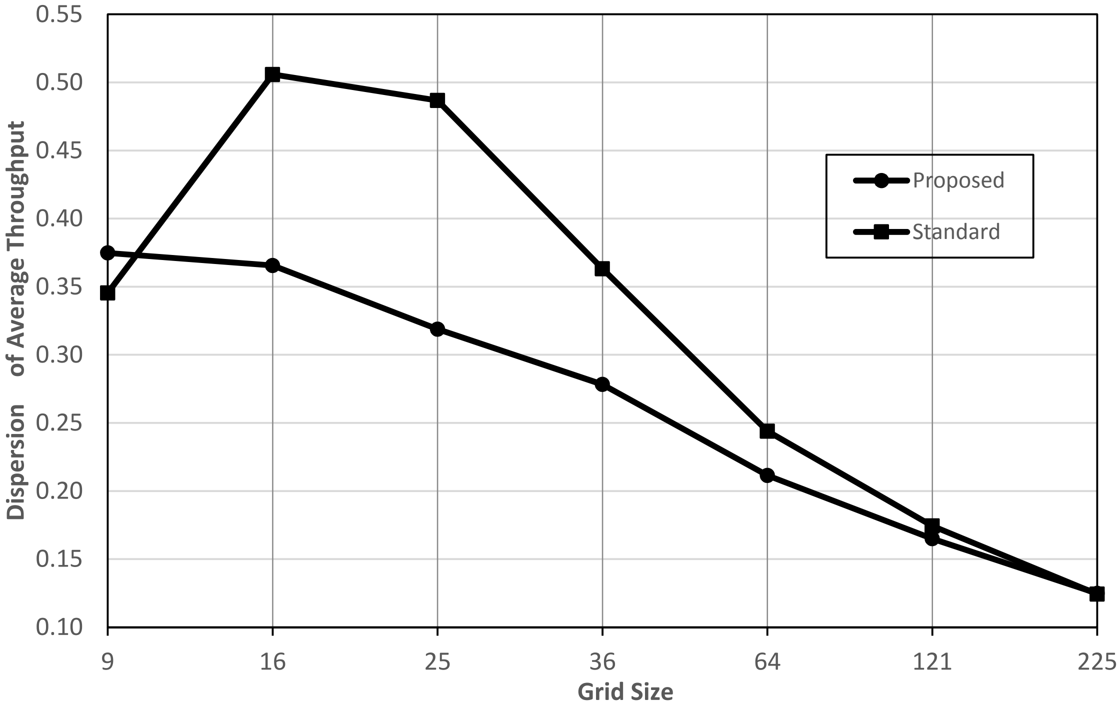

Figure 13: Dispersion of Throughput

Next we consider effect of the network boundary. As shown in Figure 9, we anticipate the effect of the boundary to strongly influence the throughput when the size of the grid is smaller than 36 nodes. The effect is expected to decrease as the size of the grid increases. Figure 14 shows the throughput distribution of the 15 × 15 gird with 225 nodes. As we explained in Table 6, these 225 nodes are divided into 15 groups in descending order of throughput improvement ratio. In Figure 14, these 15 groups are consolidated into five groups and these five groups have colors based on their throughput improvement ratio. The darker color has a lower improvement ratio and each color represents 45 nodes. The colors stand for relative improvement ratio and not absolute throughput values. There is a strong correlation that high throughput nodes with the standard method attain a low improvement ratio with the proposed method. Still their absolute throughput is high enough even after their improvement. Therefore we can recognize that the dark nodes have a high absolute throughput with both the standard and proposed method. In Figure 14, high throughput nodes are located at the boundary of the network. These nodes acquire the lowest throughput improvement ratio with the proposed method but still have the highest throughput values. This boundary effect diminishes drastically when the location of a node moves inwards in the grid by just one hop.

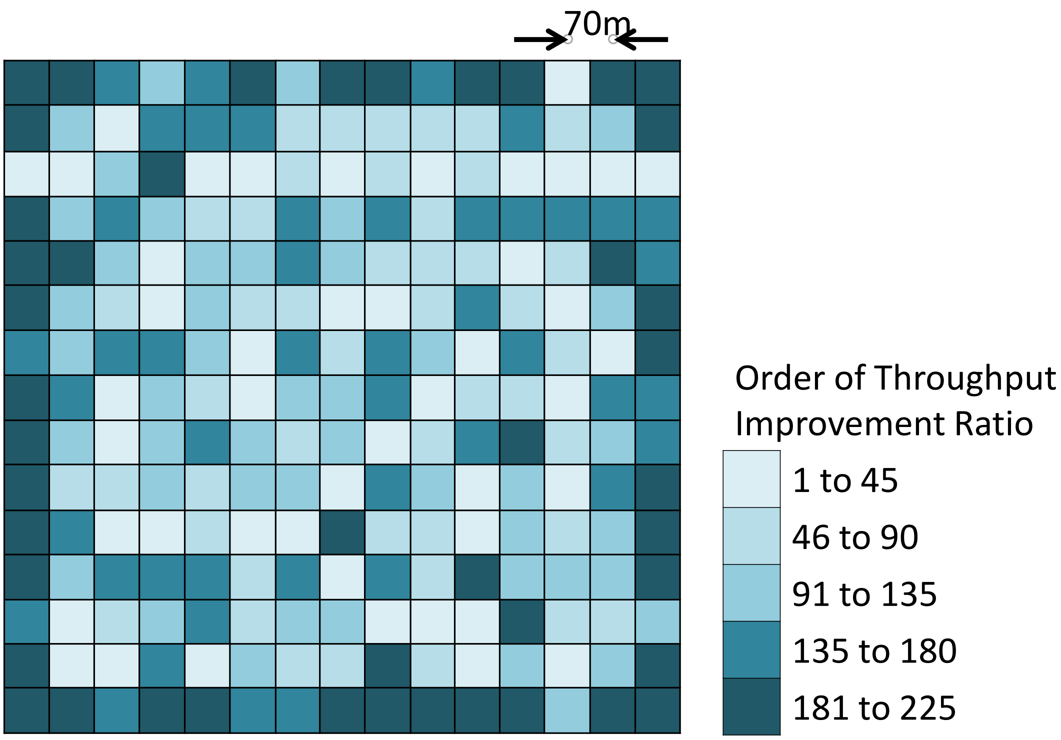

Figure 14: Distribution of Throughput Improvement Ratio at 225 Nodes Grid

2.5.2.3 Evaluation of CTS/ACK Collisions and NAV/CCA

Our proposed method cannot protect CTS and ACK frames completely from being received by the sender node. Consequently, CTS and ACK frames may be lost to collisions caused by nodes around the sender as these nodes are no longer exposed nodes (they do not receive RTS and do not suspend their transmission anymore), then the entire four-way handshaking may fail. However, CTS and ACK are small frames compared to the data frame and we assume that the possibility to lose them by collision is negligible.

Also, as we mentioned in the section 2.4.2, our proposed method may still cause exposed nodes due to the PLCP preamble and header. We also assumed this possibility is negligible. If this happens, the exposed nodes should wait for the DIFS plus a random backoff period.

To clarify these considerations, we conducted a supplemental simulation. In Table 8 we show the simulation parameters and in Table 9 we show the result.

Table 8: System Parameters for the Supplemental Simulation (ARMRC)

Frame	Type	Transmission Rate	Range	
	RTS DATA ACK	18Mbps	88m	4 hops (80m)
		24	64m	3 hops (60m)
		36	44m	2 hops (40m)
		54	20m	1 hop (20m)
	CTS	6Mbps	140m	7 hops (140m)
Load	0.9 to 1.8Mbps per node with exponential distribution			
Data Size	1,000 bytes			
Distance	Nodes are located at 20m interval in a grid. Sender and Receiver are 1 to 4 hop apart based on RTS data rate (range)			
Other	DIFS=34μs, SIFS=16μs and Slot time=9μs. Other parameters follow 802.11a standard.			

Table 9: Result of the Supplemental Simulation

RTS/Data (Mbps)	**Load per node (Mbps)**	**Entire Throughput of Grid**					
		Standard (Mbps)		**Proposed (Mbps)**		**Improvement Ratio**	
		NAV only	**NAV, PLCP, CTS/ACK collisions**	**NAV only**	**NAV, PLCP, CTS/ACK collisions**	**NAV only**	**NAV, PLCP, CTS/ACK collisions**
18	0.9	41.66	35.77	51.53	41.85	1.24	1.17
24	1.2	51.53	43.48	57.10	52.70	1.11	1.21
36	1.5	69.43	55.16	76.39	68.45	1.10	1.24
54	1.8	89.77	68.07	98.18	83.41	1.09	1.23

In this simulation we assumed a 15 × 15 grid with 20 m intervals, CTS/ACK (6 Mbps) = 7 hops/140 m and DATA=1 hop/20 m. As in Table 8, the RTS/DATA range is variable and is quantized by units of 20 m, with 4 hops/80 m at 18 Mbps, 3 hops/60 m at 24 Mbps, 2 hops/40 m at 36 Mbps, and 1 hop/20 m at 54 Mbps. Thus all RTS ranges except when RTS = 18 Mbps are completely included in the CTS range and there are no Exposed Nodes in order to maximize the effect of the proposed method. In Figure 15, the grid of RTS/DATA/ACK = 18 Mbps is shown with the same notation as Figure 9. In this figure big shaded nodes are exposed nodes and this is the only grid which has exposed nodes in this simulation. For other transmission rates higher than 18 Mbps, RTS range is completely included in the CTS range.

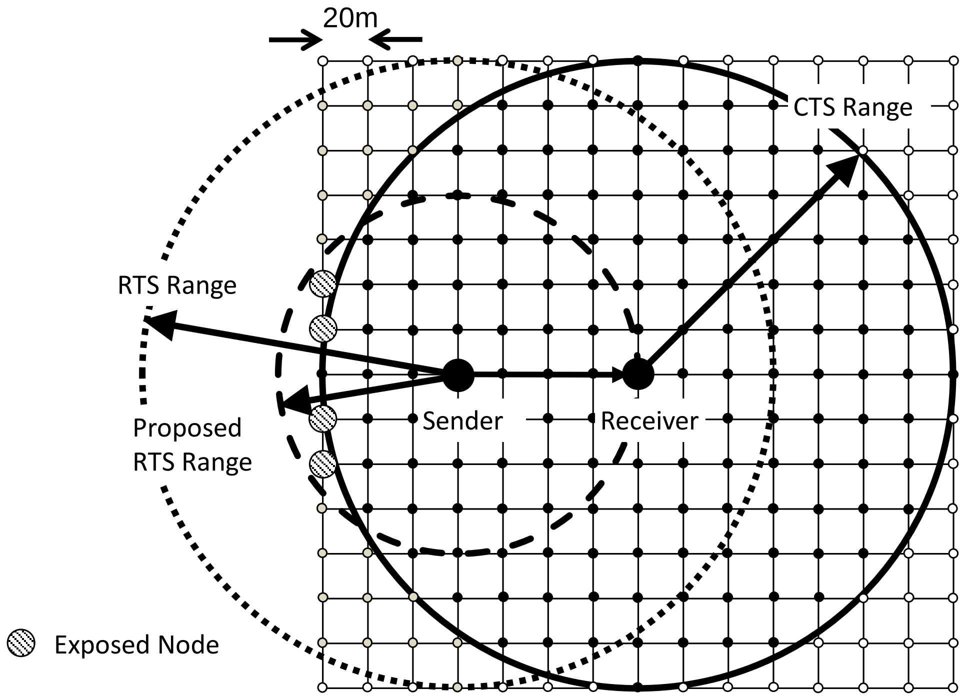

Figure 15: Grid of Supplemental Simulation at RTS/DATA/ACK=18Mbps

In Table 9, 'NAV only' means transmission suspension by only RTS/CTS NAV is evaluated. 'NAV, PLCP, RTS/ACK collisions' means in addition to NAV only, transmission suspension by CCA is induced with PLCP and CTS/ACK collisions are also evaluated. PLCP induced transmission suppression and CTS/ACK collisions degrade throughput by 15% to 25% for both the standard and proposed methods. However, the proposed method still shows a 17% to 23% improvement. Hence we can conclude that the transmission range of the PLCP preamble/header and no protection for CTS/ACK do not spoil the gains of the proposed method.

2.5.3 Considerations

We confirmed that the proposed method has a certain effect by this simulation. By eliminating exposed nodes, it may be possible to improve the entire network throughput by 30% to 50%. It has a stronger effect on low throughput nodes. In the case of small size networks, due to the influence of the network boundary, the effect of our method can be impaired somewhat. However, in our simulation we got a 30% improvement even for a small size network, and also the leveling effect of throughput dispersion is stronger for smaller size networks.

We showed that the throughput improvement ratio could be estimated roughly with formula (5). In Table 10, we summarize the estimated and simulated throughput improvement ratio for comparison.

Table 10: Comparison of Estimated and Simulated Throughput Improvement Ratio

Simulation	RTS/DATA/ACK Transmission Rate	Estimated Improvement Ratio by Formula (5)	Actual Improvement Ratio by Simulation (NAV only)
5x5 to 15x15 Grids, 70m Interval	18Mbps	0.31 (5/16)	0.29 to 0.49
15x15 Grid, 20m Interval	18Mbps	0.24 (49/201)	0.24
	24Mbps	0.22 (41/188)	0.11
	36Mbps	0.15 (26/175)	0.10
	54Mbps	0.09 (15/162)	0.09

Even though the **Equation 5** is very simple and does not consider any factors other than the number of nodes, it seems to work well. Due to the limitations of simulated finite grid sizes, for most simulated traffic all possible interfering nodes of the sender and the receiver are not in the simulated area. For example, as we see in Figure 15, all exposed nodes are not in the grid and their influences are not evaluated. We estimate that these deviated or incomplete patterns would cancel each other out and the remaining sum would be close to that for an infinite size of gird. Further theoretical analysis will be the subject of our research from now on.

2.6 Conclusion

As multi rate transmission of WLAN expands, difference in the transmission rate between the data and control frames becomes bigger. It can be up to nine times bigger using IEEE 802.11a as the maximum and minimum transmission rates are 54 and 6 Mbps, respectively, and 54 times bigger using IEEE 802.11g with maximum and minimum rates of 54 and 1 Mbps, respectively. As a result there is a substantial difference in transmission range between data and control frames. Hidden node and Exposed Node are problems caused by the spatial distribution of equipment (nodes). RTS/CTS as the resolution mechanism assume both data and control frames have the same transmission rate, but this is not optimal for a multi-rate environment. In this paper we proposed a new method ARMRC such that by adjusting the transmission rates of RTS to the same as the data frame controls its transmission range proactively. Through simulation we confirmed and quantified the effect of the proposed method. We showed that the proposed method can improve throughput per node by 30% to 50% under certain conditions. Supplemental simulation with CTS/ACK collisions and CCA by PLCP showed around a 20% improvement under certain conditions. With ARMRC we assumed that the RTS transmission rate is the same as the DATA rate and this rate is already known. Using a more general assumption, we say nodes are located with arbitrary distances and we need to define a procedure to find the optimized RTS transmission rate. In future work, we need to investigate further to validate the effect of the asymmetric transmission rate strategy and find a method of selecting appropriate parameters for each network as well as formulating a theoretical explanation for the process involved.

3 QoS Media Access Control with Automatic Contention Window Adjustment

3.1 Introduction

Due to recent rapidly increased use of smartphones, tablets and other wireless devices, IEEE 802.11 WLAN has become crucial communication method. It would be necessary to improve 802.11 based technologies to support demands from those users and QoS is one of the areas to be addressed. Because current 802.11 standard provides only one QoS mechanism EDCA as a matter of practice and in this mechanism, QoS is allocated based on probability. EDCA is known not to work well under saturated traffic [20] or highly dense deployment. We offer new approach to provide QoS based on required and actual achieved throughput. In our research we confirmed that our method provide better fairness without degrading entire network throughput and still it works under heavily loaded environment.

The first version of IEEE 802.11 standard was ratified in 1997 and since then the standard has been enhanced several times. Those enhancements are mostly focused on to increase its absolute throughput and with the latest amendment 802.11ac, the maximums throughput reaches 6.9Gbps. QoS feature was not provided with the first version of 802.11 and was not introduced until 802.11e amendment in 2003.

802.11 Wireless LAN uses CSMA/CA and defines two access methods, Distributed Coordination Function or DCF and Point Coordination Function or PCF. PCF is supported by infrastructure mode only and access point takes a role of Point Coordinator or PC which centrally manages channel access of all devices associated to the access point. PCF has Contention-free period or CFP first and Contention period or CP follows the CFP. During CFP, the access point polls each STA sequentially to solicit if the STA has data to send. STA can send data only when it is polled and collisions are avoided. During CP, PCF works as DCF which will be explained later. With this mechanism PCF is similar to cellar data network controlled by a base station. The problem is that WLAN don not use licensed band and it is difficult to avoid interferences from nearby access points operated by other parties. Interferences from nearby access points can provoke CCA and it makes difficult for the PCF access point to manage CFP. In this reason PCF is optional and has never been implemented commercially. PCF needs PC and this centralized architecture does not fit to MANET or Mesh type network. Thus we only refer to DCF in this thesis.

In DCF, any STA (client or access point) can sends when channel is idle certain period of time, DIFS. If the channel is busy, a STA to send data has to wait until the channel becomes idle, and further waits DIFS and random back off time. The random back off time is randomly selected in Contention Window or CW. CW and random back off time are integral multiple of the time slot. Every STA has its own CW. The time slot is one of basic parameter common among all STA's. Any STA which has data to send counts down by the time slot until it reaches its own random back off time. If the channel is idle until the random back off time, the STA sends data. If the channel becomes busy by that time, the STA suspends the count down and waits until the channel becomes idle again. Then the STA restart the count down from where it was suspended.

This random back off time is to avoid that more than one STA start sending at the same moment and causes collisions. But there is still possibility to cause coincidental collisions especially when number of STA is large. Size of CW is not fixed. First it is set to minimum size or CWmin and when a STA causes collision, the size is extended to twice of the current size. This is called exponential back off algorithm. If the STA continues collisions, the size keeps to be extended until it reaches to the maximum size or CWmax. If the STA succeed to send data, then the CW is reset to the CWmin.

802.11e defines two QoS mechanisms, EDCA and HCCA. EDCA is enhanced version of DCF while HCCA is enhanced version PCF. As well as PCF, HCCA has never been implemented commercially and I do not refer to HCCA in this thesis.

EDCA modified DCF scheme to add priority. The idea of EDCA is to classify traffic in four access categories or AC based on priority and to allocate different DIFS, CWmin and CWmax for each AC. Four AC's are defined as AC_VO for voice, AC_VI for video, AC_BE for best effort and AC_BK for background traffic. In EDCA, AIFS is used instead of DIFS and higher priority category has smaller AIFS, CWmin and CWmax. Then traffic or frame of higher priority category acquires smaller AIFS and CW, and statistically gets transmitted earlier than lower priority category. EDCA provides QoS based on probability. Therefore EDCA inherits weakness of CSMA/CA that it does not work well under saturated traffic because EDCA does not have mechanism to alleviate collisions. Also EDCA does not have mechanism to offer fairness of throughput among STA's. Please refer to the Figure 16 for DCF and EDCA.

In 2012, 802.11aa and 802.11ae were ratified [26] [27]. 802.11aa focuses on video traffic and enhanced EDCA AC from four to six as Intra-Access Category Prioritization. With 11aa voice and video traffic have two AC's respectively. Still probability based EDCA scheme has not been changed. Groupcast with Retries (GCR), Stream Classification Service (SCS), and Overlapping Basic Service Set (OBSS) Management are also defined in 11aa. GSC is to improve reliability of current WLAN multicast frame delivery. SCS is an optional feature to map arbitrary traffic stream to primary and alternate queues among six AC's. OBSS Management is to limit interference and capture effect from neighbor BSS or access point. It defines mechanism to quantify the load and interference status of each BSS and notifying this information to neighbor access points for channel selection and resource sharing. 802.11ae introduced priority to management frames. Each management frame is mapped to one of EDCA AC and delivered. With this mechanism we can prevent low priority management frames impeding high priority voice or vide traffic.

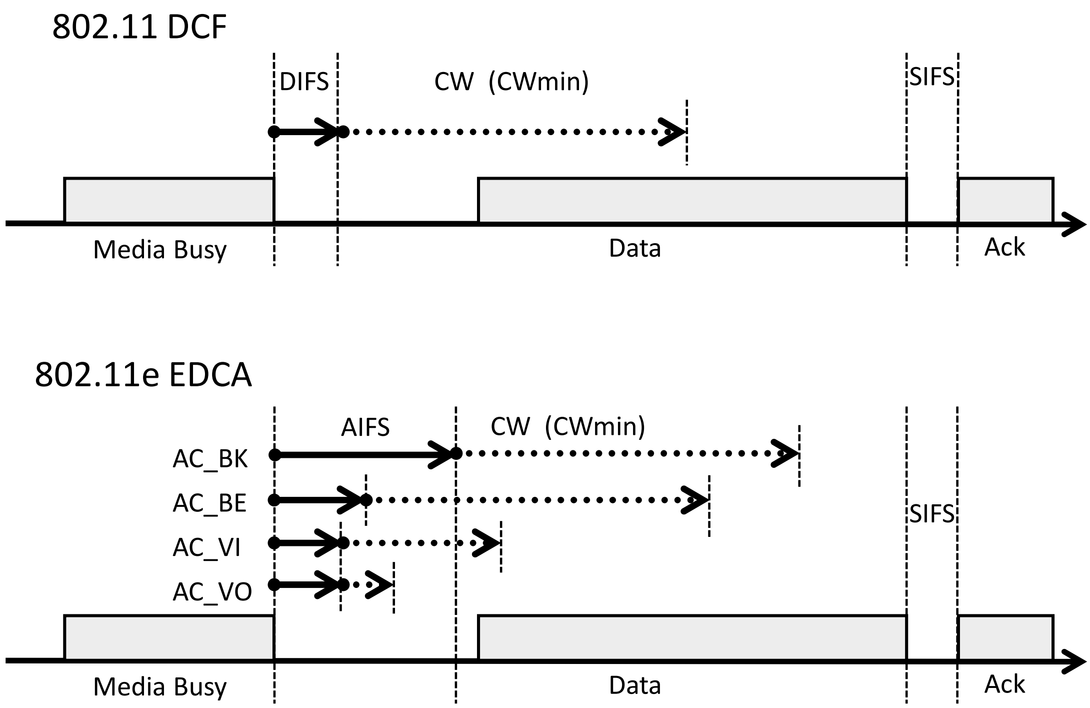

Figure 16: DCF and EDCA

These 802.11aa and 11ae features are well summarized in the document [28]. These 802.11aa and 11ae features are interesting enhancements, but still they are based on probability based EDCA or DCF mechanism. These new amendments are considered not to intend to solve the weakness of EDCA mentioned above and these are out of the scope of this thesis for now.

The rest of this part is organized as follow. Section 3.2 presents related researches and Section 3.3 describes the proposed method. In Section 3.4 we give the simulation of our proposed method, followed by the result of the simulation. In Section 3.5 we summarize our work, conclusion and future work.

3.2 Related Works

In the past substantial researches have been conducted to address QoS since the beginning of 802.11. QoS has very broad scope from physical to application layer. In this thesis I focused on MAC layer QoS features. 802.11e is one of the biggest enhancements in 802.11 history. This is very challenging subject due to the nature of contention based wireless communication. Especially with MANET or ad-hoc network, mobility of each node and no centralized control should be well considered. Wide range of past QoS researches regarding 802.11 based networks and multi-hop Ad-Hoc networks are reviewed and summarized in the survey papers [29] [30]. These papers [29] and [30] are mainly focused on resource reservation or RR and admission control respectively, but they have good amount of survey regarding MAC QoS mechanism as their coverages are QoS aware routing, QoS aware MAC scheduling, and admission control. Also the survey paper [31] provides some development of QoS aware MAC layer of Ad-Hoc networks.

Quite a few researches were reported to modify or improve DCF and EDCA random back off scheme provided by 801.11. The original CW and back off algorithm is rather simple and straight, thus numerous researches were conducted on the back off algorithm. Martin Heusse, et al. devised interesting CW adjustment method Idle Sense [32]. The original DCF expands CW to twice if a collision occurs and this is not optimized logic as STA which has data to transmit tends to obtain longer back off period. With Idle Sense, optimized CW is calculated by the number of consecutive idle time slots between two transmission attempts. In their simulation it offers high throughput, low collision and contention overhead, and good short-term fairness. Accurately Idle Sense is not QoS as it treat every STA equally. Lamia Romdhani, et al. [32] proposed Adaptive EDCF (AEDCF) for ad hoc network, which adjusts expansion rate of CW after collision and diminish rate of CW after successful transmission. AEDCF works 25% better in high traffic load condition than EDCA by their simulation. As EDCA is built on top of DCF, it cannot solve weakness of DCF in principal.

Because MANET or ad-hoc networks do not have centralized control function, it is difficult to employ Slotted ALOHA or similar strategy as well as PCF/HCCA. Still some researches were made to challenge this hurdle with hybrid-based scheme. One example is Distributed Point Coordination Function or DPCF proposed by C. Crespo, et al [33]. DPCF assumes the receiver node of traffic as the master while the sender and all neighboring nodes within the radio range of the sender are the slave. This master and slave cluster temporary form a cluster when the sender initiates transmission with RTS. They claimed that in multi-hop network with 5 nodes DPCF obtained about twice higher saturation throughput than DCF. DPCF assumes that master knows about all neighboring nodes beforehand. Any node can become master, thus entire network information is shared by all nodes. Their simulation did not consider this overhead. This may not be valid assumption for MANET and ad-hoc networks.

Another direction of research is to improve entire DCF random back off nature. A research by J. Choi, et al [34] proposed Early Back off Announcement or EBA. With EBA, sender node advertises its randomly selected next back off value in the MAC header assuming the sender will have next frame. Its neighboring nodes can know which back off time should not be used in order to avoid collision. Their simulation showed 10 to 25% throughput increase compared to DCF. It is critical that all nodes in transmission range synchronize about their back off values information each other. Their simulation assumed single data transmission rate of 11Mbps. In general MAC header is subject to be multirate transmission with different transmission coverage; therefore synchronization of MAC header information would be difficult. Another potential concern is that the authors of EBA assumed saturated traffic for their simulation. If traffic is not saturated and a sender node will not have next frame to transmit, the reserved back off slot will be totally wasted. Y. He, et al [35] proposed Reservation-Based Back off or ReB. This is another version of DCF with reserved time slot assignment as well as EBA. The major difference is that each STA keeps using the same time slot in every back off period. ReB STA does not need to exchange its proprietary ReB information but all STA’s need to be strictly synchronized by CCA. Therefore hidden terminals drastically reduce its performance and this is the same as EBA.

I briefly reviewed the related works in the area of QoS aware MAC layer for NANET and ad-hoc networks. Many researches have conducted and there has been still no dominant or widely accepted methods yet. One of the biggest challenges is to have all nodes synchronized without centralized focal point. Some researches propose access method without contention such as EBA and ReB. I believe the original DCF still has some rooms to improve as Idle Sense proved and it is feasible to build QoS in different theorem from EDCA.

3.3 Proposed Method

We designed new algorithm to calculate CW of DCF. In the original DCF, all STA's share the same CW default or initial value, CWmin. Only a collision makes the CW larger with exponential back off algorithm. Only a successful transmission set the CW back to the initial value and this is only way to make CW smaller. Our idea is to reflect required throughput and achieved throughput of STA into size of its CW. The strategy of our algorithm is that a STA which needs higher throughput should have smaller CW and a STA which has achieved smaller throughout than required should have smaller CW. We expect that this strategy will provide fairness to DCF. We developed following equations to implement our strategy into DCF scheme. Each STA can calculate its CW based on the **Equation 7**. CW after Δ is defined with the current CW and other parameters.

$$CW_i(t+\Delta) = CW_i(t) + \frac{FS_i - \gamma^i}{\gamma^i} \times \frac{FL}{ST} \qquad \textbf{Equation 7}$$

Where

FL = Transmission time of one frame

ST = Slot Time

γ^i = Target transmission frame number of STA i during Δ

FS_i = Successfully transmitted frame number of STA i during Δ

In the **Equation 7**, $\gamma^i$is defined as below;

$$\gamma^i = \sum_{j=1}^{n} \frac{T_j}{R_j} \times \frac{R_i}{T_i} \times FS_i \qquad \textbf{Equation 8}$$

Where

T_i = Achieved throughput of STA i

R_i = Required throughput of STA i

These **Equation 7** and **Equation 8** are our first examples of possible algorithms to adjust CW. There can be other possibilities and this is an area of our future research. Maybe smoothing coefficient would be introduced to the first and second member in the right side of the **Equation 7** in order to make CW adjustment quicker.

There are a couple of assumptions to make this method work. Each STA should have knowledge of required and achieved throughput of all other STA's. Especially in MANET, this is not easy to satisfy as there are no focal points to consolidate such information and some STA's may not be in radio range of all other STA's. For our current research we assumed ad-hoc network of one hop that any STA can reach any other STA directly in the simulation

We assume that throughput information can be piggybacked utilizing some field in MAC header. Duration field in MAC header of ACK frame is one possible example. Because ACK frame does not have subsequent frames, its Duration Field is always zero. Another advantage of utilizing ACK frame is that it should be sent at lowest basic transmission rate as it should be heard by as many STA as possible. This makes the transmission range of ACK frame larger and easier to share the Duration Field with other STA's. Therefore we can avoid overhead caused by introducing new management frame or control frame. As I mentioned in section 3.2, distributed architecture is better suited to MANET/ad-hoc networks and signaling of resource information is critical to achieve QoS aware MAC layer. I believe utilizing ACK frame for this purpose would solve this common requirement among distributed QoS architectures.

3.4 Simulation

We prepared simulation environments based on IEEE802.11 which are traditionally named 11, 11b and 11a. We simulated two CW algorithms, one is the original DCF and the other is our proposed method. WLAN network parameters are in the Table 11 and CW parameters of DCF, EDCA and our proposed method for 11a are shown in Table 12. Any other network parameters follow IEEE802.11 standard unless it is explicitly mentioned. Regarding 11a, we intended to simulate 54Mbps WLAN standard and in this simulation frequency band, 2.4GHz or 5GHz is not relevant. So it could be 11g instead of 11a. 11g has option to provide compatibility with 11 and size of the header can be changed. In order to avoid this unambiguity we used 11a.

Table 11: Simulation Parameters of WLAN

IEEE 802.11 Standard	11	11b	11a
Mode	Ad-hoc	Ad-hoc	Ad-hoc
Nominal Max. Throughput (Mbps)	2	11	54
SIFS Period (μsec)	10	10	16
DIFS Period (μsec)	50	50	34
Slot Time (μsec)	20	20	9
CW Max	1023	1023	1023
CW Min	31	31	15
Packet Size (byte)	1000	1000	1000
Simulation Time (sec)	60	60	60

Table 12: Contention Window Parameter of 802.11a

Method	AC	DIFS (µs)	AIFS (µs)	CWmin/max (1Slot = 9µs)	CW update
802.11 DCF	-	34	-	15 -1023	Collision/Success
802.11e EDCA	AC_BK	-	79	15-1023	Collision/Success
	AC_BE	-	43	15-1023	Collision/Success
	AC_VI	-	34	7-15	Collision/Success
	AC_VO	-	34	3-7	Collision/Success
Proposed	-	34	-	1 - 1023	Auto adjust

3.4.1 Simulation Cases

We assumed two groups of stations or STA's, and each group has 10 STA's. All STA's in the first group or Group 1 share the same throughput requirement, and the second group or Group 2 also share the same throughput which is twice higher than the first group. We prepared four or five simulation cases from light load to very saturated load. Please refer to Table 13, Table 14 and Table 15 for simulation cases of 802.11, 11b and 11a respectively.

Table 13: Simulation Case Parameters for 802.11

802.11		Case 1	Case 2	Case 3	Case 4	Case 5
Required Throughput per STA (Mbps)	Group 1	0.03	0.05	0.067	0.1	
	Group 2	0.06	0.1	0.133	0.2	
Nominal Max. Throughput (Mbps)		2	2	2	2	
Total Load (Mbps)		0.9	1.5	2	3	
Load Ratio		0.450	0.750	1.000	1.500	

Table 14: Simulation Case Parameters for 802.11b

802.11b		Case 1	Case 2	Case 3	Case 4	Case 5
Required Throughput per STA (Mbps)	Group 1	0.2	0.3	0.36	0.5	
	Group 2	0.4	0.6	0.72	1	
Nominal Max. Throughput (Mbps)		11	11	11	11	
Total Load (Mbps)		6	9	10.8	15	
Load Ratio		0.545	0.818	0.982	1.364	

Table 15: Simulation Case Parameters for 802.11a

802.11a		Case 1	Case 2	Case 3	Case 4	Case 5
Required Throughput per STA (Mbps)	Group 1	1	1.5	1.8	2	2.5
	Group 2	2	3	3.6	4	5
Nominal Max. Throughput (Mbps)		54	54	54	54	54
Total Load (Mbps)		30	45	54	60	75
Load Ratio		0.556	0.833	1.000	1.111	1.389

Traffic is generated based on Poisson distribution at each STA. Required Throughput per STA is generated throughput or load at each STA of each group. Total Load is the sum of these generated throughputs. Nominal Maximum Throughput is maximum transmission rate by the standard. For example, 11a allows transmission of frames with up to 54Mbps. Actual feasible throughput should be lower because DCF has substantial overhead caused by CCA, CW, ACK and back off time. Load Ratio is the ratio of Total Load to Nominal Maximum Throughput.

In these simulations, total 20 units of STA build one Ad-hoc network. This network is IBSS and not MANETs. Any STA is in radio ranges of all other STA's. In other words, each STA can communicate to any other STA directly without third node in between. Therefore there are no hidden nodes and RTS/CTS is not applied. These simulations assume ideal radio environment without any interferences or background noise. Also it does not consider free space loss of radio propagation. This simulation is intended to evaluate proposed MAC layer mechanism.

3.4.2 Simulation Result

In the following Table 16, Table 17 and Table 18, the results of 802.11, 11b and 11a are shown respectively. The maximum achieved throughput of entire network is about 1.6Mbps for 802.11, about 6Mbps for 11b and 32Mbps for 11a after saturation or where Load Ratio is 1.0 and higher. These are 55 to 80% of nominal throughput, and considered to be reasonable with taking overhead such as DIFS, SIFS, ACK and back off time into account. The proposed method shows definitely better throughput than the standard method. As you see in the tables, number of collisions are smaller with the proposed method. Roughly sum of successful transmission and collisions are similar amount between the proposed and standard methods. With the proposed method, substantial amount of collisions are converted to successful transmissions.

Next we show Load Ratio versus Achievement Ratio. Achievement Ratio is the ratio of Achieved Throughput to Required Throughput per Group. If fairness of throughput is completely achieved, Achievement Ratio of Group 1 and 2 should become the same value. In order to evaluate fairness, Jain's Fairness Index [37] [38] is used. This index needs optimal throughput to be calculated. The optimal throughput of each STA was derived from the total achieved throughput. For example 802.11a CASE 1 Standard CW Method, the Total Achieved Throughput is 27.48Mbps. Assuming this is the total optimal throughput, each Group 1 STA and Group 2 STA should have optimal throughput of 0.92 and 1.83Mbps respectively. In this simulation theoretically the best fairness Index could be 1.0.

Table 16: Simulation Result of 802.11

802.11		Case 1	Case 2	Case 3	Case 4	Case 5
Load Ratio		0.450	0.750	1.000	1.500	
Standard CW Method						
Achieved Throughput per group (Mbps)	Group 1	0.30	0.50	0.65	0.72	
	Group 2	0.61	0.89	0.83	0.75	
Total Achieved Throughput (Mbps)		0.91	1.39	1.48	1.47	
Achievement Rate	Group 1	1.00	0.99	0.97	0.72	
	Group 2	1.02	0.89	0.62	0.38	
Jain's Fairness Index		0.9953	0.9926	0.9461	0.8983	
Total Collisions		108	4,783	3,457	3,619	
Total Successful Transmissions		6,857	10,416	11,065	10,993	
Proposed CW Method						
Achieved Throughput per group (Mbps)	Group 1	0.30	0.49	0.56	0.56	
	Group 2	0.60	1.02	1.08	1.11	
Total Achieved Throughput (Mbps)		0.90	1.51	1.63	1.67	
Achievement Rate	Group 1	0.99	0.98	0.83	0.56	
	Group 2	1.00	1.02	0.81	0.56	
Jain's Fairness Index		0.9976	0.9988	0.9987	0.9994	
Total Collisions		115	1,008	846	359	
Total Successful Transmissions		6,723	11,336	12,235	12,512	

Table 17: Simulation Result of 802.11b

802.11b		Case 1	Case 2	Case 3	Case 4	Case 5
Load Ratio		0.545	0.818	0.982	1.364	
Standard CW Method						
Achieved Throughput per group (Mbps)	Group 1	1.97	2.82	2.72	2.71	
	Group 2	3.70	2.96	2.76	2.75	
Total Achieved Throughput (Mbps)		5.67	5.78	5.47	5.47	
Achievement Rate	Group 1	0.99	0.94	0.75	0.54	
	Group 2	0.93	0.49	0.38	0.28	
Jain's Fairness Index		0.9982	0.9109	0.9033	0.9034	
Total Collisions		5,194	3,908	8,496	8,640	
Total Successful Transmissions		42,536	43,326	41,058	40,999	
Proposed CW Method						
Achieved Throughput per group (Mbps)	Group 1	1.99	2.29	2.53	2.07	
	Group 2	3.90	3.66	3.28	3.95	
Total Achieved Throughput (Mbps)		5.89	5.95	5.80	5.80	
Achievement Rate	Group 1	0.99	0.76	0.70	0.51	
	Group 2	0.97	0.61	0.45	0.33	
Jain's Fairness Index		0.9995	0.9842	0.9538	0.9974	
Total Collisions		1,210	1,200	3,135	3,101	
Total Successful Transmissions		44,162	44,639	43,508	45,175	

Table 18: Simulation Result of 802.11a

802.11a		Case 1	Case 2	Case 3	Case 4	Case 5
Load Ratio		0.556	0.833	1.000	1.111	1.389
Standard CW Method						
Achieved Throughput per group (Mbps)	Group 1	10.02	13.96	14.01	14.04	13.99
	Group 2	17.47	14.00	13.91	13.87	13.96
Total Achieved Throughput (Mbps)		27.48	27.96	27.92	27.91	27.95
Achievement Rate	Group 1	1.00	0.93	0.78	0.70	0.56
	Group 2	0.87	0.47	0.39	0.35	0.28
Jain's Fairness Index		0.9952	0.9006	0.8982	0.8969	0.8969
Total Collisions		33,340	30,904	31,208	31,274	30,972
Total Successful Transmissions		206,136	209,676	209,380	209,322	209,660
Proposed CW Method						
Achieved Throughput per group (Mbps)	Group 1	10.00	14.02	14.12	13.85	13.93
	Group 2	19.99	17.66	17.57	17.82	17.74
Total Achieved Throughput (Mbps)		29.99	31.68	31.69	31.67	31.67
Achievement Rate	Group 1	1.00	0.93	0.78	0.69	0.56
	Group 2	1.00	0.59	0.49	0.45	0.35
Jain's Fairness Index		0.9999	0.9503	0.9479	0.9542	0.9520
Total Collisions		6,414	5,567	5,462	5,632	5,713
Total Successful Transmissions		224,958	237,576	237,676	237,528	237,535

Also in the following Figure 17, Figure 18 and Figure 19, graph of Load Ratio versus Achievement Ratio for 802.11, 11b and 11a are shown respectively. Figure 20, Figure 21 and Figure 22 are graph of Jain’s Fairness Index for 802.11, 11b and 11a respectively. In these figures, STD, PRP and GP mean Standard CW Method, Proposed CW Method, STA Group respectively.

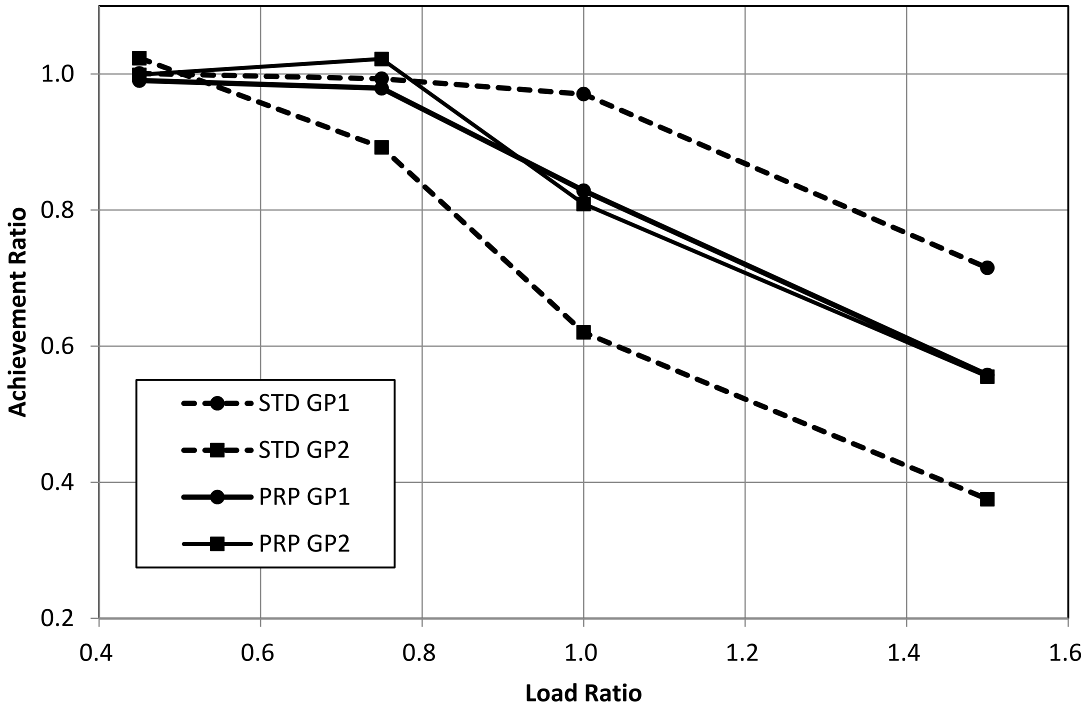

Figure 17: Achievement Ratio of 802.11

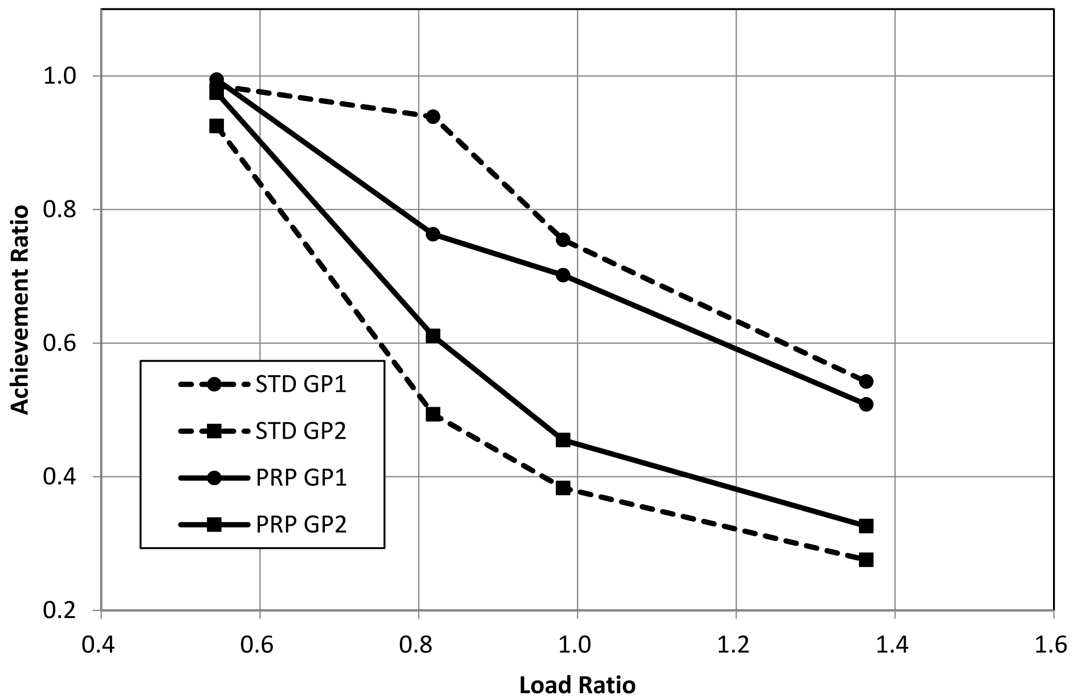

Figure 18: Achievement Ratio of 802.11b

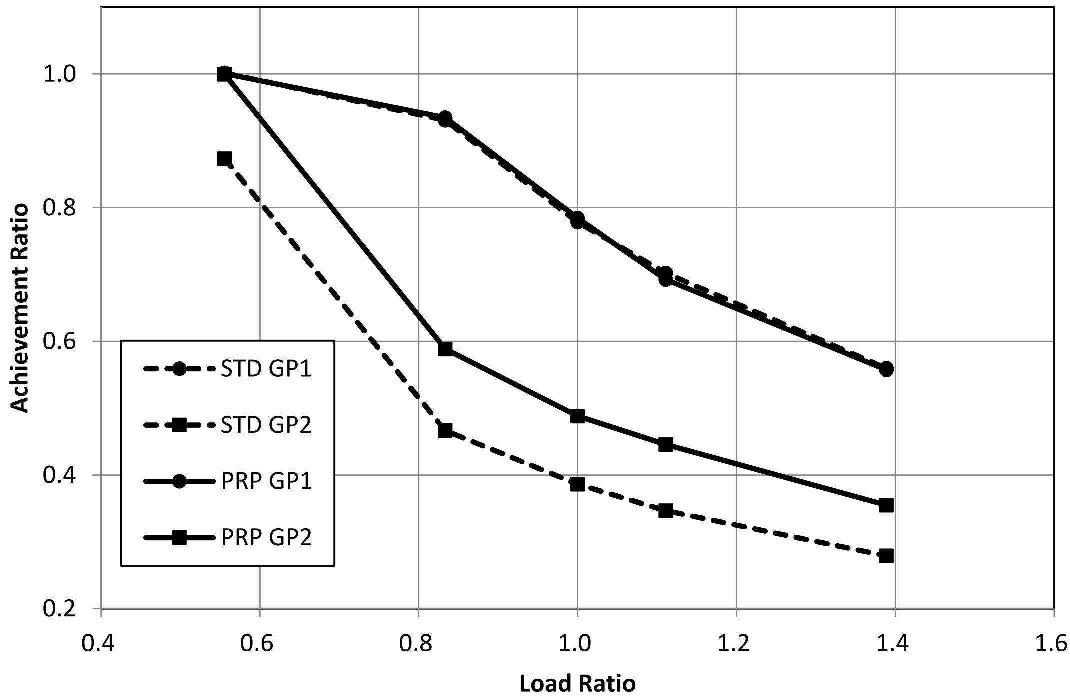

Figure 19: Achievement Ratio of 802.11a

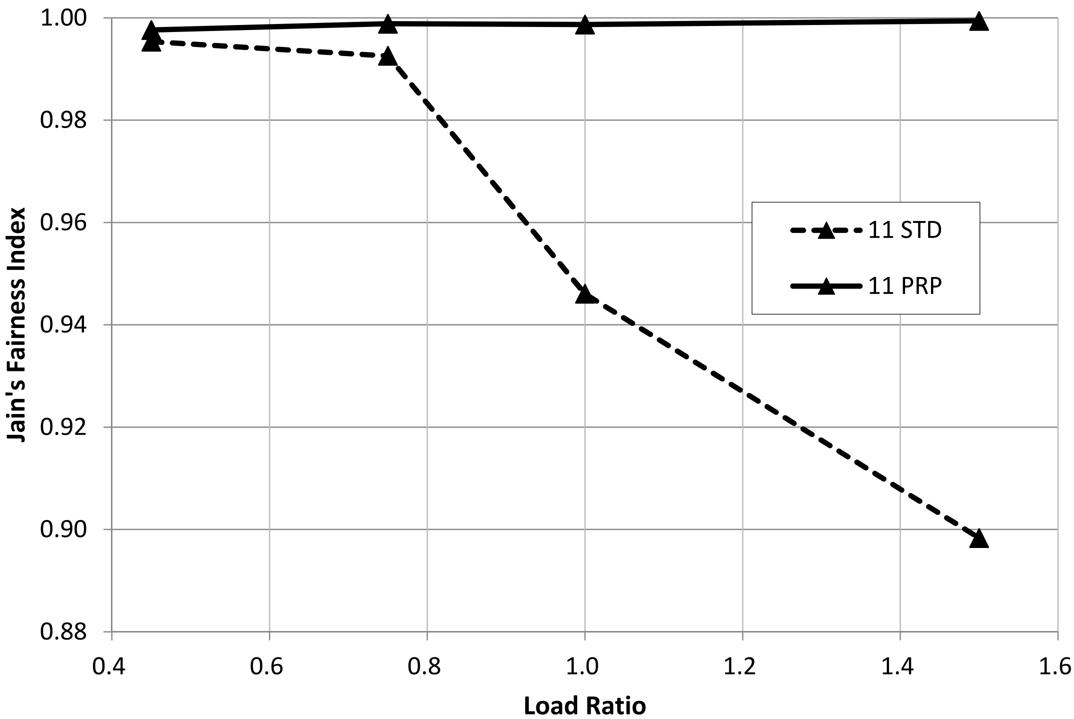

Figure 20: Jain's Fairness Index of 802.11

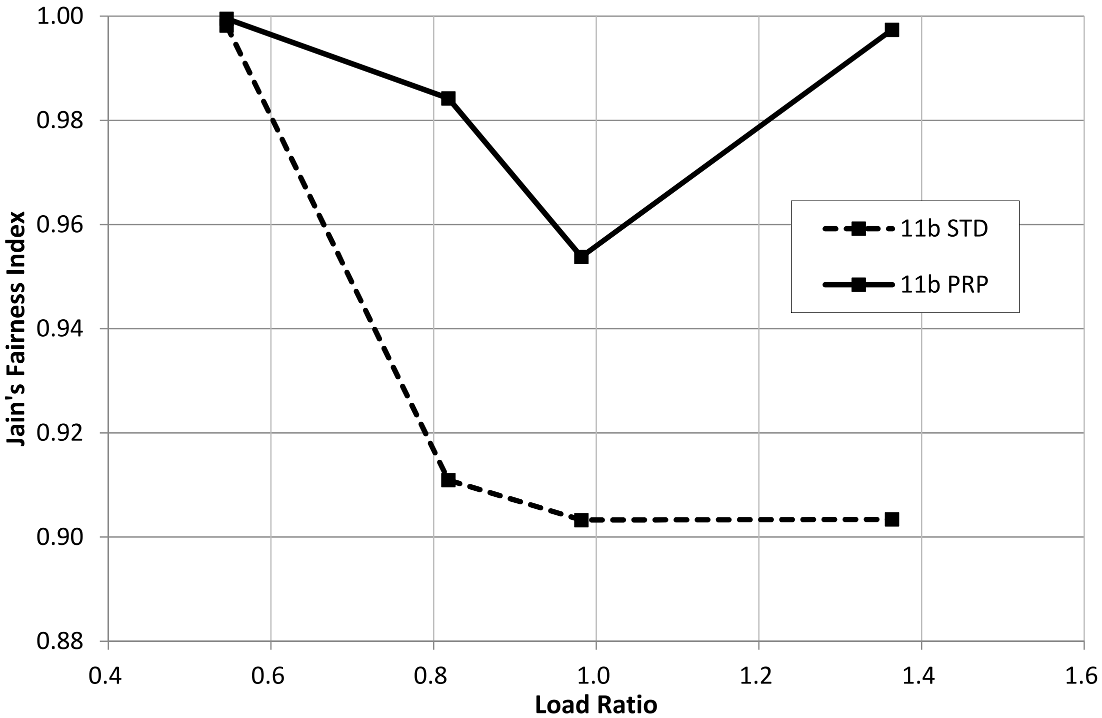

Figure 21: Jain's Fairness Index of 802.11b

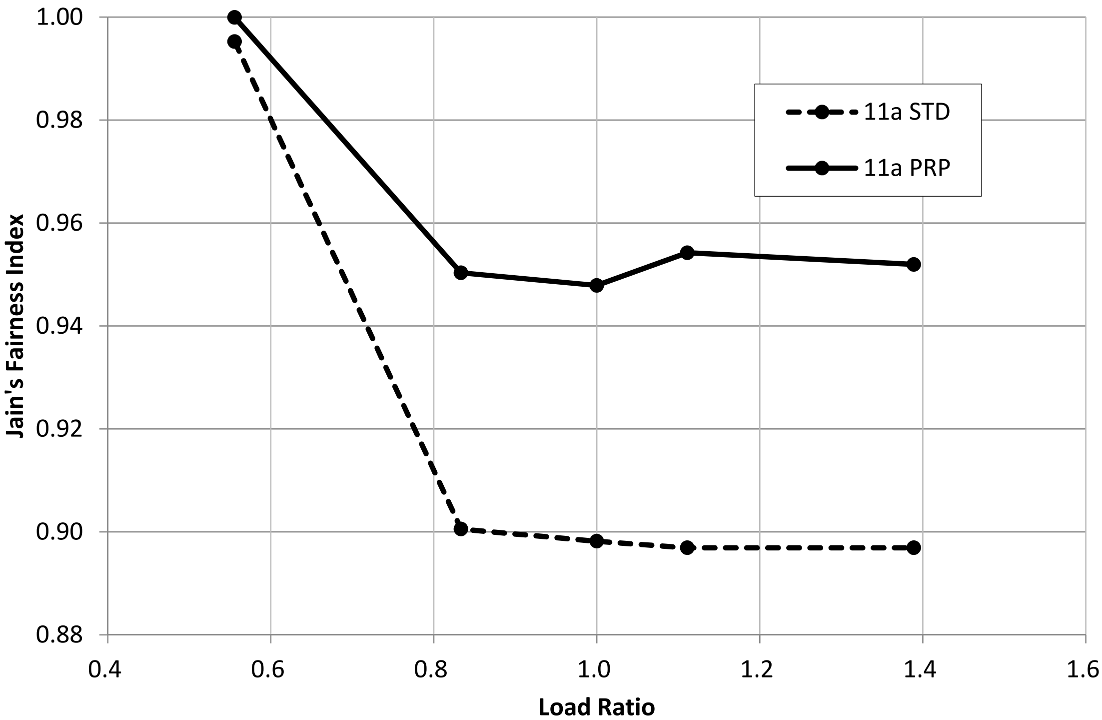

Figure 22: Jain's Fairness Index of 802.11a

As you can see in these figures, when Load Ratio is low enough, such as 0.4 to 0.6, Achievement Ratio is 1.0 for both Group 1 and 2. This is what anticipated. Achievement Ratio declines as Load Ratio increases and this is also easily expected. Load Ratio of 1.0 or higher means traffic is completely saturated, and at this point Achievement ratio should be less than 1.0. All Figures are consistent with this logical expectation.

If fairness of throughput can be guaranteed perfectly for both groups, Achievement ratio of both groups should be exactly the same number. But in these figures, Group 1 shows higher Achievement Ratio than Group 2. This is because Group 1 has lower required throughput and this means shorter transmission air time is required totally. In saturated network each STA competes to secure its air time. Standard method (DCF) provides homogeneous opportunity to access channel to all STA's. Therefore this is understandable that Group 1 can have higher Achievement Ratio as Groupe 1 needs totally shorter air time. Our proposed method adjusts CW based on achieved and required throughput, but in this simulation still it has CWmax of 1023. So it is considered to have better fairness than DCF, but its fairness should have certain limit.

It can be said that our proposed method has smaller Achievement Ratio difference between Group 1 and 2 than standard DCF. This means our proposed method provides better fairness. These observations are common among all simulated cases. This is also confirmed in the Figure 20, Figure 21 and Figure 22 as Jain's Fairness Index is always higher with proposed method. As in the Figure 21, Jain's Fairness Index of the proposed method behaves strangely. It does not simply incline or decline, but I has the bottom at the Load Ration around 1.0. I believe this behavior is due to statistical fluctuation. Also in the Figure 22, substantially smaller but similar bottom is recognized around the Load Ratio 1.0. In this simulation, rand function of C++ is used to decide transmission time at random in CW. The simulation is for 60 seconds and during this iteration the same seed for randomization is used. Thus there is a possibility that transmission times were not completely random. It should be better to run the simulation multiple times with different seed values, and sum up the results. I believe this could minimize the observed fluctuation.

We will see how Throughput and Achievement Ratio behave with each STA in both groups. The Figure 23 and Figure 24 show Throughput and Achievement Ratio of 802.11a at Total Load 30Mbps. Because Total Load 30Mbps is Load Ratio 0.556, this is not saturated situation yet. As you can see with the proposed method all STA's in both groups achieved corresponding required throughput completely. So the Achievement Ratio is 1.0 with all STA's. Interestingly the standard method shows different result. The Group 2 STA's do not achieve required throughput and their achievement ratios are under 0.9, while the Group 1 STA's achieve required throughput completely. Even without saturation, the standard method cannot utilize feasible throughput completely. The reason is considered to be collisions. As in the Table 18, the standard method has 5 to 6 time higher collision numbers.

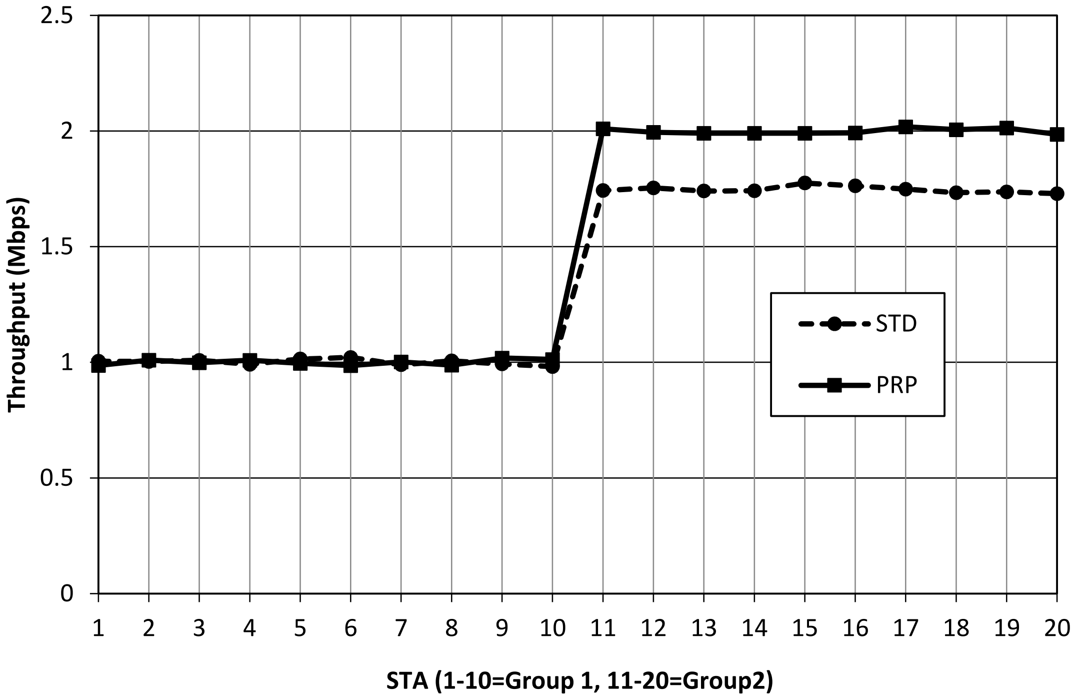

Figure 23: Throughput of 802.11a with Total Load 30Mbps

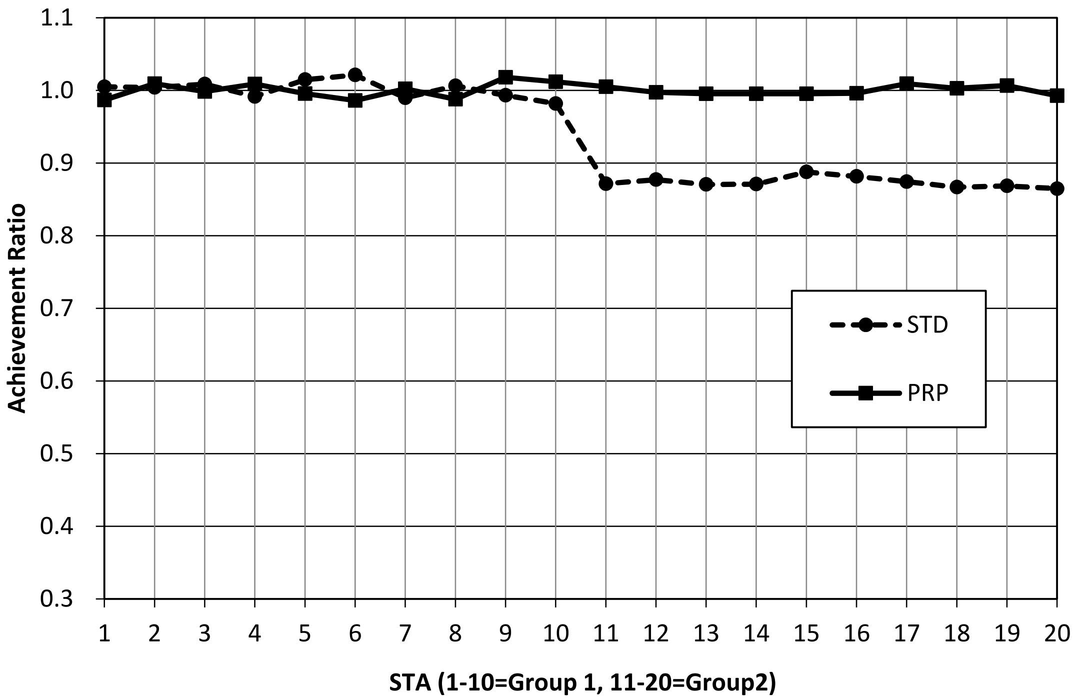

Figure 24: Achievement Ratio of 802.11a with Total Load 30Mbps

Next we look at saturated traffic. In the Figure 25 and Figure 26, graphs of Throughput and Achievement Ratio for 802.11a at Total Load 54Mbps are shown. With standard method, all STA's in spite of their groups achieved the same Throughput about 1.4Mbps. Thus the

Achievement Ratio of each group differs drastically, about 0.8 for Group 1 and about 0.4 for Group 2. Standard method provided equal access to air time irrelevantly to required throughput and fairness. This is why the two groups ended up with the same Throughput and different Achievement Ratio. I showed this fact with Total Load 54Mbps only here, but this is commonly observed with all Total Loads higher than 54Mbps which is considered beyond the saturation point.

Regarding the proposed method, as you can see Group 2 achieved higher throughput than Group 1 as Group 2 has higher Required Throughput. As a result Achievement Ratios of the two groups become somewhat closer in the two groups than the standard method. This is effective and advantage of the proposed method. It is also recognized that both Throughput and Achievement Ratio are not stable among STA's. Especially about the Group 2 the graphs fluctuate in contrast to the standard method.

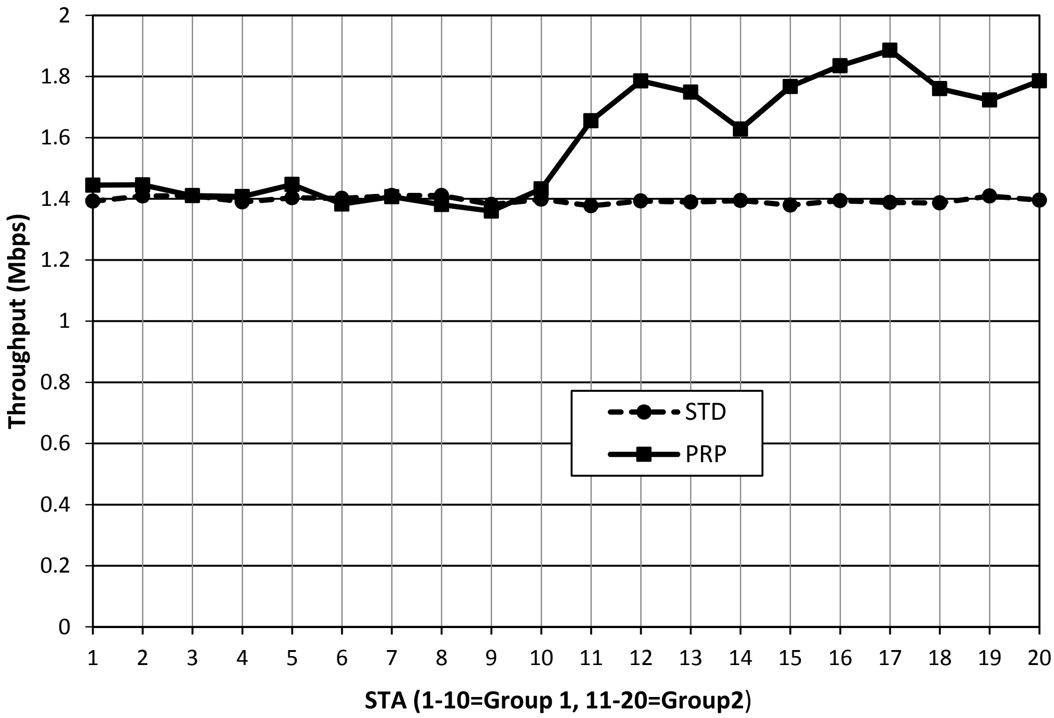

Figure 25: Throughput of 802.11a with Total Load 54Mbps

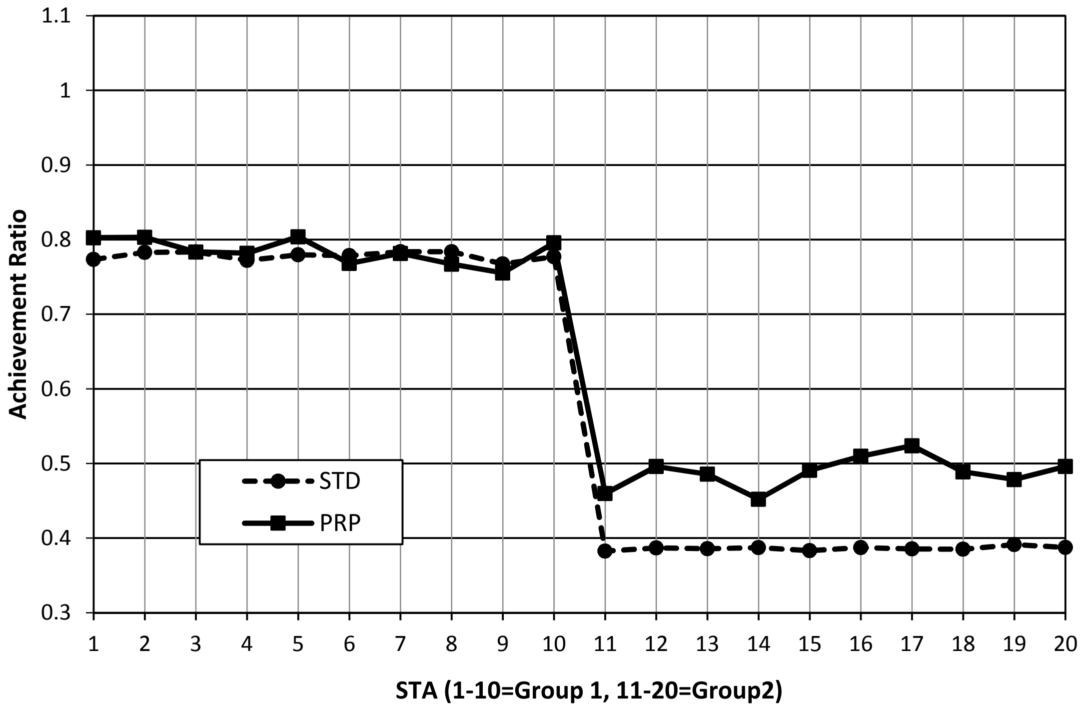

Figure 26: Achievement Ratio of 802.11a with Total Load 54Mbps

In order to evaluate the fluctuating of Achieved Throughput of the proposed method, the standard deviation of the throughput is shown in the Figure 27. Standard method provides very small deviation for any Load Ratio while the proposed method has larger deviation. Interestingly with the Group 2 the deviation of the proposed method has the sudden big peak at Load Ratio 1.0. This implies that the big throughput fluctuation of the Group 2 in the Figure 25 is exceptional situation. I believe this is another example of statistical variation. If the simulation would be conducted enough iteration with different seeds for rand function, this variation should be invisible or very small.

The Figure 27 does not deny that the proposed method has larger deviation in throughput. This seems only recognized disadvantage of the proposed method. This should be one of future next research subject to be investigate.

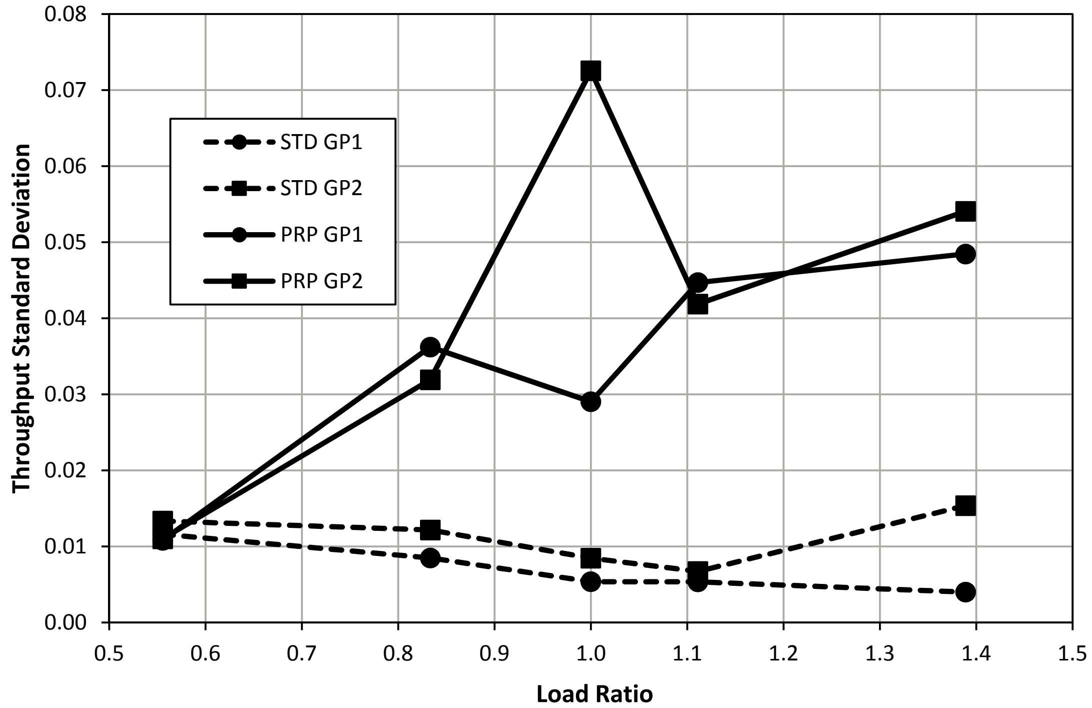

Figure 27: Throughput Standard Deviation of 802.11a STA Group 1 and 2

3.5 Conclusion

We simulated alternative CW adjustment mechanism which intended to introduce QoS to the standard DCF mechanism. We confirmed that the proposed method has certain effect and improvement. It is obvious that the proposed CW method has better total throughput, fairness and collision numbers. Total throughput is improved several to more than 10%. Jain's Fairness Index is improved several to over 10%. In saturated condition, the Index is improved from 0.9 to almost 1.0. Number of collisions is one order of magnitude smaller and number of successful transmission is increased with the similar number. These are obvious advantages of the proposed method. There seems one potential drawback with the proposed method. Deviation of throughput among STA's is larger than the standard DCF. This issue should be carefully investigated in following research.

This time, the proposed method has the same maximum limit of CW, 1023, and this limitation may cap the effect. Infinite size of CW is not practical, but we need to find optimized maximum CW for the proposed method. The optimal maximum CW could be dynamically given.

4 Conclusion

4.1 Current Research Conclusion

In this research we successfully confirmed the effect of two proposed methods, Asymmetric RTS/CTS for Exposed Node Reduction and QoS Media Access Control with Automatic Contention Window Adjustment.

Regarding exposed node mitigation by multirate support, assuming multirate transmission there is substantial difference of transmission rate between data frame and control frame. This difference is observed as difference of transmission range, therefore we can utilize transmission rate to intentionally control transmission range. First application of this mechanism is mitigation of exposed node. We proposed asymmetric transmission rate for RTS and CTS and named this proposed method as ARMRC. We could confirm the effect of exposed node reduction and improvement of throughput by simulation. With the simulated condition we observed 20 to 50% better throughput than the standard method. Also the proposed method has effect to level throughputs among nodes. Low throughput nodes with standard method have higher improvement ratio. We figured out simple estimation model of throughput improvement by the proposed method, and this fits to the simulation result well and is confirmed as effective estimation model.

Regarding QoS allocation based on achieved throughput, standard method (EDCA) increases/decreases size of Contention Window (CW) only when collision occurs or transmission succeeds. Our proposed method increases/decreases size of CW based on required/achieved throughput. When traffic is saturated standard method cannot provide fairness of throughput achievement because all nodes achieve almost the same throughput even if each node has different required throughput. Thus the achievement ratio of each node may differ largely. We had simulation and the result showed that the proposed method improves from 0.9 to 1.0 with Jain's Fairness Index for throughput achievement among each node compared to standard method. Also the proposed method has even several to over 10 percent better entire network throughput. There is no trade-off between fairness and throughput.

In the current research of both methods, possible parameters such as network topologies have not been extensively covered in the simulations. Therefore above conclusions are true only within the assumed parameters this time.

4.2 Future Research Direction

This time I could simulate only certain network topologies due to resource and time limitations. Only grid topology was simulated for asymmetric transmission rate for RTS/CTS or ARMRC. Only Ad-hoc or IBSS topology was simulated for QoS Media Access Control with Automatic Contention Window Adjustment. In the future, more extensive network topologies should be covered in both methods. Also this time the simulated WLAN was up to 802.11a with the maximum speed of 54Mbps. I should extend this to 802.11n or 11ac with higher OFDM modulation transmission. Considering effect of frame aggregation and other MAC features are also future research subject.

Also my simulations do not consider effect of SINR and related frame loss as I focused on to validate effect of MAC layer improvements. In the future more physical layer factors would be included. Finally ARMRC is a frame work and exposed node mitigation is only one application. I should figure out more applications and verify the advantage and effectiveness.

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