ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DATALINK LAYER
PROTOCOL DESIGN
FOR AERIAL ADHOC NETWORKS

M.Sc. THESIS

T. Tolga Sarı

Department of Computer Engineering

Computer Engineering Programme

June of 2021

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TASARSIZ İHA AGLARI İÇİN VERİ BAĞLANTI KATMANI PROTOKOLU TASARIMI

YÜKSEK LİSANS TEZİ

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To my family,

FOREWORD

First of all, I would like to thank my project advisor, Dr. Gökhan Seçinti for guiding me through his advises and knowledge as well as sharing lots of his experiences with us.

Also, I would like to thank all my friends for their support. Their company has always kept me entertained and motivated in times of struggle.

Finally, I want to express my endless gratitude and appreciation for my family and my wife Handan, who have supported me continuously.

June 2021 T. Tolga Sarı
(Research Assistant)

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ABBREVIATIONS

BATMAN	: Better Approach to Mobile Ad-hoc Networking
IBSS	: Independent Basic Service Set
RTS	: Request to Send
CTS	: Clear to Send
MANET	: Mobile Ad Hoc Network
VANET	: Vehicular Ad Hoc Network
DCF	: Distrubuted Coordination Function
TDMA	: Time Division Multiple Access
SNR	: Signal to Noise Ratio
RIFS	: Reduced Interframe Space
UAV	: Unmanned Aerial Vehicle
NIC	: Network Interface Card
EPT	: Estimated Ping Time
SPT	: Setup Time of RTS/CTS Chain
UDP	: User Datagram Protocol
TCP	: Transmission Control Protocol
QoS	: Quality of Service
MAC	: Medium Access Control
SDN	: Software Defined Networking

SYMBOLS

$\boldsymbol{\alpha}$	: Smoothing Factor
$\boldsymbol{\lambda}$	: Wavelength
$\boldsymbol{\tau}$	: Time delay
$\boldsymbol{r}_{los}(t)$	: Line of sight transmitted signal
$\boldsymbol{r}_{gr}(t)$	: Ground reflected signal
$\boldsymbol{d}$	: Distance between source and the destination
$\boldsymbol{\Gamma}(\theta)$	: Ground reflection coefficient
$\boldsymbol{G}_{gr}$	: Total antenna gain
$\boldsymbol{R}_n$	: Performance of n^{th} e2e connection

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SUMMARY

Unmanned Aerial Vehicles (UAVs) with Wi-Fi capabilities provide versatile and cost effective solutions for Mobile Ad-hoc Networks (MANETs). These devices can easily access and operate at any environment due to their simple and low-cost deployment and high maneuverability. Unfortunately, IEEE 802.11(a.k.a. Wi-Fi) stack is developed for networks with limited mobility/topology change in mind. Current Wi-Fi standards lack in terms of providing reliable multi-hop links for high bandwidth applications. As a result, aerial networks which need reliable & high bandwidth multi-hop communication links fail to satisfy QoS requirements. In this thesis, we aim to solve this problem by using Chain RTS/CTS for aerial Ad-Hoc networks. Chain RTS/CTS Scheme enables channel reservations using RTS and CTS frames. When moving on to 5GHz band, Chain RTS/CTS can be used in the same manner even in different bandwidths such as 40MHz and 80MHz channels. However, using 80MHz channels for all nodes effectively reduce reservable channel space. Furthermore, if middle nodes insist reserving 80MHz even if the nodes before them couldn't reserve 80MHz channels then, this reservation will effectively be wasted. In addition, this will decrease the fairness of the overall network. To improve Chain RTS/CTS in 5GHz band we introduce Smart Bandwidth Allocation which increases fairness among multiple nodes by reserving the minimum bandwidth along the path from source to destination node. This work uses IEEE 802.11 Independent Basic Service Set (IBSS) as a fundamental building block and improves overall collision avoidance (CA) performance of the network by reserving channels for node pairs along the multi-hop e2e connection. This thesis uses OMNET++ network simulator to evaluate the performance of the proposed scheme also takes ground reflections into account to accurately model aerial propagation. Our simulations show 37% throughput improvement in multi-hop links with 68% increased link setup time when compared to simple channel hopping enhancement scheme for single e2e connection.When there are multiple concurrent e2e connections our solution improves the throughput by 27% compared to Classical Channel Hopping(which alternates channels at each hop) with only 11% lower Jain's Fairness index.

TASARSIZ İHA AGLARI İÇİN VERİ BAĞLANTI KATMANI PROTOKOLU TASARIMI

ÖZET

Wi-Fi özellikli İnsansız Hava Araçları (İHA'lar), Mobil Tasarsız Ağlar (MANET'ler) için çok yönlü ve uygun maliyetli çözümler sağlar. Bu cihazlar, basit ve düşük maliyetli kurulumları ve yüksek manevra kabiliyetleri sayesinde herhangi bir ortama kolayca erişebilir ve çalışabilir. Ne yazık ki, IEEE 802.11 (diğer adıyla Wi-Fi) yığını, sınırlı hareketlilik / topoloji değişikliği olan ağlar için geliştirilmiştir. Mevcut Wi-Fi standartları, yüksek bant genişliği gereken uygulamalar için güvenilir çoklu atlama bağlantıları sağlama açısından eksiktir. Sonuç olarak, güvenilir ve yüksek bant genişliğine sahip çoklu atlamalı iletişim bağlantılarına ihtiyaç duyan hava ağları, hizmet kalitesi(QoS) gereksinimlerini karşılayamaz. Bu tezde, Havasal Tasarsız ağlar için Chain RTS / CTS kullanarak bu sorunu çözmeyi hedefliyorum. Zincir RTS / CTS Şeması, RTS ve CTS paketlerini kullanarak kanal rezervasyonlarını mümkün kılar. Zincir RTS / CTS, temel yapı taşı olarak IEEE 802.11 Bağımsız Temel Hizmet Kümesini (IBSS) kullanır ve çoklu atlamalı uçtan uca (e2e) bağlantısı boyunca düğüm çiftleri için kanalları ayırarak ağın genel çarpışma önleme (CA) performansını iyileştirir. 5GHz bandına geçerken, Chain RTS / CTS, 40MHz ve 80MHz kanalları gibi farklı bant genişliklerinde bile aynı şekilde kullanılabilir. Bununla birlikte, tüm düğümler için 80 MHz kanalların kullanılması, toplam yapılabilecek kanal rezervayson sayısını etkili bir şekilde azaltır. Ayrıca, orta düğümler, kendilerinden önceki düğümler 80MHz kanalları rezerve edemese bile 80MHz ayırmakta ısrar ederse, bu rezervasyon etkin bir şekilde boşa gidecektir. Ek olarak, bu, genel ağın adaletini azaltacaktır. 5GHz bandında Zincir RTS / CTS'yi iyileştirmek için, kaynaktan hedef düğüme giden yol boyunca minimum bant genişliğini ayırarak birden çok düğüm arasındaki adaleti artıran Akıllı Bant Genişliği Dağıtımı'nı tanıtıyorum. Bu tez, önerilen şemanın performansını değerlendirmek için OMNET ++ ağ simülatörünü kullanır, ayrıca hava yayılımını doğru bir şekilde modellemek için yer yansımalarını da hesaba katar. Simülasyonlarımız, tek bir e2e bağlantısı için basit kanal atlamalı geliştirme şemasına kıyasla% 68 artırılmış bağlantı kurulum süresiyle çoklu atlama(her atlamada kanalları değiştirir) bağlantılarında% 37 verim artışı gösteriyor. Birden çok eşzamanlı e2e bağlantısı olduğunda çözümüm, Kanal atlamaya kıyasla verimi% 27 artırıyor ve bunu % 11 daha düşük Jain'in Adalet endeksi ile gerçekleştiriyor.

1. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) offer number of services from military to civil domain attracting more demand with their increasing popularity every day. These devices can easily access and operate on any environment due to their easy and low-cost deployment and high maneuverability features. Their cost-effectiveness is due to Network Interface Cards (NIC) implementing IEEE 802.11 standards in one of the most accessible and cost-effective wireless technologies in the market, and this also enables them to operate as intelligent swarms/networks. Thus, they can easily conduct any mission requiring joint actuation and/or sensing with low capital and operational expenditure. However, success of these joint operations highly relies on effective management and robust coordination among the participating devices, which require reliable communication infrastructure.

Since, high mobility is one of the key advantages during critical missions such as search and rescue, reconnaissance, etc.; it nearly makes preserving a static network topology impossible and enforces any communication policy to adopt ad-hoc behaviour. Unfortunately, existing wireless protocols for ad-hoc networks (IEEE 802.11 mesh, B.A.T.M.A.N., Bluetooth 5 etc.) relying on off-the-shelf hardware are not able to provide acceptable performance for these systems. Since, they (i) have long topology discovery/update times, (ii) utilize static channel configurations and (iii) flooding based control packet dissemination, which can easily consume most of the available bandwidth [2].

Figure 1.1 shows the results of the OMNET++ simulations, which measures the communication link throughput between two end systems, for UDP and TCP loads, requiring various number of ad-hoc middle nodes to communicate in IEEE 802.11 a/g, where only single channel is utilized in the network and nodes are 100 meters apart have 100 meters altitude. As seen in the figure, available bandwidth drastically suffers when number of hops increases to maintain end-to-end (e2e) links. 802.11 Wi-Fi stack is developed with the limited mobility in mind, where link qualities may

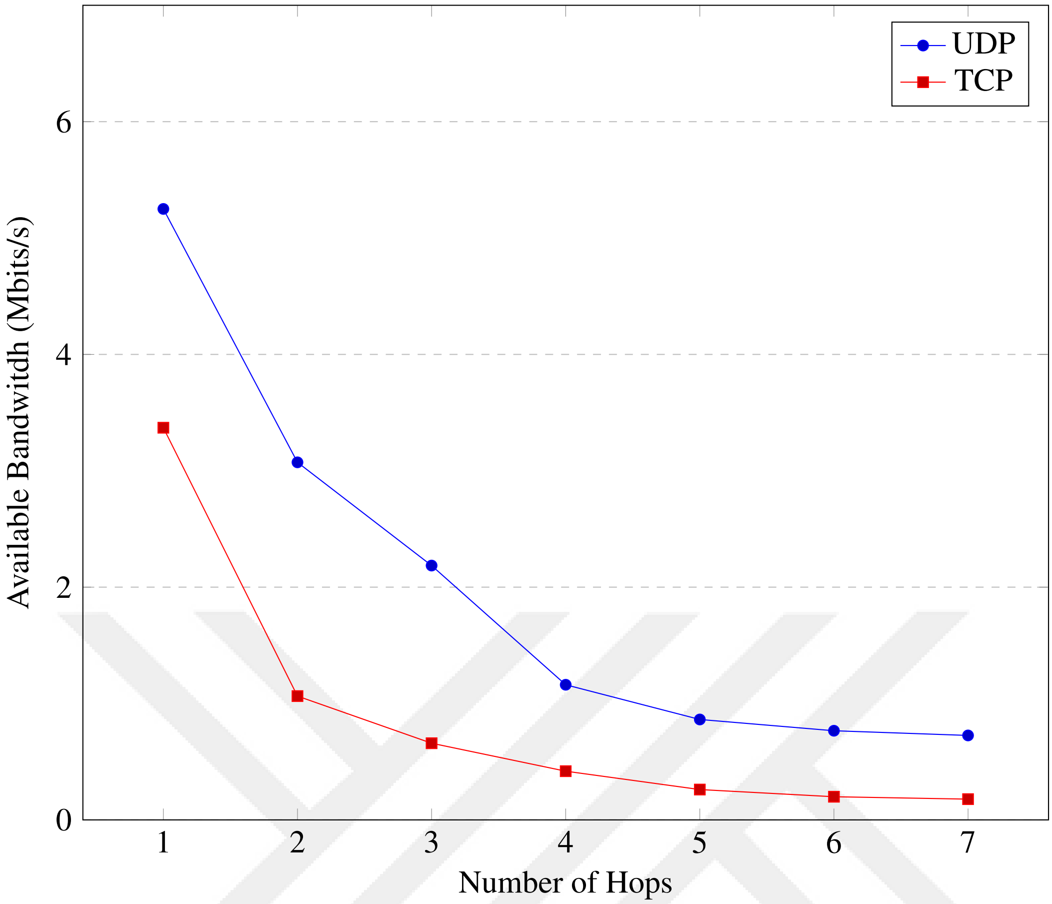

Figure 1.1 : Single channel performance for different types of apps against number of hops from at 100m using 802.11a/g QPSK.

differ throughout the operation but network topologies mostly stay static. Despite the fact that they support ad-hoc links with Independent Basic Service Set (IBSS) to realize uncoordinated direct wireless connections, their half-duplex link property with collision avoidance, which only targets single hop, severely affects their overall performance for e2e connection requiring multiple middle hops. In addition, existing vendor-specific network drivers also prioritize their own packets originated from their own applications during transmission rather than forwarding other node's packets while acting as routers/switches in middle hops [3]. These tendencies combined lead bandwidth degradation shown in the figure 1.1 for devices trying to communicate through multiple middle nodes.

In order to address the issues stated above, we propose a new reliable data-link protocol extending IEEE 802.11 standard for aerial networks. The protocol offers two major improvements, which are built on top of the current collision-avoidance, namely RTS/CTS mechanism: (i) it first enhances existing single-hop functionality to allow link reservation on multiple hop links, (ii) it then enables seamless channel hopping on middle-hop nodes to achieve near full-duplex wireless links to improve e2e throughput significantly.

The proposed protocol basically reserves links on an active route while the link stays active. In order to setup the reservation, the related requests and responses are disseminated by all the nodes on the communication route, ensuring simultaneous collision avoidance among all the nodes from source to destination. While this happens, the setup time is sampled and used to estimate the timeout window for the next chain RTS/CTS. We use the existing RTS/CTS mechanism on IEEE 802.11 as the main enabler in our protocol in order to implement described simultaneous collision avoidance framework. We first modify RTS/CTS frame structure defining a new field to hold e2e destination MAC address to differentiate whether the RTS/CTS chain has ended or not during the reservation setup dissemination phase. In the protocol all nodes listen to the medium for all available channels and because of this, any node can get any packet that matches its MAC address from any channel. Combining this with the Chain RTS/CTS, if the route is reserved with alternating channels, the continuous flow between source and the sink node is realized. Because every hop is at different channels from their neighbouring hops and therefore a hops does not affect the quality of its neighbouring hops.

1.1 Purpose of Thesis

Main results of this thesis are listed as follows.

- A new channel reservation scheme is introduced, offering an extension on top of existing IEEE 802.11 protocol, enabling multi-hop collision avoidance and seamless channel hopping.
- We dynamically adjust the timeout value of the RTS/CTS chain by continuously sampling and estimating multi-hop communication links.
- We introduce Smart Bandwidth Allocation which improves overall throughput and fairness by not reserving more channels for already bottlenecked e2e link.
- Lastly, We validate the improvement in overall throughput for e2e communication throughput extensive simulation coded in OMNET++ discrete event simulation.

1.2 Literature Review

High mobility of the UAVs cause rapid changes to network topology which degrades the performance of the whole network when used with standard protocols [2, 4]. Yuan transfers environment and UAV info to a separate control unit to achieve better communication performance by using software-defined networks(SDNs), basically SDNs relieve the UAVs wireless utilization and increase the performance [5]. In this context Zhang, uses packet routing which is determined from the information of current network, such as location and power of the UAVs, and provide load balancing algorithm and central energy of the network [6]. In addition to this Rametta, uses the same method for the video streaming on the other hand, White uses similar virtual network functionalities to telemetry tracking and anomaly detection [7, 8]. In [9] authors propose SDN control framework UAV swarms that is configured with software defined radios. Its control structure divides problems into self sub-problems that can be solved in each UAV in the network by using SDRs. Next, [10] gives information about a generic ad-hoc network with SDN capabilities, this work provides the bare minimum test-bed information for Mobile ad hoc networks with SDN capabilities, in addition to this authors provide real world results for various configurations. In addition to this [11], uses SDN controller with the knowledge every UAV's probable position and moving direction predict how the network topology changes and compensates this change. Similarly [12] looks out for opportunities to schedule parallel transmissions by identifying exposed terminals to increase network performance, the authors enable this by exploiting the geographical data of the nodes and show improvements over 802.11 DCF for multi hop communications. [13] generated a mathematical model for the UAV networks and used the parameters of the model to implement a routing algorithm to increase the bandwidth of the network. [14] calculates optimal contention windows sizes to reduce synchronization delays on ad-hoc networks.

Instead of using SDNs to increase performance of the mobile ad-hoc networks, following works propose improvements at MAC layer. In work [15], authors try to reduce exposed terminal count by adjusting the transmit power of the RTS frames. Similarly [16], analyzes the effects of using different transmission levels in ad-hoc networks derived from 4-dimensional Markov Chain model, they authors consider different types of collisions and model their probabilities accordingly, after that they provide both analytical and simulation results. In [17], authors combine average hop count with total SNR of the path to find optimal routes and create an effective routing algorithm to both increase the network throughput and lower latency. [18] analyses RTS/CTS based congestion where a node may become unable to transmit any packets during long periods of time, and introduces backward compatible RTS/CTS validation. The authors of [19] try to tackle multiple hidden node problem by reserving the channels using a dedicated control channel, they present m-RCR which is obtained by modelling channels as M/M/K queues and using 2-d Markov Decision Processes. Trying to improve VANETs [20], proposes new transmission modes between vehicles to increase performance of vehicular networks. The authors also provide a way to select optimal vehicle for relaying and a method to select which transmission mode to use. [21] measures 802.11 DCF performance on VANETs for different contention window sizes this relations is obtained using 2D Markov Chain Models. The authors calculate the parameters such as collision probability and packet drop rate. In contrast [22], proposes a method to give fully connected MANET nodes to switch between 802.11 DCF and dynamic time-division multiple access (D-TDMA) depending on the traffic conditions. Lastly [23] analyzes UAVs with wireless communication capabilities under several scenarios with changing communication parameters such as communication range, throughput, and energy usage.

On the other hand, pure routing based approaches exist for Aerial Ad Hoc Networks. Works [24, 25] deeply examine and evaluate different routing protocols in terms of various QoS metrics on MANETs such as AODV and OLSR. [26] looks at MANETs that has two subnets and calculates the optimal number of gateway nodes to maximize overall network performance for a uniform message traffic loading. [27] proposes dynamic clustering scheme and hierarchical routing for Unmanned Aerial Vehicle (UAV) relayed tactical ad hoc networks which increases general QoS of the network. Next, [28] provides integration scheme of IP and MANET. The authors provide gateway registration, discovery, advertisement and invalidation algorithm which can enable multi-gateway and load-balancing. Authors of [29] try to find associations between different packets that are independent. The authors suggest that these associations can be usefull for different MANET protocols.

Different from these approaches we optimize long range multi-hop links by securing the communication links by reserving the route via chain RTS/CTS scheme while not using a separate control channel. The proposed method increases the throughput of both TCP and UDP flow's performance with a cost of additional setup time caused by RTS/CTS chain.

1.3 Hypothesis

Since the ad-hoc networks suffer from high number of collisions and they are crowded in term of 2.4GHz band silencing a part of the network for the sake of multi hop end to end link should improve the overall performance of these multi hop links.

2. CHAIN RTS/CTS

2.1 Overview

Ad-hoc networks have multiple e2e connections generally scattered around the network. Thus, some connections need to use multiple middle nodes for routing. These middle nodes can also have their own traffic or can participate routing of other e2e connections. As a result, these multi-hop links' performance suffer because the relay nodes have high traffic/interference which exponentially decreases the throughput at each hop.

In order to ease this performance impact, we reserve channels for each edge along to path from source and the destination node. We achieve this by repeating RTS broadcast of the source node along the route until the destination node. When the destination node receives the RTS, it starts its own CTS broadcast towards the source node and this is also repeated in the same fashion. While repeating this broadcast, the channels are alternated along the route. This results better overall utilization and throughput. Also, to increase the priority of the setup process of the RTS/CTS Chain the interframe time for the RTS/CTS packets are chosen to be Reduce Interframe Space (RIFS).

To further increase the throughput, we equip UAVs with multiple NICs. Thus, each NICs can be assigned to an unique edge of the UAV. This artificially results full duplex operation as an UAV can receive from one channel and relay from another.

The reservations stay active as long as the link stays active. Neighbouring nodes refresh their timer as long as they sense DATA/ACK packets from the nodes that they received RTS/CTS broadcast. Additionally for TCP applications the nodes also start transmitting if they sense TCP FIN. This scheme makes UAV networks more robust for dynamically changing scenarios. Dynamic channel allocation also enables the UAVs with near full-duplex communication capabilities as they can receive from one channel and transmit from another if they have multiple antennas that are tuned to available channels.

First part of figure 2.1 illustrates an established connection after RTS/CTS chain here red-green-blue arrows stand for channels 1-6-11 respectively. Furthermore, second part shows the corresponding communication sequence.

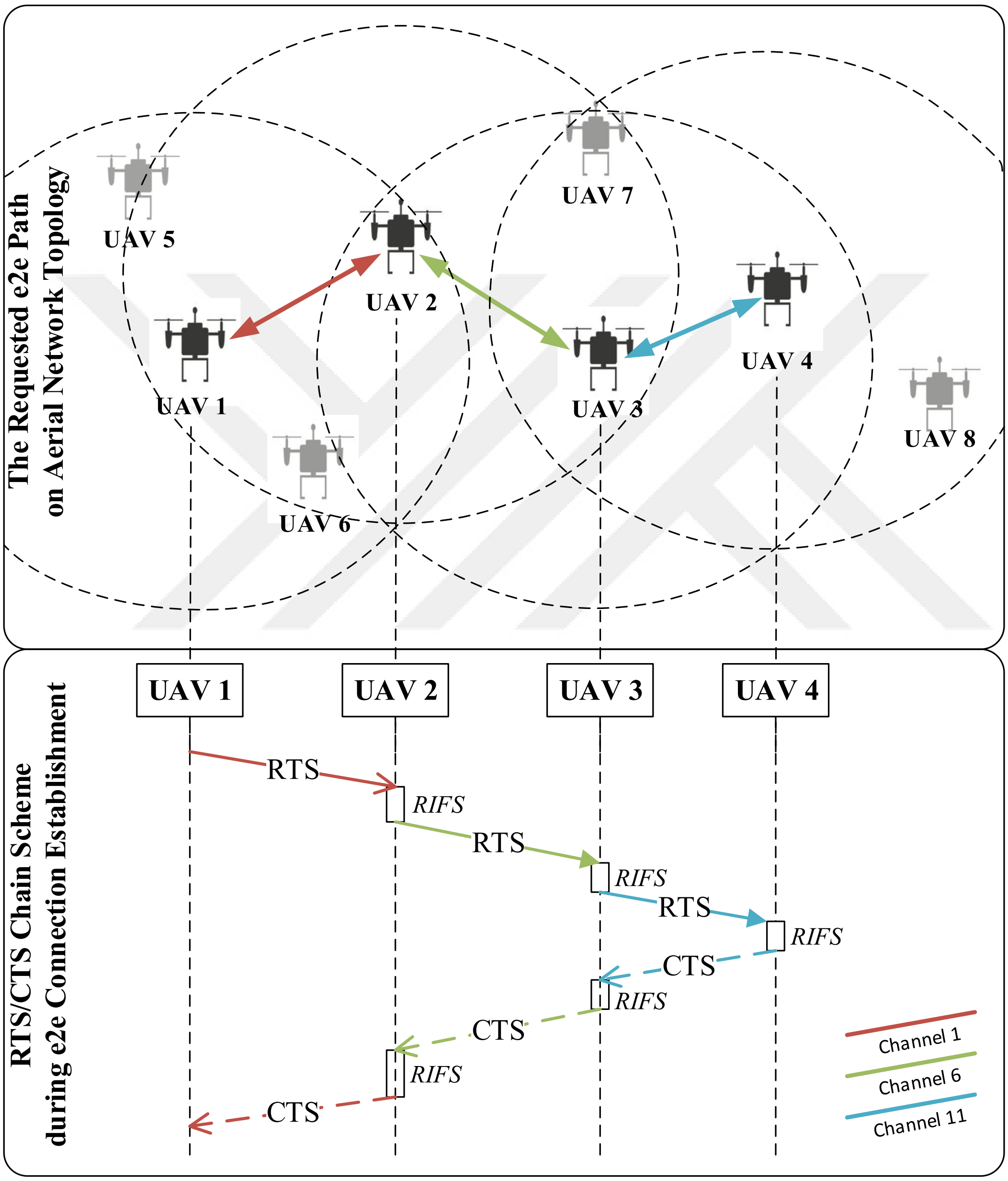

Figure 2.1 : Established connection

For this example, selected route in is through UAVs 1-2-3-4 and this route can be selected by using any routing algorithm. The RTS frame of the UAV-1 is repeated **at different channels** until the destination node is reached. This is shown with different colored arrows in figure 2.1.

2	2	6	6	6	4
Frame Control	Duration	Receiver Address	Sender Address	End Point ID	FCS

Figure 2.2 : Extended RTS/CTS header. End Point ID is inserted to RTS/CTS frame [1, chapter 4].

When an UAV experiences different RTS/CTS broadcasts for different channels, it is unable to transmit from those channels for the duration of the RTS/CTS. Thus, the channels that it can't use is the union of the RTS/CTS signals. For example, UAV-6 can not communicate using the channels-1 or channel-6, because it receives channel-1 RTS from UAV-1, channel-1 CTS from UAV-2 and channel-6 RTS from UAV-2. As a result it can only send packets from the channel-11.

After the connection is established, neighbouring nodes can communicate using at the channel which is the union of their RTS/CTS broadcasts. This is shown in the first part of figure 2.1. For example UAV-2 blocks channel {1,6} whereas UAV-3 blocks the channels {6,11}, the union of these sets is channel-6 therefore, when UAV-2 and UAV-3 wants to communicate they will use the channel-6.

The implementation permits multiple chains to be formed in a network. However at 2.4 GHz band, a node can not participate in multiple chains because there are not enough channels. Because nodes need 2 spare channels(one channel to receive and another channel to transmit) that are not used in the medium. As a result at 2.4 GHz band a node can only participate at one chain.

In order RTS packets to be repeated towards to destination node, first the RTS/CTS headers must be changed by adding End Point ID shown in figure 2.2. This field is used to select next hop towards to destination, or determine whether a node is the destination or not. Normally, only CTS broadcast mutes the channel however, for bidirectional data flow RTS broadcast must also mute. This protects the source node from hidden terminals.

The crucial part of the communication is selection of the transmission channel. Since the mission parameters change constantly, the timeout value of the RTS/CTS chain must adapted as well. To calculate RTS/CTS duration, setup time of RTS/CTS chain(SPT) is stored using moving average which is at the formula 1, where α is smoothing factor for the moving average.

$$EPT = \begin{cases} (1-\alpha)\times EPT + \alpha \times SPT & \text{if chain is formed} \\ 2\times EPT & \text{otherwise} \end{cases} \tag{2.1}$$

If a timeout happens then simply the *EPT*, which is estimated ping time, doubles. Adaptively adjusting the timeout time makes the setup process more smooth as it prevents unnecessary timeout by having sub optimal timeout value.

We add an additional packet handler to existing Wi-Fi implementation. Basically, the packet handler acts differently depending on the node's location on the network topology using the End Point ID and Receiver Address fields.

We use the algorithm 2.3 to process incoming RTS/CTS frames. The packet handler takes action whether the node is 1)source node, 2) target node, 3) a relay node, 4) an outsider node. It does this by using the End Point ID field (*line 3*).

If the RTS/CTS frames' receiver address is the same for the receiving node's MAC address, then this means that this node is on the multi-hop communication link(*lines 9-21*). Additionally, if the node's MAC address is the same with the End Point ID then this means that the node is final node for the given chain(*lines 4-8*). If not then the node must find a way to the final node by looking up to the routing table using the End Point ID(*lines 10 and 16 for RTS and CTS chain respectively*).

The nodes stay muted by refreshing their timers as long as they keep sensing a transmission from the node that first send RTS or CTS signal to them. If the outsider nodes sense a transmission from the channel that they are forbidden to transmit, nothing happens and their timer does not get refreshed(*lines 23-26*). Lastly, muted nodes check packet's TCP headers, and if the packet is TCP FIN packet the nodes can start communication(*lines 27-28*).

2.2 Smart Bandwidth Allocation

Moving 5GHz band increases available channels enabling nodes to participate at multiple chains. This immediately raises the maximum number of chains that can be formed in the network. IEEE 802.11n/ac enables combining neighboring channels for increased throughput. This can also be combined with Chain RTS/CTS. The source node can request 40MHz and 80MHz chains by sending multiple RTS broadcasts at neighboring channels. However, there is a catch. If all the chains are formed

```
Function packetHandler(p):
    if p.dst == selfMacAddr then
        if p.endPointID == selfMacAddr then
            // End nodes
            if p.isRTS then
                InitiateCtsChain()
            else
                ConnectionEstablished()
            end
        else if p.isRTS then
            // Middle Node in Forward Chain
            nextHop ← getNextHop(p.endPointID)
            channel ← getAvailableChannel()
            if channel then
                EchoRTS(channel, nextHop)
            end
        else if p.isCTS then
            // Middle Node in Backward Chain
            nextHop ← getNextHop(p.endPointID)
            channel ← getAvailableChannel()
            if channel then
                EchoCTS(channel, nextHop)
            end
        end
    else
        // Outsider Nodes
        if p.isRTS or p.isCTS then
            HaltTx(p.channel)
        else if isHalted(p.channel, p.src) then
            HaltTx(p.channel)
        else if isTcpFIN(p) then
            ContinueTx(p.channel)
        end
    end
end
```

Figure 2.3 : Chain RTS/CTS behaviour of the nodes in the network.

with maximum bandwidth then, maximum number of chains will drop. Additionally, requesting maximum bandwidth can be wasteful in terms of resource usage. For example, if an e2e connection requests 80 MHz bandwidth and the node at the 3rd hop can only use 20 MHz, this node will bottleneck the entire e2e connection. As a consequence, the throughput will be as if the chain was formed with 20MHz channels. Thus, first 2 links will highly be under utilized. Smart Bandwidth Allocation solves

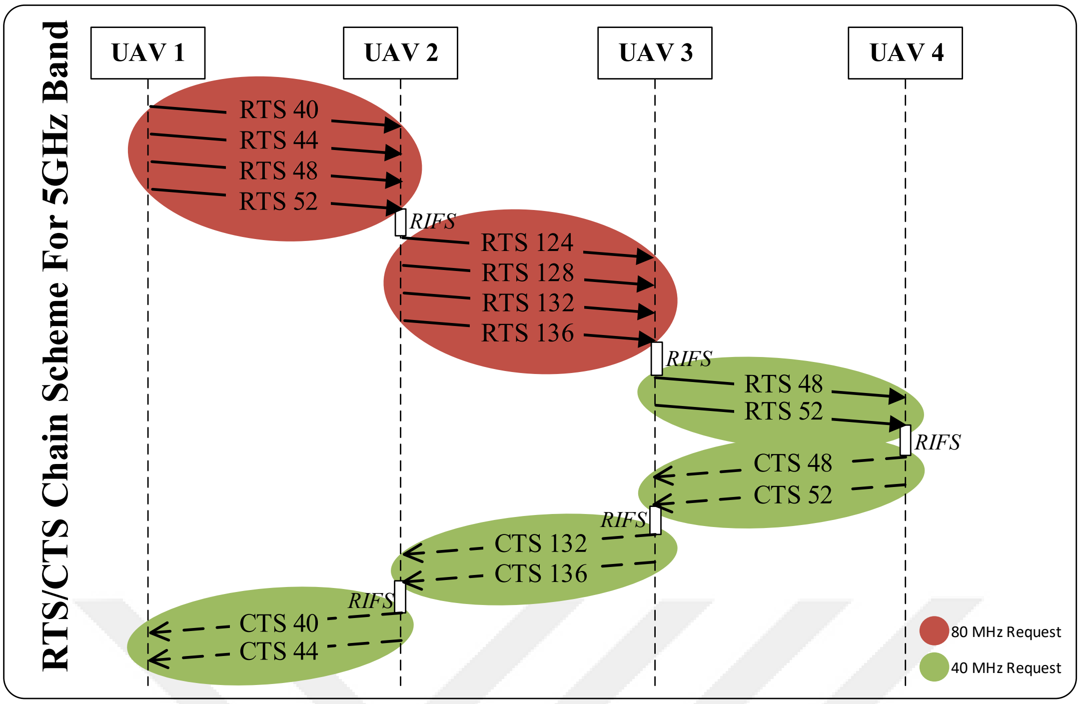

Figure 2.4 : Smart Bandwidth Allocation at 5GHz.

this problem by requesting minimum bandwidth available throughout the path to destination node. Basically, for the given scenario the formed chain will be 20MHz. This, increases link utilization and it also increases maximum number of chains.

Smart Bandwidth Allocation is built on top of RTS/CTS structure at 5GHz. For example when requesting 80MHz bandwidth using RTS/CTS the node will transmit 4 RTS frames at 4 different 20MHz channels. The receiver of the RTS frames transmits CTS back to sender if the received channels are available. As a result 80 MHz of requested bandwidth could be reduced to 40 MHz. This is shown in figure 2.4. In this example, UAVs 1,2 and 4 have spectrum space to communicate using two 80MHz channels, however UAV-3 has total of 80MHz bandwidth available. Thus it can split these to two 40MHz channels for I/O. UAV-1 starts the chain regularly, sending RTS packet from 4 20MHz channels, and UAV-2 does the same. Next, since UAV-3 can only use 40MHz of bandwidth, it sends 2 20MHz RTS frames to UAV-4. Since UAV-4 is the destination, It starts backward CTS chain for 40MHz and as a result 40MHz chain is formed. We use this structure to determine smallest available bandwidth along the path and use this bandwidth. This improves overall throughput because it opens path for other concurrent e2e connections because it does not use non-essential bandwidth. Which in turn increases fairness.

3. PERFORMANCE EVALUATION

3.1 Overview

We start simulations in OMNET++ network simulator. In OMNET++ we model UAVs as wireless hosts with multiple NICs onboard. In the simulations the UAVs fly at 100m altitude and two ray ground reflection model is used when simulating propagation of the signals. Two ray ground reflection model has 2 transmitted signals line of sight transmission r_{los} and ground reflected signal r_{gr}. The equation 3.1 shows the line of sight component of the transmitted signal where λ is wavelength, G_{los} is total antenna gain along line of sight path [30]. Additionally $s(t)$ is transmitted signal and d is distance between transmitter and receiver.

$$r_{los}(t) = Re\left\{\frac{\lambda\sqrt{G_{los}}}{4\pi} \times \frac{s(t)e^{-j2\pi d/\lambda}}{d}\right\} \quad \textbf{(3.1)}$$

The reflected component is given in equation 3.2. Here, $\Gamma(\theta)$ is ground reflection coefficient and $x+x'$ is distance to reflection point and distance from reflection point to receiver respectively. Lastly, τ is the delay between the line of sight and reflected signal. Then total received signal will be $r_{los}(t)+r_{gr}(t)$.

$$r_{gr}(t) = Re\left\{\frac{\lambda\Gamma(\theta)\sqrt{G_{gr}}}{4\pi} \times \frac{s(t-\tau)e^{-j2\pi(x+x')/\lambda}}{x+x'}\right\} \quad \textbf{(3.2)}$$

We start measurements with the triple handshake time when for the cases when the channel hopping is employed or chain RTS/CTS is employed. Next, evaluate the throughput of the connection various cases for both UDP and TCP flows. Lastly we evaluate the aggregated throughput of the scheme on a 7x7 grid for multiple concurrent e2e connections. Finally, we conclude measurements with fairness simulations. The table 3.1 show the simulation parameters used in the simulations.

Simulation Parameter	Value
Number of Drones (Cooperating + Competing)	8 + 4
Number of Channels	3, 20
Distance Between Nodes	100m
Altitude	100m
Antenna Strength	1.4mW
Antenna Sensitivity	-85dBm
Antenna Energy Detection	-85dBm
Background Noise Power	-90dBm
SNIR Threshold	4dB
Modulation	QPSK
Traffic Model	Full buffer

Table 3.1 : Simulation parameters

3.2 OMNET++

OMNeT++ is an modifiable simulation library and framework, which is mostly used foundation of network simulators. It can be used to simulate various kinds of networks such as wired and wireless communication networks, and such. Additionally it supports domain-specific functionality ad-hoc networks, wireless sensor networks, IP protocols, etc with help of different frameworks. It has IDE based Eclipse which supports graphical runtime environment which enables visually seeing the simulation. On top of this, OMNET++ supports threaded simulations in which a simulation case is handled by a thread. Which accelerates performance evaluation substantially.

One of the most powerfull framework(which is also used in this thesis) is INET Framework. It is open-source and provides many different models OMNeT++ simulations. These models can be IP protocols, applications, transport layer protocols, routing algorithms. Also it has support for layer 1-2 models such as 802.11 stack and different radio models. These radio models can be simple as unit disk radio which doesn't consider BER or it can be complex as Dimensional Radio which considers BER as well as frequency content and can simulate effects of crosstalk between channels. Many frameworks are derived from INET such as LTE or Vehicular networks. In this thesis, we derive our hosts from **AdhocHost** class and equip them with multiple wireless interfaces. The simulations start with populated ARP and routing tables, which means that every host knows the MAC address of other hosts and the path to them. The radios of wireless interfaces are modelled with **ApskScalarRadio**. On top of this we set pathloss model as **TwoRayGroundReflection**. As a result channel collisions and bit errors accurately. Then we assign proper carrier frequencies to radios and carry out the simulations.

The simulations create logs of packets sent, packets dropped, collisions, etc... We extract these logs and process them with python to generate our plots.

3.3 Connection Setup Time

The results of setup time simulations is given in figure 3.1. Here the first case is **802.11g**, which only uses 1 channel to communicate for all nodes. Next case is channel hopping which uses 3 channels to alternate between each hop denoted as **CH**. Both of these cases suffer from competing nodes' traffic. Next cases are Chain RTS/CTS scenarios. **Chain** case uses 1 channel for chain RTS/CTS and communication, **Chain + CH** uses 3 channels for chain RTS/CTS and communication. These nodes do not suffer from competing nodes' traffic because they use chain RTS/CTS. Finally **CH + DTC** uses equations 1 and 2 to fine tune timeout window for the RTS/CTS chain. The additional setup time is 77% increased for static timeout window, employing adaptive timeout window decreases this setup time penalty to 68%. However this penalty is neutralized by the increase of quality of the communication links and also channel reservation time. After the CTS chain reaches the source node TCP handshake or normal UDP flow may start.

3.4 UDP and TCP Performance

Next, we evaluate UDP and TCP performance of proposed MAC scheme. Figure 3.2 has the throughput results for the TCP throughput. The immediate results show that adding more channels increases the performance in any case. For example

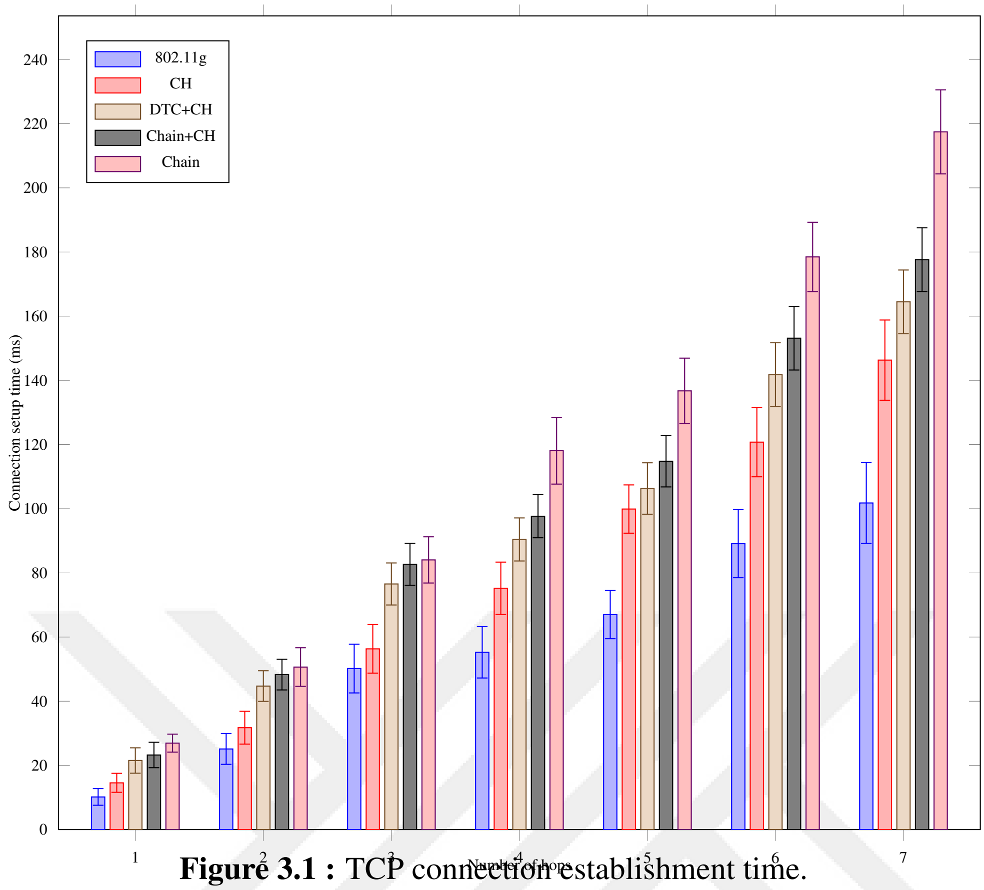

Figure 3.1 : TCP connection establishment time.

performance of CH is better than 1 channel chain RTS/CTS. This happens because the TCP traffic is bidirectional and having one channel to receive and another channel to transmit is better than having one channel in a silent medium.

The results also indicate that Chain RTS/CTS also improves performance for the single hop links as well as multi-hop links. This is the result of bidirectional nature of the TCP and 802.11 MAC. Chain RTS/CTS reserves channels around both sender and the receiver, thus there are fewer collisions for TCP and CSMA ACKs around the nodes.

Lastly the channel hopping performance drops when same channels start to be repeated. This is result of interference range being greater than the communication range. This effect is also amplified because the signal attenuation is smaller in air simulations. Despite thatscheme outperforms other methods even after 3 hops and overall it performs performs 37% better than CH case.

Following this we also analyze the UDP performance of the chain RTS/CTS compared to the other cases in figure 3.3. The performance of chain RTS/CTS with channel hopping shows similar results to TCP flow. The single hop performance is also

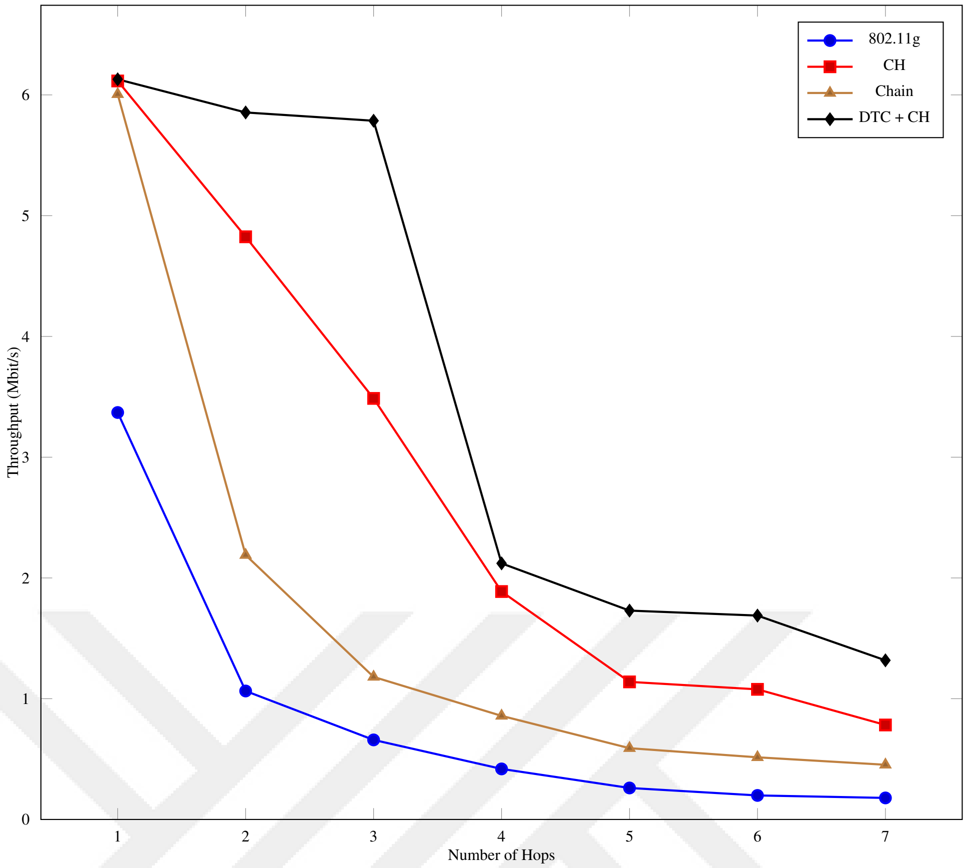

Figure 3.2 : Throughput of TCP sessions(Mbit/s).

increased. The result of this due to fact that the sink node sends CSMA ACK to source node in order to confirm successful communication. As a result source node is also protected from the hidden terminals and, it can sense ACKs and send next segment faster.

3.5 Mesh Performance

Using the results of previous simulations, we evaluate protocols when there are multiple concurrent e2e connections in figure 3.4. Chain RTS/CTS potentially blocks the paths for other e2e connections for sake of better stability and throughput. On the other hand non-chain e2e connections suffer from increased collision therefore poor QoS.

The results show that existing 802.11g as worst contender which can not provide average throughput more that 0.25 Megabits/second. Even with one channel Chain RTS/CTS outperforms 802.11g by 472%. This difference is vast compared fig 3.3

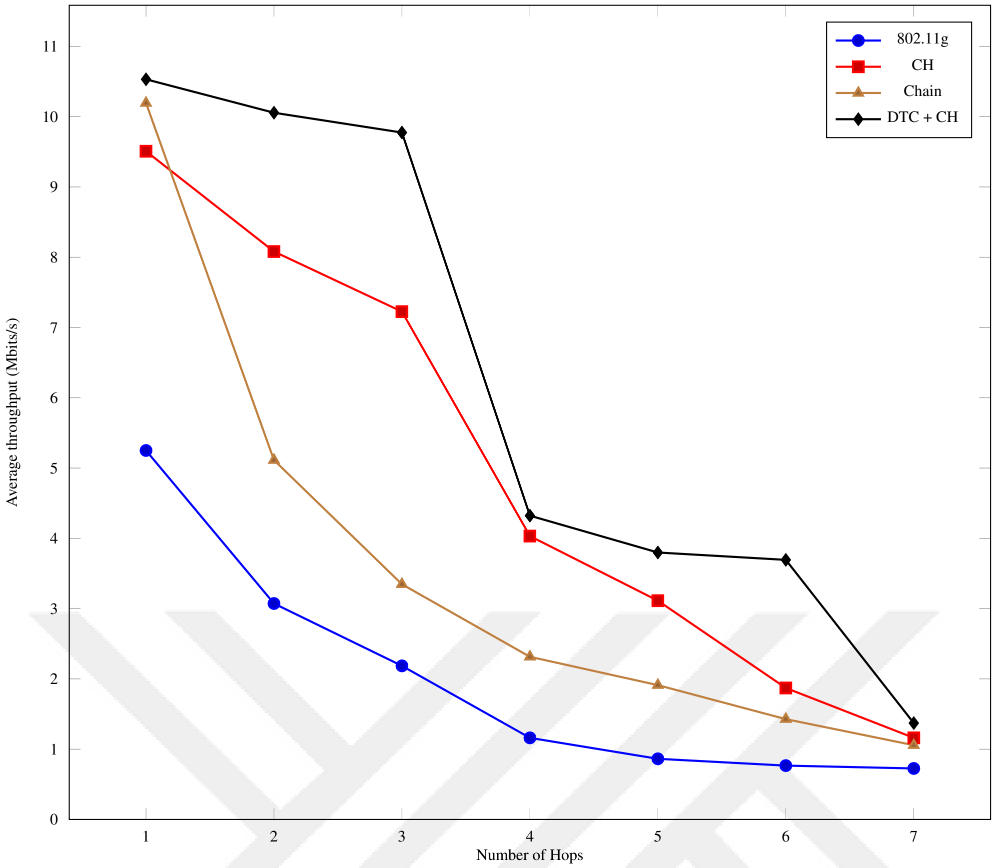

Figure 3.3 : Average throughput of UDP sessions(Mbits/s).

because average hop count is high (due to randomly selected connection on 7x7 grid) where chain schemes dominate 802.11g.

On the other hand, Classic Channel Hopping scheme performs 96% better than Chain RTS/CTS with one channel. This is due to lower interference around to nodes. Because, nodes can select non-interfering channels for consecutive hops. Lastly, combining Channel Hopping with Chain RTS/CTS outperforms Classic Channel Hopping by 20%. Which basically combines channel reservation and channel hopping to achieve lowest interference between the middle nodes.

We also measure fairness of schemes with Jain's Fairness Index [31] which is given by equation 3.3. In this equation $R_1, R_2, ..., R_n$ shows performances of e2e connections 1,2,...,n respectively.

$$\mathscr{J}(R_1, R_2, \ldots, R_n) = \frac{(\sum_{i=1}^{n} R_i)^2}{n \cdot \sum_{i=1}^{n} R_i{}^2} = \frac{\overline{\mathbf{R}}^2}{\overline{\mathbf{R}^2}} \tag{3.3}$$

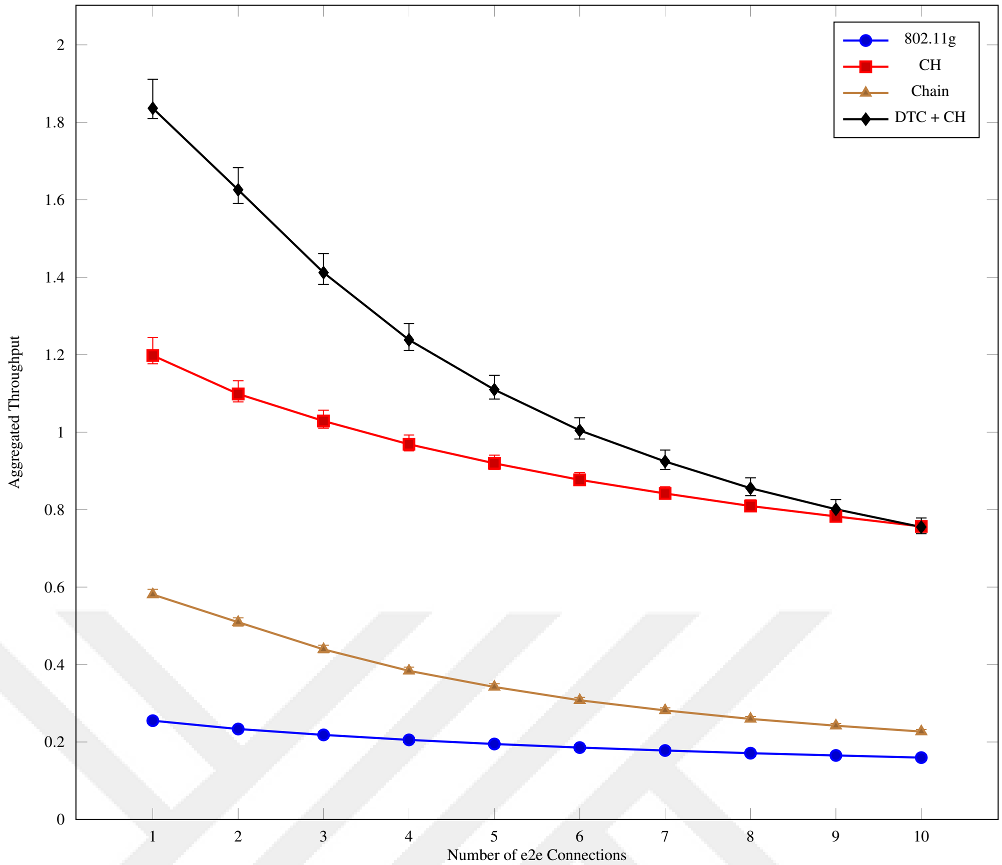

Figure 3.4 : Average throughput of multiple concurrent TCP sessions(Mbits/s).

This index basically measures if all the e2e connections have similar throughput. Fairness index varies between (1,1/n) and 1 shows that all of the e2e connections has the same throughput therefore completely fair.

Figure 3.5 shows the results of the fairness index for the simulations at the 2.4GHz band. The results show that chain based schemes have worse fairness compared to standard protocols. This was expected because in some cases, chain of one e2e connection can block path for another connection. Which is certainly unfair, however on the bright side average throughput increases.

Next, we move onto 5 GHz band and evaluate Smart Bandwidth Allocation with multiple channels widths (20-40-80 MHz). For this part we simulate; Channel Hopping with 20MHz and 80MHz channels, Chain RTS/CTS with 80MHz channels and lastly, Smart Bandwidth Allocation. Figure 3.6 shows the results 5GHz simulations. A 80MHz channel has 4.9 times more throughput compared to 20MHz channel due to increased number of carriers and lesser ratio of pilot carriers [32].

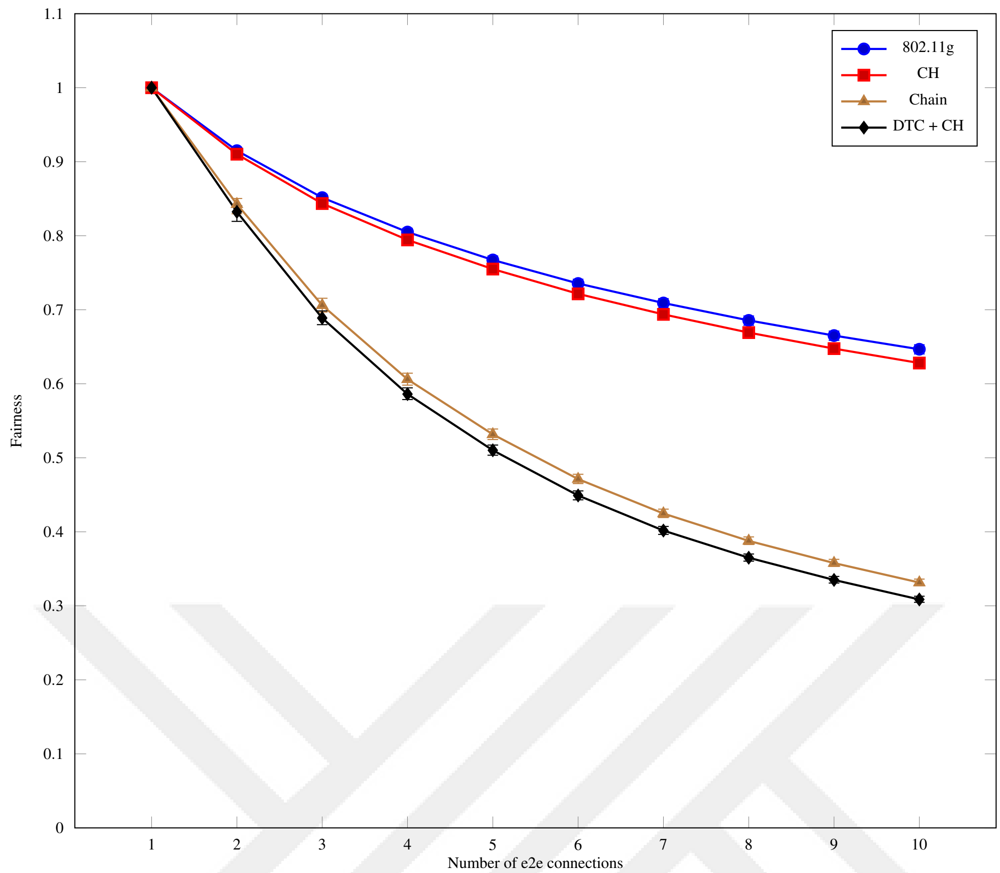

Figure 3.5 : Chain RTS/CTS fairness at 2.4GHz band.

Thus, 20MHz Channel Hopping is clear loser because of sheer lack of modulation throughput.

Smart Bandwidth Allocation performs 4.67% better compared to fixed 80 MHz channels for each link. This is not because of fastest e2e links getting faster. This happens because links stop greedily reserving 80MHz channels even if they can not utilize them effective. This naturally opens paths for other e2e links. Therefore, average chain count increases and overall throughput rises.

Lastly, we evaluate the fairness of our protocols against the Classic Channel Hopping scheme at 5GHz in figure 3.7. We again use Jain's Fairness Index for this simulation. The results show that standard protocols are more fair than chain schemes. However, Smart Bandwidth Allocation provide 23% better fairness compared to 80Mhz Chain RTS/CTS. Since Smart Bandwidth Allocation does not waste channels, it gives other e2e links more opportunities to form their own chains and thus, it shares the medium more fairly with them.

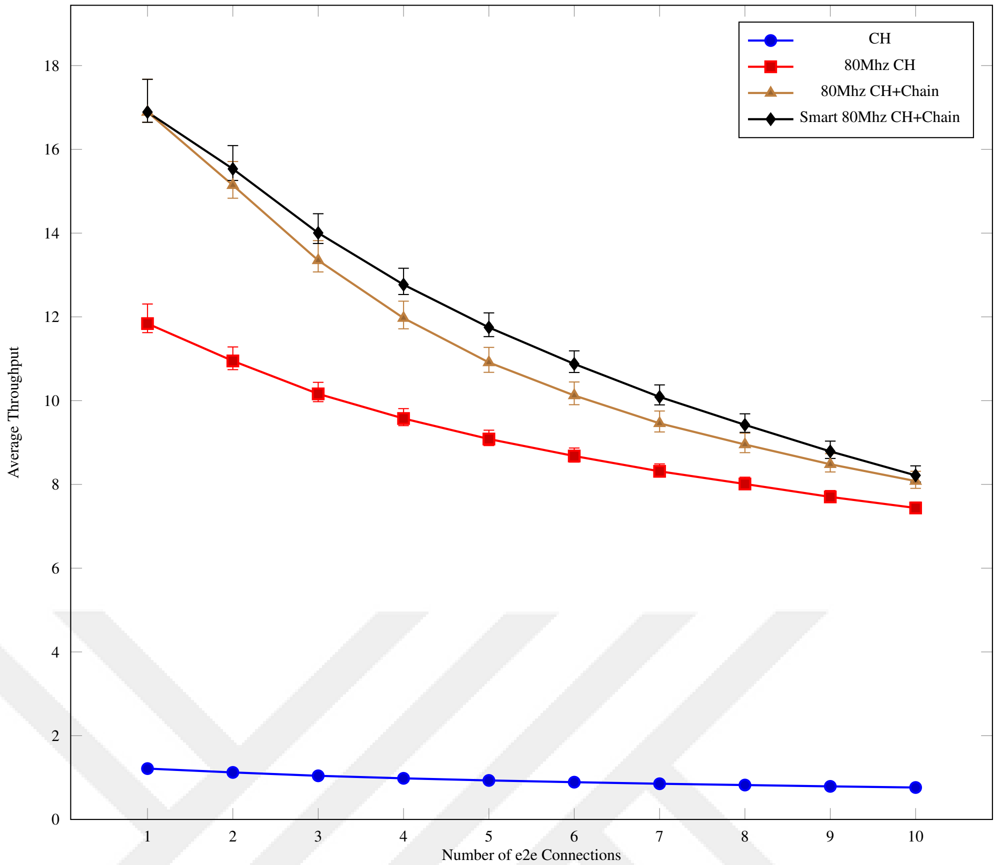

Figure 3.6 : Smart Bandwidth Allocation vs static chain for 80Mhz.

The simulation results show that the proposed protocol increases the performance against classic channel hopping scheme. It performs best when there are enough channels. Since the interference distance is greater than the communication distance, simply repeating channels after 3 hops still suffers performance loss. At 5GHz band Chain RTS/CTS is still more faster compared to the Classical Channel Hopping. Additionally moving to 5GHz band enables multiple chains to pass through same node which increases maximum chain count in the network. Lastly, using Smart Bandwidth Allocation Chain RTS/CTS both perform faster and has better fairness compared to Static Chain.

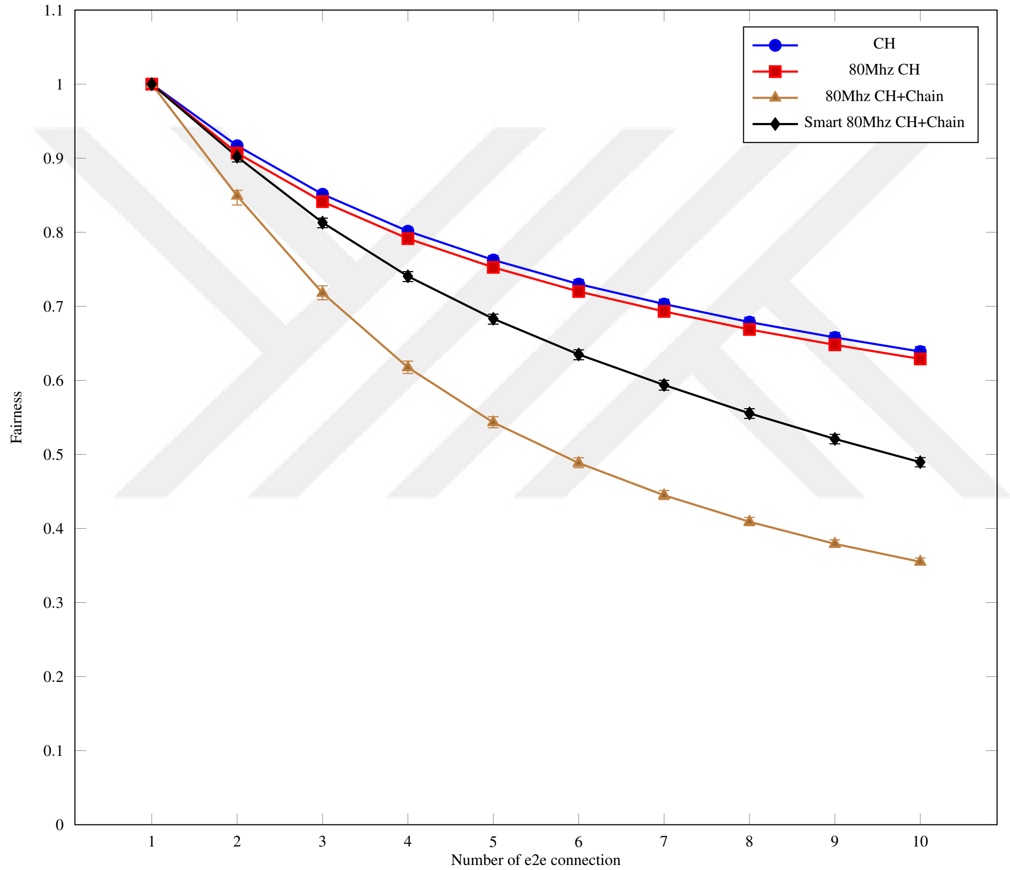

Figure 3.7 : Fairness of Smart Bandwidth Allocation vs static chain for 80Mhz.

4. CONCLUSIONS AND FUTURE WORK

Since the communication link quality degrades as the number of intermediate hops increase, we first employ channel hopping to reduce number of collision by better utilizing the available channels in the medium. Following this to further decrease the number of collision we reserve the selected channels along the link by employing Chain RTS/CTS by extending the available 802.11 RTS/CTS mechanism. This results on average **68% setup time penalty** with **37% performance improvement** compared to channel hopping. This overall performance can further be increased if more channels can be used as it can enable multiple chains to be formed.

For the future work, the protocol will be implemented on board SDRs on UAVs, which will be used to change communication properties according to available sensor and mission data.

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2021