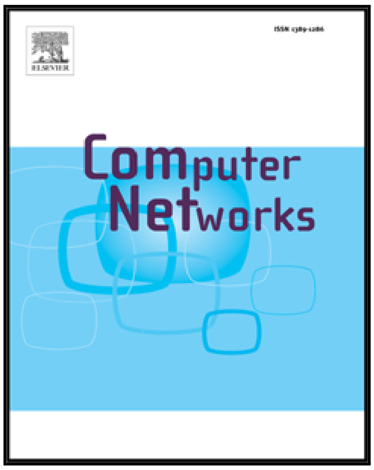

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Network Coordination Function for Uplink Traffic Steering in Tightly Coupled LTE Wi-Fi Networks

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Abstract

Tight coupling of LTE and Wi-Fi networks is accomplished by binding their protocol stacks. LTE Wi-Fi radio level integration with IPSec tunnel (LWIP) corresponds to realizing this binding at IP layer. A collocated deployment of LWIP enables greater flexibility in utilizing the channel efficiently. With the advent of bandwidth-hungry smartphone Apps and IoT applications, the cellular uplink resources become highly demanding. This enforces Wi-Fi to support efficient uplink transmissions since the uplink transmissions through Wi-Fi suffers high contention because of distributed nature of Wi-Fi MAC. In order to improve Wi-Fi channel utilization by leveraging the potential of LWIP in controlling and coordinating the transmissions through LTE and Wi-Fi links, we introduce Network Coordination Function (NCF) in LWIP. The proposed NCF focuses on coordinating the uplink transmissions through Wi-Fi in a network with high load. NCF enhances the channel utilization of Wi-Fi network by regulating the packet arrival rate to the Wi-Fi link and also by revamping medium access techniques at the Wi-Fi interface of users associated with LWIP node. NCF is composed of four different uplink traffic steering algorithms with diverse objectives which improve Wi-Fi channel utilization by (i) minimizing collisions among LWIP users, (ii) increasing transmission opportunities for Wi-Fi users that are connected to legacy Wi-Fi APs operating on the same channel, and (iii) ensuring fairness for both LWIP and Wi-Fi users. Interestingly, NCF has not only improved the throughput of LWIP users but also the throughput of Wi-Fi users. Simulation experiments reveal that NCF has reduced collisions in the Wi-Fi uplink by 13-53% and improved throughput by 10-37% as compared to Wi-Fi offloading and Distributed Coordination Function (DCF).

Keywords: LTE-Wi-Fi Aggregation, Traffic steering, Interworking, Link Aggregation, LWIP.

1. Introduction

Smart phones have gained high popularity, thanks to the availability of the myriad of Apps through various App stores. Some of the multimedia Apps are the root cause of exponential growth in mobile data [1]. This data demand puts pressure on network operators to look for new and affordable solutions. On the one hand, the high cost of license spectrum in mobile networks prevents operators from buying more frequency bands. On the other hand, free and large availability of unlicensed spectrum enables Wi-Fi as the best choice for addressing the high data demand. As a result, offloading mobile data traffic into Wi-Fi has attracted interest from operators and standardization bodies. Third-Generation Partnership Project (3GPP) has shown interest in developing standards for WLAN data offloading since Release 8. The technical specifications (TS) developed by 3GPP for interworking includes Rel.8 - PMIP based mobility and ANDSF, Rel.9 - eANDSF, Rel.10 - IP Flow Mobility (IFOM), Rel.11 - location based selection of gateway for WLAN and Rel.12 - WLAN network selection, Multiple PDN connections, and IP preservation. All these strategies focus on realizing LTE Wi-Fi interworking through Evolved Packet Core (EPC) core (viz.,

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at Serving Gateway (S-GW) and Packet Gateway (P-GW)). The granularity of offloading in these strategies is at flow level. Such gateway-based solutions are not quick in the case of dynamic channel variations (viz., shadowing and fading) or in the case of low user mobility. For moving a flow from cellular to Wi-Fi incurs more signaling at core network. To overcome this inefficiency in regulating traffic flows across LTE and Wi-Fi networks and to enable a finer control over interfaces, the decision making entity for offloading should be placed next to Radio Access Network (RAN) part of LTE and Wi-Fi networks. This requirement has pushed the decision making entity all the way from the EPC to small cell evolved NodeB (SeNB), which ensures a tight coupling between LTE and Wi-Fi RANs.

Integration of LTE and Wi-Fi RANs can be realized at different layers of the protocol stack. Recently, 3GPP had developed the specification for aggregating Wi-Fi with LTE eNB at PDCP layer [2] and coined this finer level of aggregation as LTE Wi-Fi Aggregation (LWA). A tighter integration of LTE and Wi-Fi at IP layer is known as LTE-Wi-Fi radio level integration with IPSec tunnel (LWIP) [3], 3GPP has developed the specification for LWIP. We have focused on interworking at IP level (as shown in Figure 1), unlike LWA, LWIP does not involve any protocol level modifications both at eNB and UE but still achieves the aggregation benefits. Also, interworking at IP layer allows the existing commercial UEs to readily work with LWIP node (aggregated LTE small cell and Wi-Fi access point) and thus enabling a quick deployment of LWIP nodes. 3GPP LWIP has the following advantages:

- EPC need not manage Wi-Fi AP separately, and it is controlled directly by the LTE small cell (SeNB) inside an LTE Wi-Fi aggregated node.
- Radio level integration allows effective radio resource management across Wi-Fi and LTE links.
- LTE acts as a licensed-anchor point for UE's communication with the network.

LWIP could be realized in two ways, (1) Collocated LWIP (2) Non-collocated LWIP. In collocated LWIP, SeNB and Wi-Fi AP are located in the same device and tightly integrated at RAN level in an LWIP node, whereas in the latter case, Wi-Fi AP and SeNB are connected via a standardized interface referred as X_w [4]. As the LWA specifications are completed in Rel-13 by 3GPP, a study item on enhanced LWA (eLWA) [5] has been initiated. The scope of eLWA includes the addition of uplink transmissions via Wi-Fi. The study item focuses further on optimizing the PDCP layer for increased data rates and support for 60 GHz. Also, in LWIP context, the uplink traffic steering is still in its infancy, where the user-centric traffic steering decision can lead to under utilization of the channel resources.

Motivation: The main problem that we would like to address in this paper in LWIP context is to reduce the number collisions due to uplink contentions in the Wi-Fi domain. Wi-Fi MAC is contention based (DCF); it allows a node to transmit on the expiry of chosen backoff value, which leads to collision if backoffs of two or more nodes expire at the same time. This collision probability increases with the number of contending nodes in the network. LWIP involves tight coupling of LTE and Wi-Fi, which enables LTE to have a finer control over Wi-Fi. We will explored this property of LWIP to coordinate the uplink transmission in Wi-Fi to reduce the number of collisions in the Wi-Fi domain. Towards this, we propose uplink traffic steering in the context of LTE Wi-Fi integration with multiple objectives, such as the optimal fraction of uplink traffic to be steered, coordinated channel access, reduction in number of collisions with distributed control and fair operation with other Wi-Fi nodes on the channel. In this paper, we discuss optimizing the uplink traffic steering across LTE and Wi-Fi links to enable efficient use of Wi-Fi channel by introducing coordination among the UEs during uplink transmission through Wi-Fi, with LTE as the anchor point for communication. The proposed Network Coordination Function (NCF), which is implemented at LWIP node and LWIP UEs, aims at maximizing the channel utilization of Wi-Fi link as compared to Distributed Coordination Function (DCF) mechanism while still ensuring fairness in the channel access. NCF aims to maximize the network level throughput along with fairness with a central coordination of LWIP users, but in case of DCF, user level fairness is ensured in a long run even though it may not lead to efficient channel utilization.

Proposed NCF includes novel medium access control algorithms and flow regulation algorithms employed at SeNB and UE with above mentioned objectives. The list of proposed algorithms are as follows

1. Fast UpliNk through Direct medium access (FUND)

2. FUND with fair Channel Access (FUND++)
3. Dynamic Optimal Uplink Traffic steering Algorithm (DOUTA)
4. Enhanced UpliNk With viRtuAl Polling (E-UNWRAP)

These algorithms operate at different layers with multiple objectives but all the algorithms have one common objective, which is to maximize the Wi-Fi channel utilization by reducing channel time wasted due to collisions.

The main contributions of this paper are given below.

1. Proposed four NCF based novel uplink traffic steering algorithms for achieving efficient uplink transmissions through Wi-Fi.
2. Analytically obtained the Wi-Fi uplink offload fraction, which yields efficient utilization of Wi-Fi channel.
3. Proposed a Dynamic Optimal Uplink Traffic steering Algorithm (DOUTA) for improving network throughput by reducing collisions *i.e.,* the time lost in unsuccessful transmissions.
4. Proposed a fast medium access mechanism (FUND) for efficient uplink transmissions and also an enhancement of FUND (FUND++) which ensures fairness among all the nodes accessing the channel.
5. Proposed a coordinated Wi-Fi transmission mechanism (E-UNWRAP) for reducing collisions caused by LWIP nodes on Wi-Fi channel.
6. Modeled FUND and FUND++ algorithms of NCF and compared their respective theoretical performance results with the simulation results.

Rest of the paper is organized as follows: Section 2 summarizes literature pertaining to LTE-WLAN integration. Section 3 details the need for uplink traffic steering and enumerates the challenges associated with its design and implementation. Section 4 presents the proposed NCF framework and four novel NCF algorithms. Section 5 analytically models the proposed NCF algorithms. In Section 6, the performance results of the proposed NCF algorithms are reported and compared with existing solutions from literature. Finally, Section 7 concludes the work and comments on the future of LTE Wi-Fi uplink solutions.

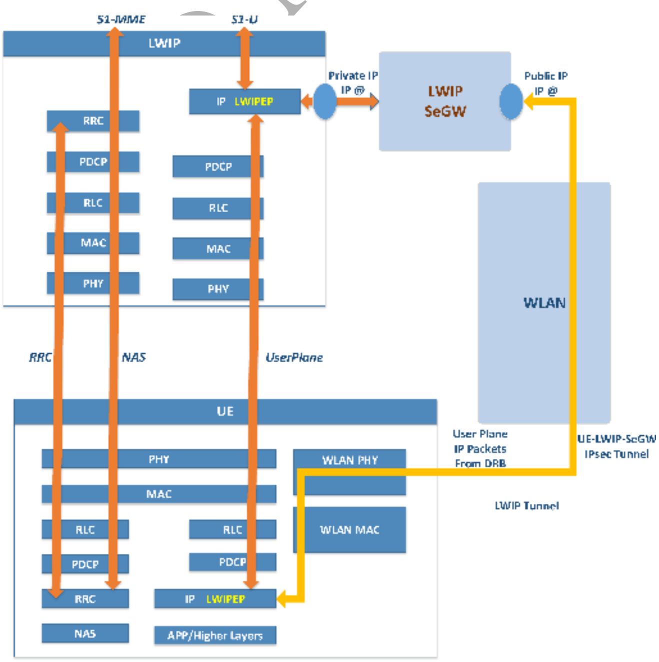


Figure 1: LWIP architecture standardized by 3GPP.

2. Related Work

In this section, we elaborate the evolution of LTE Wi-Fi integration and present the state-of-the-art integration architecture. Further, we protrude on the problems which exist in LTE Wi-Fi interworking context and how our proposed solution differs from the existing works in the literature.

It has become a prime topic of interest for the operators to use the unlicensed band efficiently, numerous works have been done with an objective of introducing LTE operation in unlicensed band [6] without affecting regular Wi-Fi UEs. But our focus is not to introduce LTE in the unlicensed band. Instead, our objective is to improvise the Wi-Fi utilization effectively by using the licensed carrier (LTE). Various architectures have been proposed by 3GPP on LTE Wi-Fi interworking context till Rel-12, all these interworking strategies extended their supported by regulating flow offloading at the cellular Core Network (CN) to Wi-Fi network. However, the current study focuses on Radio Access Network (RAN) level integration between LTE and operator deployed Wi-Fi networks. These enhancements try to enable coordinated radio resource management, improve user Quality of Experience (QoE), and reduce battery power consumption.

The evolution of LTE Wi-Fi interworking in 3GPP has started from Rel-8. The user mobility with IP address preservation for all the traffic from 3GPP access to Wi-Fi access is standardized in Rel-8. Enhancements of Rel-8 includes WLAN accessible via legacy 3G-Core. S2-a and S2-b are the standard interfaces which exist between cellular and Wi-Fi networks [7]. S2-b interface is a Proxy Mobile IPv6 (PMIP) based interface between PGW and non-trusted non-3GPP access, which provides the user plane with related control and mobility support between evolved Packet Data Gateway (ePDG) and the PDN GW. For S2-b, an IPSec tunnel is established between UE and e-PDG (Evolved Packet Gateway), where the operator need not trust the Wi-Fi network. S2-a corresponds to trusted access to cellular data through Wi-Fi. The Wi-Fi APs connected through S2-a interface mostly include operator deployed Wi-Fi hotspot. In case of both S2-a and S2-b based interworking solutions, the offloading decision is taken at the core network, and it involves high signaling overhead and hence incurs more latency. Also, a UE can be attached to either LTE or Wi-Fi, at any given time. Access Network Discovery and Selection Function (ANDSF) has also been introduced as part of Rel.-8. It is an entity within EPC of the System Architecture Evolution (SAE) for 3GPP compliant mobile networks. The primary purpose of ANDSF is to assist UE to discover non-3GPP access networks, such as Wi-Fi, that can be used for data communications in addition to 3GPP access networks, such as LTE and it provides UE's information about available networks and policies for selecting and using such networks. UE may then employ IP flow mobility (IFOM), multiple-access PDN connectivity (MAPCON) or non-seamless Wi-Fi offload according to operator policy and user preferences.

Access Network Discovery and Selection Function enhancements (eANDSF) has been proposed in Rel-9 which includes cellular network information, device mobility state and further deals with intelligent network selection and traffic steering. The 3GPP Rel-10 specifies a variety of deployment scenarios for interworking between EPC networks it allows a universal network connection irrespective of whether it is based on GTP or PIMP with the help of UE support. In Rel-11, SaMOG - I *i.e.,*S2-a mobility on GTP has been introduced which has an S2-a interface using GTP via trusted WLAN and without UE impact which is dealing with SaMOG II. Location based selection of gateways for WLAN has also been discussed in this release. In Rel-12, multiple IP connectivities via trusted WLAN using GTP has been introduced, which is coined as eSaMOG. Network-based IP flow mobility, LTE-WLAN aggregation at PDCP layer (LWA) and LTE Wi-Fi interworking with IPSec tunnel (LWIP) have been introduced in Rel-13. We have developed a prototype for LWIP and detailed its performance benefits in [8]. The prototype complies with commercial UE (Nexus 5) without involving modification at the protocol stack [9]. Several enhancements on LWA, which is known as enhanced LWA (eLWA), are on discussion in Rel-14 which includes uplink support, enhanced mobility, and optimizations for high-speed 802.11 technologies (802.11ax, 802.11ad, and 802.11ay).

We have discussed a few offloading solutions for different architecture of LTE and Wi-Fi integration. Significant work has been done for LTE Wi-Fi interworking which involves offloading decision made at cellular gateway of LTE network [10] [11], [12], [13], [14]. Also, comprehensively work has been carried out on modeling the downlink performance of cellular gateway-based solutions [15], [16], [17]. In [18] the authors have shown that delaying the application data transmission till a user gets in Wi-Fi coverage has reduced the load on the cellular network. The authors project that offloading through Wi-Fi is the most preferable, even though it reduces the load on the cellular network, the solution leads to inefficient utilization of Wi-Fi resources due to contention. In [19] authors have proposed different LTE Wi-Fi interworking techniques, where flow offloading is realized by steering traffic at the transport layer, network layer, and link layer. All the work focuses on flow offloading, however, not much work has been done in tight coupling of LTE Wi-Fi networks (based on Rel-13), which gives LTE a finer control over Wi-Fi interface transmission.

Here are some works which try to explore this tighter level of interworking. In [20] the authors have evaluated the tight coupling solution between LTE and Wi-Fi, at PDCP (Packet Data Convergence Protocol) layer (a.k.a. LWA) for enhanced reordering. They have also discussed the security aspects of the tight coupling framework. The capacity of LWA is analytically modeled in [21] by considering the effect of shadowing.

There are a few downlink optimization works on LWA. In [22] the authors have proposed a Proportional Fair Traffic Splitting in downlink, where traffic for each user can be split across macrocell and an LTE or Wi-Fi small cell. The proposed algorithm is developed based on "water-filling" approach across multiple links. In [23], authors have developed a low complexity solution for maximizing the network utility, leveraging the multi-link aggregation capability of users in the network. A closed form expression is also developed for aggregated user traffic in case of LWA.

It is reported in [24] that not much work has been done in uplink traffic steering, rather works have been done in the context of power saving. The existing uplink traffic offloading techniques aim to save the battery power of the UEs. Here are a few existing uplink traffic offloading works in literature with the objective of power efficiency and proportional routing. In [25] the authors have proposed two uplink traffic offloading algorithms to improve the energy efficiency of the UEs and to increase the offloaded data volume under the concurrent use of access technologies that IFOM provides. In the first algorithm, UEs with high volume data are promoted and given priority in accessing Wi-Fi Access Point (AP) to offload their data. In the second algorithm, a proportionally fair bandwidth allocation over the data volume needs of the UEs is developed. In [26], a weighted Proportionally Fair Bandwidth (PFB) allocation algorithm, for the Wi-Fi access, in conjunction with a pricing-based rate allocation for the LTE uplink transmission is developed. In [27] authors have proposed an energy efficient offloading algorithm which chooses the users to be offloaded at a lower computational complexity, with an objective of minimizing the energy spent by the users associated with LTE and Wi-Fi networks. None of the existing works have focused on improving the Wi-Fi channel utilization by using existing LTE interface for coordinating the Wi-Fi transmission.

Even though there exist numerous solutions on steering across LTE and Wi-Fi interfaces in downlink, interestingly, not much work has been done in uplink traffic steering. Unlike other LTE Wi-Fi interworking solutions, LWA/LWIP has a tighter level of integration which offers LTE a finer control over the Wi-Fi link, enabling the LWA/LWIP node to take quick local decisions can for efficient usage of Wi-Fi resources.

To the best of author's knowledge, this is the first uplink traffic steering work enabling efficient utilization of Wi-Fi channel in the context of LWIP.

3. Design Requirements for Uplink Traffic Steering Algorithm

In this section, we emphasize the need for enabling uplink transmission through Wi-Fi in LWIP architecture, and present all the possible optimizations available at different layers of protocol stack.

Uplink traffic demand of mobile users is increasing like that of downlink traffic due to various bandwidth-intensive multimedia applications [28]. This enforces that Wi-Fi link of LWIP should be effectively used for carrying some of the uplink traffic from the mobile users. Unlike other LTE Wi-Fi interworking techniques, where only the gateway takes flow routing decisions [29] and [30], LWIP has sophisticated control over Wi-Fi so that it can regulate and coordinate both uplink and downlink transmissions through Wi-Fi. The LTE coordination can be done at the granularity of flow routing or even regulating the medium access. Figure 2 shows optimizations that could be applied at different layers of protocol stack.

Optimizations which could be applied at different layers of the protocol stack are as follows.

1. **Application Layer :** Choosing the best link (LTE/Wi-Fi) for transmission among multiple links associated in a device can be done at the application layer with limited information about each link.

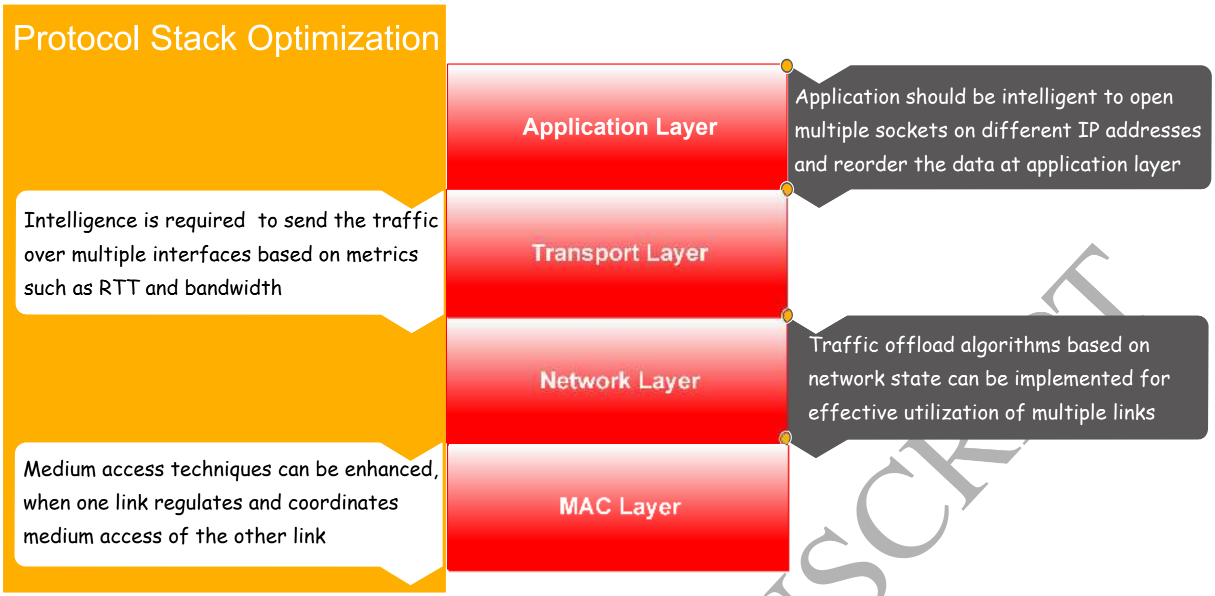


Figure 2: Optimizations at different layers of protocol stack.

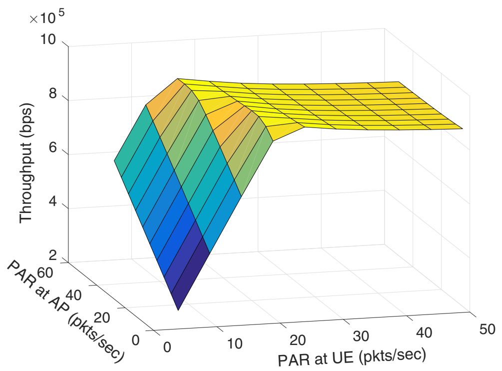


Figure 3: Throughput observed with 5 UEs in LWIP network.

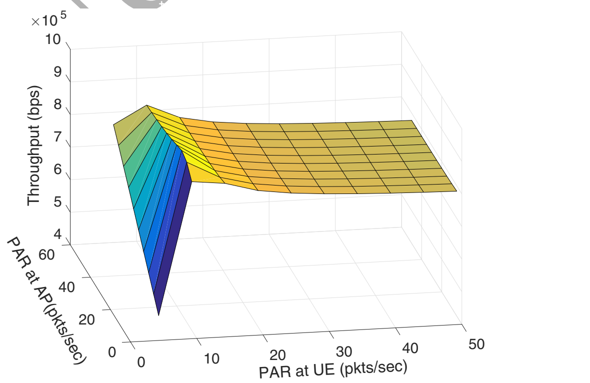


Figure 4: Throughput observed with 10 UEs in LWIP network.

Samsung download booster [31] is one such application which creates multiple sockets and executes HTTP range request for downloading a file which again gets reordered by application layer buffer. The available goodput information is used to decide a number of HTTP queries that have to be made on a given interface. At the application layer, each HTTP request binds to single TCP connection. Hence packet level steering can not be supported.

2. **Transport Layer :** The transport protocol at the sender side creates multiple sub-flows for a single TCP connection as in Multipath-TCP (MPTCP). Each sub-flow can take different paths (e.g., different interfaces in multi-homed devices) to reach the destination. Scheduling application layer data into a sub-flow is based on parameters like Round Trip Time (RTT), Available Bandwidth and link delay. The packets received through multiple paths are reordered at MPTCP layer of the destination.
3. **IP Layer :** Realizing interworking of multiple interfaces at IP layer allows a decision to be made with a finer granularity of information about the links (LTE/Wi-Fi). A quick decision making in terms of flow/packet level offloading can be done at IP layer. The decision making is independent of above layers. An intelligent traffic steering algorithm can be implemented at this layer. Figures 3, 4 and 5 show variations in the throughput of the network for different packet arrival rates (PAR) at AP and

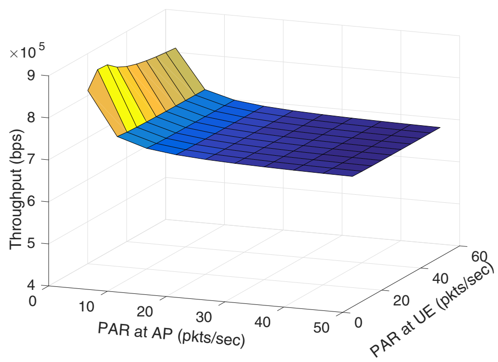


Figure 5: Throughput observed with 20 UEs in LWIP network.

UEs with varying number of users. These results are obtained by using Wi-Fi Preferred Algorithm (WPA) [32] [33]. WPA is a simple scheme in which a UE prefers to use Wi-Fi whenever Wi-Fi link is available and switches to LTE link if the Wi-Fi link is down. It is clearly visible, from the results, that there exists an optimal PAR that results in high throughput for each of the three cases studied. But high throughput can be reaped in only if packets sent to Wi-Fi link are regulated in order to control contentions in the channel. Also Figure 5 that the network reaches the saturated throughput quickly (for low PAR) when the number of users is high. However, it needs a high load (PAR) to reach saturated throughput in case of less number of users (refer Figure 3). When the number of users increases, the saturation throughput decreases. This happens due to high contention in the network. If this contention is controlled by proper coordination through the secondary interface like LTE, it will result in improved network throughput. This can be done efficiently at IP layer with cross-layer inputs.

4. **MAC Layer :** MAC layer enhancements can be done by regulating the medium access with multiple interfaces coordinating. A Wi-Fi device starts contending once a packet arrives at the Wi-Fi MAC queue, but if the rate of contention is regulated, then it can lead to better utilization of the channel in highly loaded cases. Also, operating with DCF mode can further be enhanced with finer coordination from an auxiliary interface like LTE.

In this work, we have included the LTE coordination at both IP layer and MAC layer of UE and LWIP node.

3.1. Design requirements for Uplink traffic steering algorithm

Figure 6 shows the feasible optimization at different regions viz., saturated and unsaturated regions. In the unsaturated region, the uplink activity of UEs associated with LWIP node can be offload from LTE interface to Wi-Fi interface, to effectively use the Wi-Fi channel. In saturated region, the channel efficiency can be achieved by avoiding collisions among users contending in the uplink. Reduction in collisions can be achieved by coordinating uplink transmissions in Wi-Fi channel with the help of a primary carrier like LTE. Here are some requirements for designing efficient uplink traffic steering algorithms:

1. The uplink traffic mechanism should operate fairly with other users operating in Wi-Fi channel.
2. The uplink traffic mechanism should aim to reduce the number of collisions in Wi-Fi channel compared to DCF.
3. LTE coordination can be done at millisecond granularity, so the granularity of decision making should hold till next control broadcast.

3.2. Uplink traffic steering algorithms

We have developed NCF, which includes four uplink traffic steering algorithms abiding the above mentioned design principles. The NCF algorithms are centrally coordinated in taking decisions. NCF focuses

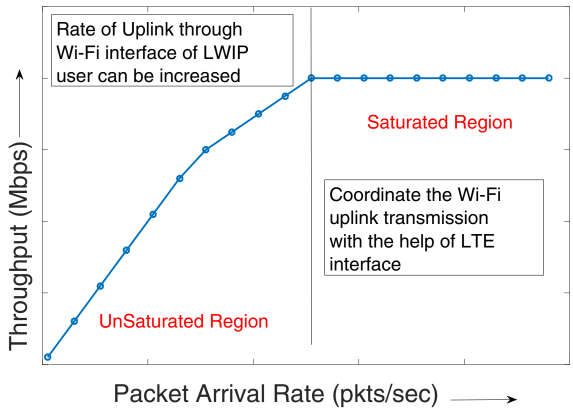


Figure 6: The optimization which is feasible in Wi-Fi domain.

on the solution which improves overall network performance in terms of throughput and channel utilization. Figure 7 shows the diverse design objectives for developing NCF algorithms.

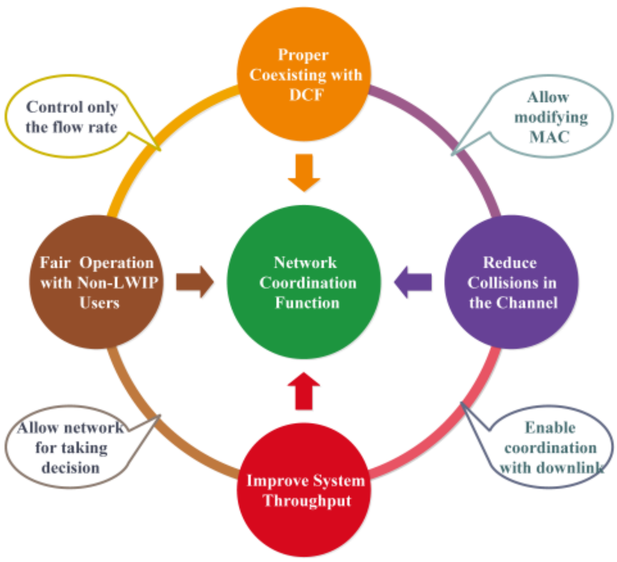


Figure 7: Objectives of Network Coordination Function.

- FUND is preferred where the time duration is given to LWIP user and legacy user in accessing the Wi-Fi channel is proportional.
- FUND++ is most appropriate where the transmission opportunity given to LWIP and legacy user in the channel is constant.
- DOUTA is chosen where user Wi-Fi MAC has to be kept unaltered and obtain a better throughput only by optimizing the flow rate.

- E-UNWRAP is recommended when LWIP users and legacy Wi-Fi users contend for the channel at the same time. Internally, the LWIP users collisions are resolved by LWIP node, so LWIP users do not physically collide, and thereby do not waste channel resources.

4. Network Coordination Function

In order to realize efficient uplink traffic steering in LWIP, in this work we propose a Network Coordination Function (NCF) which is realized at LWIP node by implementing various uplink traffic steering algorithms. In this work, we propose four different uplink NCF algorithms for efficient utilization of Wi-Fi resource in LWIP system. NCF facilitates the network to take intelligent decisions rather than individual UEs deciding to steer the uplink traffic onto LTE or Wi-Fi link. The NCF algorithms work by leveraging the availability of LTE as the anchor to improvise the channel utilization of Wi-Fi. Also, these algorithms do uplink traffic steering by taking inputs from both LTE and Wi-Fi links. NCF coordinates both the LTE and Wi-Fi transmissions by regulating the uplink flow rate and improvising the existing medium access techniques. Figure 8 shows proposed NCF algorithms and their features. Among NCF algorithms, DOUTA implementation does not require any changes to the existing UEs. But other NCF algorithms require a minor update to UE's Wi-Fi firmware. The NCF algorithms operate with different granularity: DOUTA operates continuously, whereas FUND and FUND++ operate in an interleaved fashion. E-UNWRAP can operate both continuously and interleaved manner. Decision-making interval of these algorithms is in the order of ms as LTE, which is the coordinating entity, and it will be delivering control messages at a regular interval of one ms. For instance, LWIP node computes the scheduling order of LWIP-UEs' Wi-Fi uplink transmissions and conveys the same to LWIP-UEs through control signals of LTE on licensed band in a reliable manner. This scheduling order has to remain unmodified till the arrival of new scheduling order even if all the LWIP-UEs have completed one cycle of uplink transmissions through Wi-Fi. The proposed centralized uplink algorithms try to operate fairly with other Wi-Fi nodes in the channel.*It is notable that NCF algorithms focus on optimizing the Wi-Fi uplink transmissions considering that LTE is available to send the outstanding packets which Wi-Fi could not able to transmit. For all the NCF algorithms, we study the performance of the Wi-Fi uplink transmissions with an assumption that LTE performance is unaltered due to scheduled MAC in LTE.*

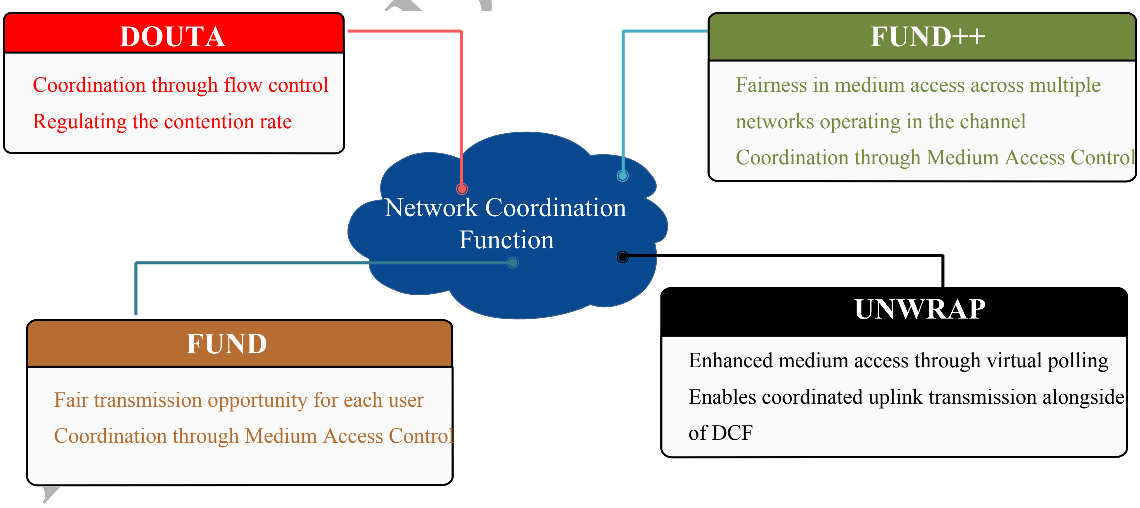


Figure 8: Algorithms of Network Coordination Function.

Table 1 in a nutshell presents the operating layer of different NCF algorithms and the kind of operations performed by them. A network operator can employ these algorithms one at a time or couple the algorithm operating at IP layer with the one operating at MAC layer. Among NCF algorithms DOUTA does not require any modification at UE side, so it can be readily deployed with modifications restricted only to LWIP node. If finer level of coordination at MAC layer is required, then FUND, FUND++, and E-UNWRAP can be employed. It is to be noted that the proposed NCF algorithms focus on improving the network throughput without changing the semantics of Wi-Fi QoS.

Table 1: Characteristics of proposed NCF algorithms.

Algorithm	Operating Layer	Operation performed
DOUTA	IP Layer	Controlling the packet steering rate
FUND	MAC Layer	Facilitates fair medium access opportunity
FUND++	MAC Layer	Regulates medium access duty cycles
E-UNWRAP	MAC Layer	Coordinates through virtual polling

4.1. Dynamic Optimal Uplink Traffic steering Algorithm (DOUTA)

DOUTA is designed with the objective of controlling collisions in the Wi-Fi channel by regulating the packet steering rate to LTE and Wi-Fi interface of LWIP node (downlink) and at UE (uplink). Figures 3 4 and 5 shows that by varying the number of users in the network and varying the packet arrival rate, network throughput reaches maximum value at some packet arrival rate. DOUTA explores and finds that optimal point. Packet steering rate (PSR) to LTE or Wi-Fi link corresponds to the fraction of packets sent to LTE or Wi-Fi queues out of total incoming packets from higher layer. Figure 9 and 10 show the traffic steering structure at LWIP node and at UE, respectively. The Traffic Steering Master (TSM) runs DOUTA algorithm and obtains the PSR to LTE and Wi-Fi interface for both LWIP node and LWIP-UEs. The traffic steering slave (TSS) obtains the uplink PSR from TSM and regulates the UE uplink traffic through Wi-Fi and LTE interfaces. We have considered a scenario with an LWIP node and set of N LWIP-UEs associated to it. The objective function of the optimization problem is to maximize network throughput, subjected to medium access constraints (abiding by DCF rules). Each UE runs different applications, and the volume of traffic generated by each UE is non-identical. This makes the optimization problem constraints multi-dimensional. The optimization problem and their constraints are discussed below.

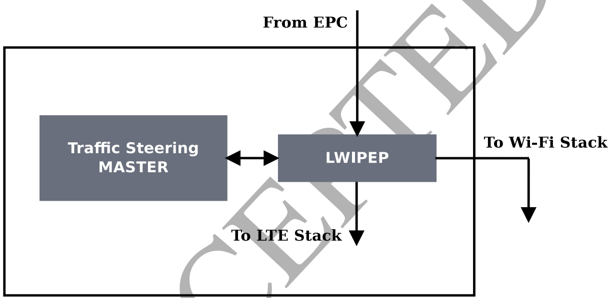


Figure 9: Traffic Steering at LWIP Node.

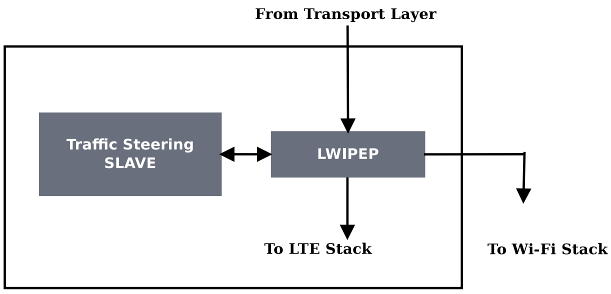


Figure 10: Traffic Steering at UE associated to LWIP Node.

4.1.1. Optimal uplink packet steering rate

An optimization problem is formulated for maximizing the total network throughput given 'N' LWIP-UEs and one LWIP node in the LWIP system. The optimal fraction of incoming packets that has to be sent through Wi-Fi interface of LWIP node and LWIP-UE can be obtained by solving the following objective function,

$$Maximize\ \ \Phi = \frac{P_t P_s (1-P_e) E[PL]}{(1-P_t)\sigma + P_t P_s (1-P_e) T_s + P_t (1-P_s) T_c + P_t P_s P_e T_e} \tag{1}$$

where,

$$P_t = 1 - \left[\prod_{i=1}^{N}(1-\tau_i^{UE})\right](1-\tau^{AP}) \tag{2}$$

$$\tau = \frac{2(1-2P_f)q}{q[(W+1)(1-2P_f)+(W\ P_f\ (1-(2P_f)^m)]+2(1-q)(1-P_f)(1-(2P_f))} \tag{3}$$

$$q = 1 - exp(-\lambda \times E[S_t]) \tag{4}$$

$$P_s = \frac{\sum_{i=1}^{N}\tau_i^{UE}\left[\prod_{j=1,j\neq i}^{N}(1-\tau_i^{UE})\right](1-\tau^{AP}) + \tau^{AP}\prod_{i=1}^{N}(1-\tau_i^{UE})}{P_t} \tag{5}$$

Subject to the following constraints,

$$N \geq 1;$$
$$0 \leq {}^{W}\lambda_i^{UE'} \leq \lambda_i^{UE}\ ,\ i \in [1\, to\, N];$$
$$0 \leq {}^{W}\lambda^{AP'} \leq \lambda^{AP};$$

Φ is the objective function to be maximized, which is a closed form expression for the throughput of a Wi-Fi network, derived from [34] by considering the Wi-Fi channel to be ideal with non-saturated traffic. In Equation (1), P_e corresponds to the packet error probability and $E[PL]$ corresponds to the expected payload length. P_t corresponds to probability that at least one transmission happens in the network which is expressed by Equation (2) and P_s corresponds to the probability that a given transmission is successful. λ_i^{UE} represents i^{th} UE's packet generation rate (to be sent uplink) and λ^{AP} represents the packet arrival rate to LWIP node (to be sent in downlink). ${}^{W}\lambda_i^{UE}$ and ${}^{W}\lambda^{AP}$ denote the packet steering rate (fraction of the packets to be sent to Wi-Fi interface queue) of LWIP-UE and LWIP node, respectively. ${}^{W}\lambda_i^{UE'}$ and ${}^{W}\lambda^{AP'}$ denote the optimal packet steering rates, and they act as control parameters which can be varied in order to maximize Φ. The remaining packets of the stream (${}^{L}\lambda_i^{UE} = \lambda_i^{UE} - {}^{W}\lambda_i^{UE}$) are sent to LTE queue so that they could be delivered over LTE interface. This optimization problem can be extended by considering other stand-alone Wi-Fi devices on the channel. After inclusion of other devices, the objective function Φ remains unaltered where as P_t and P_s have minor modifications to factor in transmissions of all the other devices. τ corresponds to the transmission probability of a given node expressed in Equation (3). It also shows the relation between τ and probability of having at least one packet in the buffer q. Equation (4) shows the relation between λ and q. $E[S_t]$ corresponds to expected time per slot, $E[S_t] = ((1-P_t)\ \sigma) + (P_t(1-P_s)T_c) + (P_tP_s(1-P_e)T_s) + P_tP_sP_eT_e$. Here $\sigma, T_c, T_s,$and T_e correspond to duration of time slot in case of idle, collision, successful transmission, and channel error respectively. Values for $\sigma, T_c, T_s,$and T_e are dependent on durations of SIFS, DIFS, packet transmission, and ACK transmission. The relation between τ, P_t, and P_s are given in Equation (5). The throughput of the system (Equation (1)) increases with the increase in the success probability, which is controlled by λ and number of users (N). For a network with known user count, throughput is solely controlled by λ. Hence regulating λ varies the network throughput. The control parameter ${}^{W}\lambda_i^{UE'}$ varies from zero to λ_i^{UE}, one of the best solutions would be all of ${}^{W}\lambda_i^{UE'}$ get zero and ${}^{W}\lambda^{AP'}$ will take the value of λ^{AP}, which reflects that Wi-Fi will operate only in downlink mode and all the uplink has to be sent through LTE, which contradicts with our objective of enabling efficient uplink transmissions through Wi-Fi. A network operator can decide the lower bound on the fraction of uplink to be supported through Wi-Fi. Enforcing it in the lower bound of the above mentioned constraints, the optimization solution will fetch the best packet steering rate for LTE and Wi-Fi links with minimum uplink transmission rate.

Algorithm 1 Dynamic Optimal Uplink Traffic Steering Algorithm (DOUTA)

Input:
$\lambda_i^{UE}, \lambda^{AP} \leftarrow$ Packet arrival rates of i^{th} UE and LWIP node's AP
$N \leftarrow$ Number of active users in the channel
${}^{L}\lambda_i^{UE} \leftarrow$ Fraction of packets steered to LTE interface of i^{th} UE
${}^{W}\lambda_i^{UE} \leftarrow$ Fraction of packets steered to Wi-Fi interface of i^{th} UE
Output: ${}^{W}\lambda^{AP'} \leftarrow$ Optimal packet steering rate to Wi-Fi interface at AP
${}^{W}\lambda_i^{UE'} \leftarrow$ Optimal packet steering rate to Wi-Fi interface of i^{th} UE

```
for Every T milliseconds do ▷ Trigger interval is 'T' millisecond ▷ Compute the optimal offload fraction
    Φ(^W λ^{AP'}, λ^{AP}, ^W λ^{UE'}, λ^{UE})
    if ^W λ^{AP} > ^W λ^{AP'} OR ^W λ_i^{UE} > ^W λ^{UE'} i ∈ [1 to N] then
    ▷ Current packet steering rate of LWIP-AP or LWIP-UE is higher than the obtained optimal traffic steering rate - regulate the packet steering at UE or AP
        Steer a traffic fraction λ_δ to interface I_k =LTE
        Ω(λ_δ, I_k)
    else if ^W λ^{AP} == ^W λ^{AP'} and ^W λ^{UE} == ^W λ^{UE'} then
    ▷ Current packet steering rate is optimal, do not let the packet steering rate to increase or decrease
        ω(^W λ^{AP'}, ^W λ^{UE'})
    else
            ▷ Interfaces are not loaded, packet steering rate can be increased to achieve high throughput
        Steer a traffic fraction λ_δ to interface I_k =Wi-Fi
        Ω(λ_δ, I_k)
    end if
end for
```

4.1.2. Algorithm for uplink traffic steering

Algorithm 1 shows the working procedure of DOUTA. The incoming packets are steered to LTE and Wi-Fi queues in order to achieve maximum system throughput. The optimization algorithm is triggered at every T milliseconds interval to find the optimal fraction of packets to be sent through Wi-Fi interface. We have conducted an experiment to monitor the network throughput at different granularity of time interval 'T' viz., 10, 100 and 300 milliseconds. Figure 11 shows the instantaneous network throughput reported at LWIP node. If a decision-making algorithm runs at an interval of 10 or 100 milliseconds, it can lead to a misleading decision as the variation in the network throughput is very high. But the decision taken at an interval of 300 milliseconds is stable and captures the actual network state as depicted in Figure 11.

If the current packet steering rate through Wi-Fi interface is greater than the optimal packet steering rate, then the packet steering rate to Wi-Fi interface is reduced by, steering a fraction of the packets (λ_δ) to LTE interface, which is denoted by Ω. The function Ω controls the fraction of traffic that has to move from LTE to Wi-Fi interface and vice-versa, whereas ω sustains the traffic offload rate when the global optimal solution is reached. DOUTA algorithm is scalable as it does not involve any additional signaling overhead. All the input parameters for the proposed algorithm such as uplink traffic arrival rate for each UE (obtained from the buffer status report (BSR)) and observed throughput of a UE (in both the links) are obtained by LWIP node through LTE uplink control channel. The output of DOUTA algorithm (i.e., allowable uplink traffic rate) is conveyed to UEs through downlink control channel of LTE. Since, this algorithm does not involve any core network signaling, it is highly scalable. Also, DOUTA algorithm of NCF can be adopted by LWIP networks without any protocol stack level modifications at UE side, which is an added advantage. The optimization problem shown in Equation (1)is solved using Matlab-based solver which solves it in the order of milliseconds. In case of real deployment, for different incoming packet arrival rates and for different number of UEs the optimal allowable uplink traffic rate can be precomputed and then stored as a look-up table. Such a look-up table based solution eliminates the need for running a solver at LWIP node.

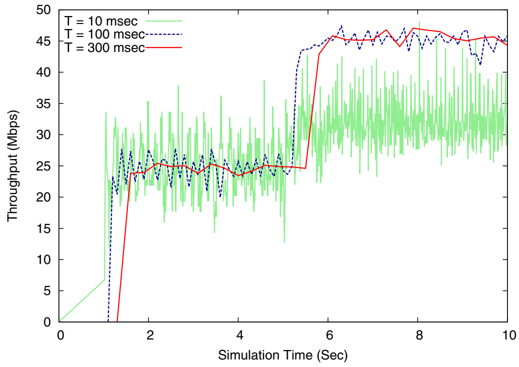


Figure 11: Instantaneous network throughput observed for different decision making intervals (T).

4.2. Fast UpliNk through Direct medium access (FUND)

DOUTA algorithm aims to improve the network throughput by regulating the traffic at IP layer. This approach can maximize the network throughput by regulating the flows (load), but it can not solve the collisions in the channel (which is the major reason for poor throughput in dense deployment scenario), which can only be done by coordinating the uplink transmissions at the MAC layer. Hence we propose FUND algorithm with an objective to coordinate the uplink transmission at MAC layer in order to improve the Wi-Fi channel utilization by reducing collisions among the LWIP-UEs which is detailed as follows.

Algorithm 2 Fast UpliNk through Direct medium access (FUND)

Input: $U_i \leftarrow$ Uplink requirement of i^{th} LWIP-UE
$N \leftarrow$ Number of active device operating in Wi-Fi channel
$m \leftarrow$ Number of LWIP-UEs having uplink demand
$T^F_{ON}, T^F_{OFF} \leftarrow$ Duration of FUND ON PERIOD and FUND OFF PERIOD
$T^F_{CYC} \leftarrow T^F_{ON} + T^F_{OFF}$
Output: Scheduling order for LWIP-UEs (S_o)

```
for Every FUND CYCLE (T^F_CYC) do
    if FUND ON PERIOD then
        S_o ← F(U_i, n, L)                      ▷ Proportional allocation based on flow requirement
        Notify LWIP-UEs about S_o through LTE control information
        Employ FUND medium access procedure
    else                                         ▷ FUND OFF PERIOD
        Set S_o for all the LWIP-UEs to NULL     ▷ LWIP-UEs do not transmit in FUND OFF PERIOD.
        Every other node does data transmission following DCF procedure
    end if
end for
```

$F_{ON} \leftarrow \frac{Number\ of\ active\ LWIP-UEs}{Total\ number\ of\ active\ nodes\ in\ the\ channel} \implies \frac{m}{N}$

$T^F_{ON} \leftarrow T^F_{CYC} * F_{ON}$ ▷ is duration of the FUND ON PERIOD

$T^F_{OFF} \leftarrow T^F_{CYC} * (1 - F_{ON})$ ▷ is duration of the FUND OFF PERIOD

FUND Operation Procedure: The entire duration of the transmission is divided into two access periods as depicted in Figure 12. A FUND CYCLE comprises of FUND ON PERIOD and FUND OFF PERIOD. During FUND ON PERIOD, the UEs associated with LWIP will operate based on Algorithm 2. In Figure 12, during FUND ON PERIOD, fast uplink is done by enabling LWIP-UE to transmit after the PIFS time interval, which ensures that LWIP-UE will occupy the channel earlier than any standalone Wi-Fi station using DCF mechanism. LWIP-UEs transmission/scheduling order is pre-computed by LWIP node and sent through LTE control messages. The scheduling order is computed by choosing those LWIP-UEs which has uplink data to transmit; this information is obtained from buffer status report (BSR) (which is reported to LWIP node by every UE through LTE uplink control channel). The list of chosen users are ordered in a round-robin fashion to create the scheduling order. Every LWIP-UE after receiving the scheduling order (S_o) through LTE control message waits for their opportunity. S_o remains unmodified till next scheduling order is given via LTE control message. Every LWIP-UE waits for their opportunity and transmits. During FUND OFF PERIOD none of the LWIP-UE contends for the channel. If an LWIP-UE wants to transmit in the next FUND CYCLE, it should notify the uplink requirement U_i (of an i^{th} LWIP-UE) in advance. LWIP node uses U_i in order to do a proportional allocation in uplink transmission $\mathcal{F}(U_i, m)$. Here m corresponds to the number of LWIP-UEs with the uplink requirement. FUND algorithm finds the number of nodes actively contending in the channel (N), by observing the transmissions in the channel with unique Wi-Fi MAC addresses.

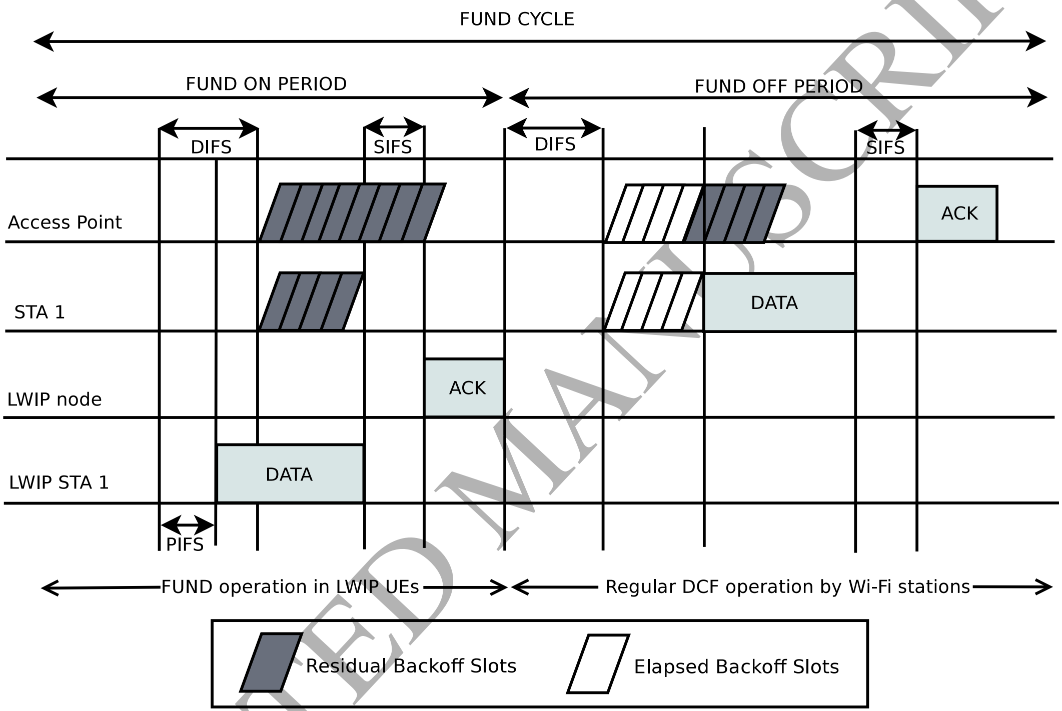


Figure 12: Operation of FUND algorithm.

4.3. FUND with fair Channel Access (FUND++)

FUND++ is designed in order to enhance FUND operation more fairly with non-LWIP UEs in the Wi-Fi channel. Algorithm 3 details the medium access regulation introduced by FUND++. Similar to FUND, FUND++ has FUND++ ON PERIOD and FUND++ OFF PERIOD. Duration of FUND++ ON PERIOD and FUND++ OFF PERIOD are regulated in order to achieve fair transmission with non-LWIP UEs. FUND++ ON PERIOD and FUND++ OFF PERIOD are controlled based on successful packet transmission of LWIP and non-LWIP nodes in the channel. If more collisions are observed during FUND++ OFF PERIOD (DCF), then the duration of FUND++ OFF PERIOD is extended in order to allow the non-LWIP-UEs to get fair amount of successfully transmitted packets with those of LWIP-UE. Number of packets successfully transmitted by i^{th} LWIP-UE and i^{th} Non-LWIP-UE through Wi-Fi interface is denoted as S_L^i and S_{NL}^i, respectively. In this algorithm, T_{ON}^{F+} and T_{OFF}^{F+} corresponds to the FUND++ ON PERIOD and FUND++ OFF PERIOD, respectively. T_{CYC}^{F+} FUND++ CYCLE ($T_{CYC}^{F+} = T_{ON}^{F+} + T_{OFF}^{F+}$). The FUND++ algorithm starts with $T_{ON}^{F+} = \frac{m}{N} * T_{CYC}^{F+}$, then based on the successful packet transmission observed by LWIP-UEs and non-LWIP-UEs, the value gets changed to $T_{ON}^{F+} = \frac{\sum_i S_{NL}^i}{\sum_i S_{NL}^i + \sum_i S_L^i} * T_{CYC}^{F+}$. If more packets collide, then FUND++ OFF PERIOD gets extended. This ensures fairness in successful packet transmission across LWIP-UEs and non-LWIP-UEs. The comparison between FUND and FUND++ is as follows.

FUND vs FUND++:

- In case of FUND, the time for LWIP transmissions is kept constant (only based on active users). In a FUND cycle, users are given uplink opportunity based on their QoS requirements.
- In case of FUND++, the FUND++ ON and FUND++ OFF PERIODS are varied according to the fraction of successfully transmitted packets by LWIP-UEs and non-LWIP UEs in the channel.
- FUND++ is fair to other Wi-Fi nodes in the channel compared to FUND and it also preserves the high throughput achieved using FUND.

Algorithm 3 FUND++

Input: $S_L^i \leftarrow$ Number of packets successfully transmitted by i^{th} LWIP-UE
$S_{NL}^i \leftarrow$ Number of packets successfully transmitted by i^{th} non-LWIP-UE
$T_{ON}^{F+}, T_{OFF}^{F+} \leftarrow$ Duration of FUND++ ON PERIOD and FUND++ OFF PERIOD
$T_{CYC}^{F+} \leftarrow T_{ON}^{F+} + T_{OFF}^{F+}$ ▷ A FUND++ cycle duration.
$U_i \leftarrow$ Uplink requirement of i^{th} LWIP-UE
Output: Scheduling order (S_o) for LWIP-UEs and $T_{ON}^{F+}, T_{OFF}^{F+}$
Initial Value: $T_{ON}^{F+} \leftarrow \frac{m}{N} * T_{CYC}^{F+}$ and $T_{OFF}^{F+} \leftarrow T_{CYC}^{F+} - T_{ON}^{F+}$
for Every FUND++ CYCLE (T_{CYC}^{F+}) **do**
  if FUND++ ON PERIOD **then**
    $S_o \leftarrow \mathcal{F}(U_i, n, L)$ ▷ Proportional allocation based on flow requirement
    Notify LWIP-UEs about S_o through LTE control information
    Employ FUND medium access procedure
  else ▷ FUND++ OFF PERIOD
    Set S_o for all the LWIP-UEs to $NULL$ ▷ LWIP-UEs do not transmit in FUND++ OFF PERIOD.
    Every other nodes does data transmission following DCF procedure
  end if
  $T_{ON}^{F+} \leftarrow \frac{\sum_i S_{NL}^i}{\sum_i S_{NL}^i + \sum_i S_L^i} * T_{CYC}^{F+}$
  $T_{OFF}^{F+} \leftarrow \frac{\sum_i S_L^i}{\sum_i S_{NL}^i + \sum_i S_L^i} * T_{CYC}^{F+}$
end for

4.4. Enhanced UpliNk With viRtuAl Polling (E-UNWRAP)

The problem that exist with FUND and FUND++ algorithms is that they divide the channel access for LWIP-UEs and non LWIP-UEs separately (FUND ON CYCLE and FUND OFF CYCLE). A non LWIP-UE following DCF is prevented from transmitting uplink during FUND ON PERIOD because the channel is occupied by LWIP-UEs after PCF duration. In order to relax this bifurcation of channel access time, and to allow any non LWIP-UE to contend for the channel at any given time, we propose Enhanced UpliNk With viRtuAl Polling (E-UNWRAP) algorithm. This algorithm coordinates the medium access for LWIP-UEs and ensures no collisions among LWIP-UEs even they follow DCF mechanism like any other non LWIP-UE. The term virtual polling corresponds to LWIP node polling each LWIP-UE for uplink packet availability in its Wi-Fi queue. This polling is done using LTE link. E-UNWRAP works with two basic approaches, (1) Scheduling Wi-Fi transmission with auxiliary LTE interface and (2) Regulating the Wi-Fi contention window. PCF mode of Wi-Fi supports scheduling of Wi-Fi transmissions using polling mechanism. However, polling is inefficient due to periodic query on each UE's Wi-Fi interface even when the packets are not available with UE [35]. The null frame is sent as the reply by UE to Wi-Fi AP when there is no packet to transmit in uplink. Note that, the underutilization of resources observed in Wi-Fi domain can be resolved by leveraging the availability of LTE interface. Whereas in LWIP, LTE control messages can be used to make query to the UE about its Wi-Fi queue status, which can further be used in creating a scheduling order for the uplink transmission. This can ensure that no two UEs connected to LWIP node can transmit at the same time. The actual collisions which are happening in the channel among LWIP-UEs are nullified. This way of resolving the collisions is possible only with LWIP architecture. E-UNWRAP also has an objective to regulate the virtual contention period (VCP), which is achieved by observing the collisions among other nodes in the channel hence it operates by taking a number of observed collisions in the channel as input.

The virtual contention period can be operated in three possible modes.

1. **Constant Cycle Operation:** In constant cycle operation the virtual contention period (VCP) has fixed cycle duration which is unaltered. Given the fixed cycle duration, based on the effective throughput that can be achieved in an LWIP node, the uplink steering can be regulated.
2. **Varying Cycle Operation:** In varying cycle operation, the VCP has time varying cycle which is controlled by taking input as collisions observed on the channel. Based on the collisions observed during DCF period (non-VCP), the VCP is made to shrink or expand dynamically. During the non-VCP period LWIP-UEs contend along with stand-alone Wi-Fi users in the network. Only difference between VCP and non-VCP period is that the contention window regulation (explained in Section 4.4.1) is done only in VCP.
3. **Full Cycle Operation:** In Full cycle operation, the LWIP-UEs are made to work as if the VCP period is available all the time. LWIP node schedules each uplink transmission of user based on number of packets in the user's queue. Also, full cycle operation allows changing the contention window of LWIP-UE. In the following, we have detailed the working procedure of full cycle operation.

4.4.1. E-UNWRAP with FULL cycle operation for Virtual Polling

E-UNWRAP solves two basic problems, the scheduling problem and contention window regulating the problem. Scheduling in E-UNWRAP deals with how a user has to be scheduled (i.e., the order in which LWIP-UE has to transmit) and the granularity of scheduling (msec or μsec). Contention window regulation unit works by regulating the contention window growth of LWIP-UEs.

Scheduling Order: Decision made on the scheduling order is based on packet availability in the Wi-Fi queue can be categorized into standard order and regulated order,

Standard order (STD-ORD): It is a fixed schedule of LWIP-UEs transmission done based on the availability of uplink Wi-Fi data at the UE. For instance, LWIP-UE 1 has a smaller contention window than LWIP-UE 2. But the order for scheduling uplink transmission is LWIP-UE 2 followed by LWIP-UE 1, then LWIP-UE 1 will not transmit even after expiry of its contention window. Instead, it will wait for the LWIP-UE 2's transmission. After completion of LWIP-UE 2's transmission, LWIP-UE 1 will start its uplink transmission.

Regulated order (REG-ORD): It follows a flexible schedule which is done dynamically based on the availability of uplink Wi-Fi data at the UE. Uplink transmissions for all the LWIP-UEs are scheduled in prior. A universal hash function is used to ensure a proper coexistence with non-LWIP-UEs, and to enhance an interleaved transmissions among LWIP-UEs. REG-ORD is employed in Algorithm 4.

Contention Window Regulation: Contention window regulation procedure (CWRP) has two main purposes: (1) To support developing the REG-ORD and (2) To coexist fairly with non-LWIP-UEs. CWRP supports REG-ORD by controlling the backoff value of LWIP-UE which in turn makes the transmission to be ordered. A universal hash function is used to choose individual UE's backoff slots. The hash function ensures that there is no collision among the users connected to LWIP node still maintaining the fair channel access with other users in the channel. A universal hash function, $h_{a,b}(x) = ((ax + b) mod\, p)$, where p is the prime number greater than or equal to the average contention window (operational contention window: CW_{opr}). The value of average contention window is varied based on number of collisions observed in the channel in last observation period. Algorithm 4 shows that CW_{opr} increases when $\frac{\sum \theta^i_{col}}{T^s_{pkt}}$ is greater than collision threshold, where θ^i_{col} corresponds to the number of transmissions got collided for an i^{th} user in the channel and T^s_{pkt} counts the total number of successful packets transmitted. CW_{opr} doubles when the

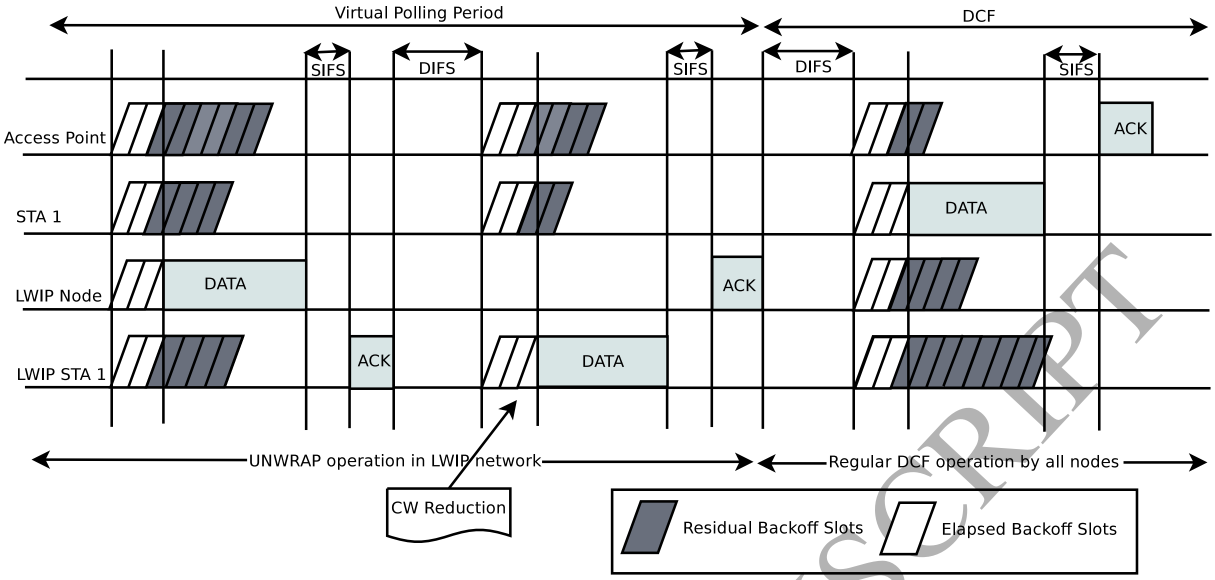


Figure 13: Operation of UNWRAP algorithm (Variable Operation Time).

collisions observed in the channel is more than CT_{col}, this increase is done for every VCP. Also, CW_{opr} decreases exponentially when the number of collisions observed is lesser than the threshold. This introduces harmony in transmission with Non-LWIP-UEs operating in the channel, at the same time collisions among LWIP-UEs are resolved internally.

Algorithm 4 Enhanced UpliNk With viRtuAl Polling (E-UNWRAP) - Full Cycle operation of VCP

Input: $\theta^i_{col} \leftarrow$ Collision observed by i^{th} user in the channel during the observation period.
$N \leftarrow$ Number of users in the channel
$p \leftarrow$ First prime number greater than CW_{opr}
$T_{pkts} \leftarrow$ Total number of transmissions in observation period
$N^{UL} \leftarrow$ Number of users having uplink data to transmit
$CT_{col} \leftarrow$ Collision threshold
Output: $a, b \leftarrow$ Coefficients for hash function

```
for N^UL uplink users do
    h(a,b) ← (ak + b) mod p          ▷ k is an unique user ID (can be MAC ID)
end for      ▷ a and b ensure no collision by assigning different contention slots among N^UL uplink users
if (Σ θ^i_col) / (Σ T_pkts) ≥ (CT_col) then
    CW_opr ← CW_opr * 2
else
    CW_opr ← CW_opr / 2              ▷ Reduce the contention window and find new hash function
end if
if CW ≥ CW_max then
    CW ← CW_max
end if
Broadcast a, b, p to all users in prior
```

4.5. Realization of NCF Algorithms in LWIP

This subsection describes the implementation details of proposed NCF algorithms. NCF works across (layers 2 and 3) MAC and IP layers of LWIP node. Some of the proposed NCF algorithms need LWIP-UEs to perform certain operations based on the input received from LWIP node.

In the case of DOUTA, LWIP node instructs its associated LWIP-UE about the allowable number of uplink packets that can be transmitted by that LWIP-UE. To obtain the number of uplink packets to be transmitted in the uplink, the optimization problem (Equation (1)) has to be solved. Solving the optimization problem is done at LWIP node, whereas throttling the number of uplink packet transmissions through Wi-Fi interface is done at LWIP-UE.

In case of FUND, during FUND ON PERIOD, LWIP-UEs will transmit one after the other, according to the transmission order given by LWIP node. During FUND OFF PERIOD, LWIP-UEs will not contend with non LWIP-UEs (stand-alone Wi-Fi UEs) for transmissions. Determining the transmission order for LWIP-UEs and notifying FUND ON and OFF PERIODs to LWIP-UEs are done by LWIP node, whereas performing uplink transmissions in the obtained transmission order is done by LWIP-UEs. In case of FUND++, the procedure involved is similar to that of FUND except for the duration of FUND ON and OFF PERIODs which are regulated to achieve better fairness across LWIP-UEs and non LWIP-UEs.

In case of UNWRAP, LWIP-UEs choose their backoff values based on a function determined by LWIP node. This backoff window function ensures no collisions across LWIP-UEs in the virtual polling period. During DCF period, LWIP-UEs backoff window function follows legacy DCF mechanism. The function for choosing backoff is given by LWIP node to its associated LWIP-UEs.

4.6. Benefits of NCF Algorithms

DOUTA: It can be observed that DOUTA is focused on steering the traffic at LTE and Wi-Fi links of LWIP and at LWIP-UE efficiently, in order to reduce the collisions in Wi-Fi domain and also to improve the uplink sending rate through Wi-Fi. Using Wi-Fi link for serving only downlink data is not desirable since it restricts the uplink traffic strictly to go through LTE link. Also, Wi-Fi offload is not the best solution as the underlying MAC (which uses DCF function) leads to high collisions in Wi-Fi channel. DOUTA provides the optimal steering of packets across LTE and Wi-Fi links by considering this trade-off. We have compared the performance of DOUTA with network level Wi-Fi offloading described in [19].

All other NCF algorithms do uplink traffic steering by filling the Wi-Fi queue first, if the Wi-Fi queue of an LWIP-UE/LWIP node is full then the remaining packets are sent through LTE link. Hence their performances are compared with DCF mechanism of Wi-Fi.

FUND: Efficiently does a fast medium access and ensures the fraction of time given to each user is fair.

FUND++: Regulates FUND++ ON PERIOD in order to ensure successful transmissions by each node to be proportional.

E-UNWRAP: Coexists with regular Wi-Fi DCF mechanism in grabbing the transmission opportunity but reduces collisions among LWIP-UE, which leads to improvement in the network throughput.

4.7. Joint Scheduler over NCF algorithms

NCF algorithms focus only on improving the channel utilization of Wi-Fi link, but in order to utilize both LTE and Wi-Fi links effectively a joint traffic scheduling solution is required. A traffic scheduler steers the incoming traffic across LTE and Wi-Fi links at LWIP node and LWIP-UEs. We have employed a Joint Scheduler (JS) on top of NCF which steers the incoming traffic from the higher layer (viz., transport layer) to Wi-Fi queue first, and if the Wi-Fi queue is filled, the remaining traffic is sent to LTE queue.

5. Theoretical Analysis of NCF Algorithms

In this section, we present analytical models of FUND and FUND++ algorithms and evaluate their performance. The symbols used for modeling are given in Table 2. The performance of algorithms is studied by varying the number of devices associated to LWIP node. Number of devices operate on the channel is denoted by n, out of which number of devices (UEs) associated with LWIP node is denoted by m. Figure 14 shows the Markov chain representation for contention of a Wi-Fi device in non-saturated traffic scenario. The state I denotes that a Wi-Fi device is idle and with q probability a device (station) contends.

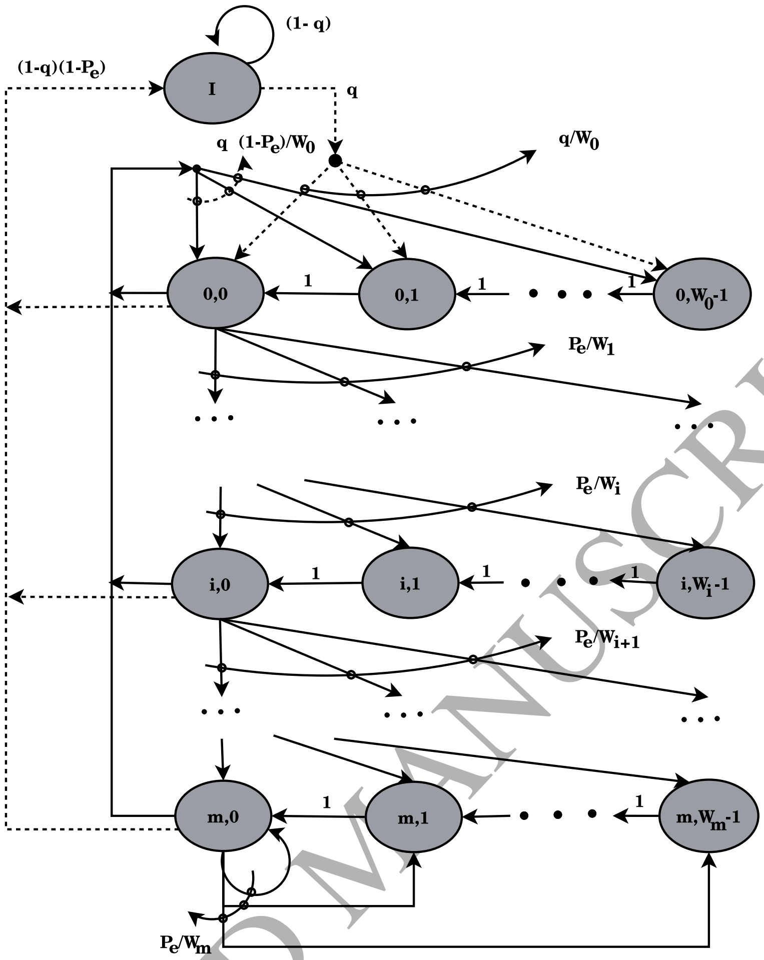


Figure 14: Markov chain representation of Wi-Fi MAC contention in non-saturated traffic scenario.

5.1. Analytical Model of FUND Algorithm

During FUND ON cycle, every LWIP node's transmission is scheduled in prior, so collisions are avoided. Also an LWIP node's transmission can not be interfered by transmissions of other Wi-Fi stations operating in the channel, as non-LWIP-UEs transmissions are preceded by DIFS time interval, where as LWIP-UEs transmission starts after PIFS time. Throughput of FUND algorithm is obtained using the equation below.

$$\mathcal{S}_{FUND} = f \times \mathcal{S}_{FUND\_ON} + (1-f) \times \mathcal{S}_{FUND\_OFF} \tag{6}$$

$\mathcal{S}_{FUND}$ is the throughput of FUND algorithm. f denotes the fraction of time FUND ON PERIOD is employed. $\mathcal{S}_{FUND\_ON}$ denotes throughput of the network with m LWIP-UEs. $\mathcal{S}_{FUND\_OFF}$ denotes the throughput of the network when DCF is employed by $N-m$ non-LWIP-UEs, this is extended from [34].

$$\mathcal{S}_{FUND\_OFF} = \frac{P_t P_s (1-P_e) E[P_L]}{(1-P_t)\sigma + P_t(1-P_s)T_c + P_t P_s (1-P_e) T_s + P_t P_s P_e T_e} \tag{7}$$

Table 2: Notations used for modelling NCF algorithms.

Parameter	Notation
Total no. of devices in the channel	N
Packet arrival rate of AP	λ^{AP}
Packet arrival rate of i^{th} UE	λ_i^{UE}
Expected length of data packet payload	$E[PL]$
Data packet transmission time	PL_{Time}
Duration of an empty *timeslot*	σ
Expected time per slot	$E[S_t]$
Transmission probability in a randomly chosen *timeslot* of an AP	τ^{AP}
Transmission probability in a randomly chosen *timeslot* of a UE	τ^{UE}
Durations of ACK frame	T_{ACK}
ACK timeout interval	$ACK_{TimeOut}$
DIFS	T_{DIFS}
SIFS	T_{SIFS}
PIFS	T_{PIFS}
Duration of 802.11 PHY and MAC headers	T_H
Propagation delay on Wi-Fi link	τ_p

$$Tt = T_{PIFS} + T_H + PL_{Time} + T_{SIFS} + T_{ACK}$$
$$\mu = \frac{1}{Tt}$$

T_t denotes the time for a successful packet transmission in FUND ON PERIOD. μ is the service time of packet.

$$\mathcal{S}_{FUND\_ON} = \begin{cases} \frac{1}{f} \times \sum \lambda_i^{UE} \times E[PL] \times \left(\frac{PL_{Time}}{Tt}\right) & \text{if } \left(\frac{1}{f} \times \sum \lambda_i^{UE} < \mu\right) \\ \mu \times E[PL] \times \left(\frac{PL_{Time}}{Tt}\right) & \text{otherwise} \end{cases}$$

PL_{Time} is the packet transmission time and T_{ACK} is the MAC-ACK transmission time. Throughput of FUND ON PERIOD ($\mathcal{S}_{FUND\_ON}$) varies based on packet arrival rate and service rate as shown above. Figure 15, shows the throughput of FUND algorithm in case of both simulation and analysis. For simplicity we have assumed that $m = N/2$, and every user is having same packet arrival rate. x-axis denotes the individual user packet arrival rate and y-axis denoted the throughput of the system. The model is evaluated by varying number of devices N. It is clearly observed that the developed analytical model matches with the simulation results in Figure 15.

5.2. Analytical Model of FUND++ Algorithm

FUND++ enhances the fairness of non-LWIP-UEs by giving more transmission opportunities. Also it strives to achieve number of successful packet transmissions by Non-LWIP-UEs to be in proportion with LWIP-UEs successful packet transmission. Network throughput of FUND++ in a steady state can be represented as follows:

$$f \times \mathcal{S}^{+}_{FUND\_ON} = (1 - f) \times \mathcal{S}^{+}_{FUND\_OFF} \tag{8}$$

In Equation (8), f denotes the fraction of time FUND++ ON PERIOD is employed.

$$\implies f = \frac{\mathcal{S}^{+}_{FUND\_OFF}}{\mathcal{S}^{+}_{FUND\_OFF} + \mathcal{S}^{+}_{FUND\_ON}}$$

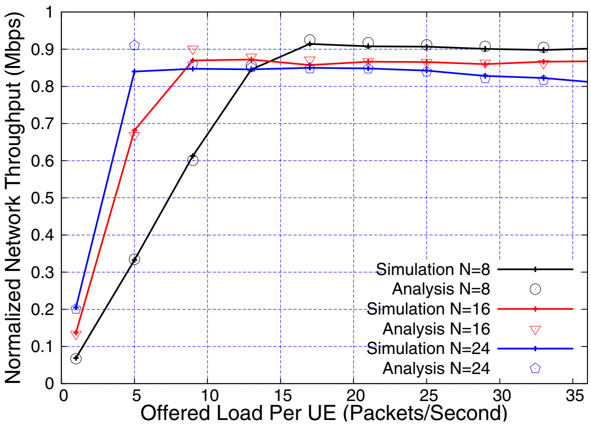


Figure 15: Network throughput of FUND algorithm.

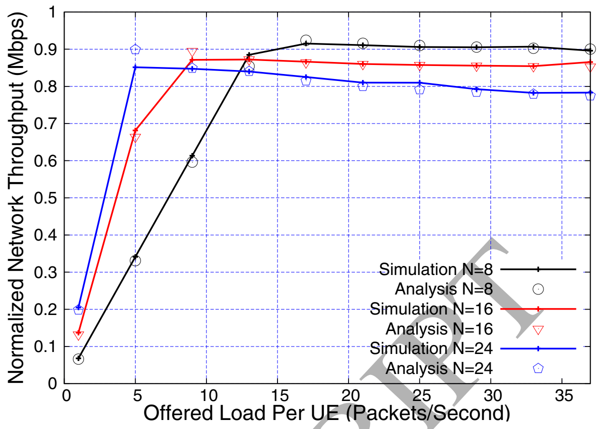


Figure 16: Network throughput of FUND++ algorithm.

$$\mathcal{S}^{+}_{FUND\_ON} = \begin{cases} \frac{1}{1-f} \times \sum \lambda_i^{UE} \times E[PL] \times \left(\frac{PL_{Time}}{Tt}\right) & \text{if } \left(\frac{1}{1-f} \times \sum \lambda_i^{UE} < \mu\right) \\ \mu \times E[PL] \times \left(\frac{PL_{Time}}{Tt}\right) & \text{otherwise} \end{cases}$$

The value of $S^{+}_{FUND\_OFF}$ is same as in equation (7), but the probability that a Non-LWIP-UE has packet to transmit q is dependent on f. The value of q for a Non-LWIP-UE is obtained from [34] and fraction of time FUND++ ON PERIOD employed (f) affecting q value is given below

$$q = 1 - e^{-(\lambda_i^{UE} \times E[S_t] \times \frac{1}{f})} \tag{9}$$

It is clear from the above equations that q is dependent on f, and f is dependent on the throughput of FUND++ ON and FUND++ OFF PERIODS, which again depends on q. So the value of f and q are obtained using numerical techniques. Figure 16 shows the performance of simulation and analytical model. The analytical model has closely approximated the simulation performance. It gives an insight that f which is a fraction, on regulating it controls the user level fairness (in case of FUND algorithm) and network level fairness (in case of FUND++ algorithm). The operation of NCF algorithm can be designed by tuning f based on the operator requirement without degrading the notion of fairness.

6. Performance Evaluation

In this section, we evaluate NCF to determine the performance of its uplink steering algorithms in terms of throughput. Also, we monitor the effect of NCF algorithms for enhancing the utilization of Wi-Fi channel in LWIP system. Here, we present the performance evaluation in Wi-Fi context, by considering that LTE interface has a scheduled MAC and it is available to carry out the uplink traffic which cannot be sent through Wi-Fi uplink. The performance of the NCF algorithms is compared with most widely used DCF based medium access of Wi-Fi. The evaluation aims at obtaining three crucial metrics of analysis for all the experiments.

- How efficiently collisions are reduced - Observed Collisions
- How much throughput of Wi-Fi network has improved because of NCF - Observed Throughput
- How NCF works fairly with non-LWIP-UEs in accessing the channel - Observed Fairness

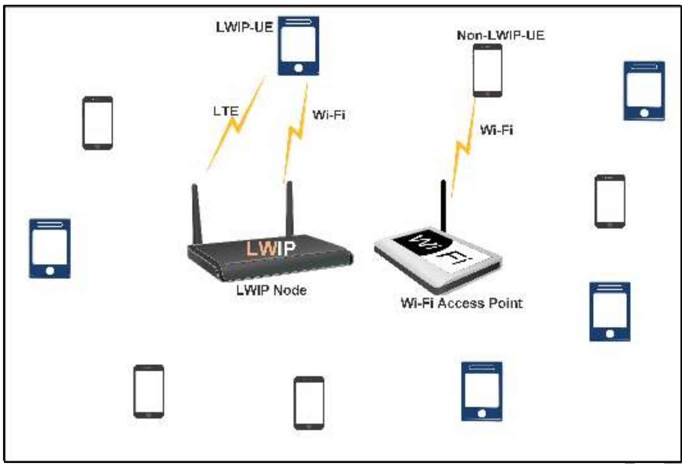


Figure 17: Experimental Scenario.

Table 3: Simulation Parameters

Parameter	**Value**
Number of Nodes operating in Wi-Fi channel	N $\in$[10 to 30]
Fraction of users connected to LWIP Node	N/2
Non-LWIP Wi-Fi users	N/2
Simulation Time	100 Seconds
Mobility Model	Static
Packet arrival rate per device	[10^2 to 10^3] packets per sec
Number of seeds	5
DIFS	28 μsec
PIFS	20 μsec
SIFS	10 μsec
Payload size (IP Packet)	1470 bytes
MAC LWIP-Users	NCF
MAC Non-LWIP-Users	DCF
MAC+PHY header size	24+16 bytes
ACK size	16 bytes
PHY data rate	65 Mbps

6.1. Simulation Setup

Figure 17 depicts the simulation scenario with an LWIP Node and a Standalone Wi-Fi AP. The evaluation setup scope is confined to one hop (between UE and LWIP node). Set of LWIP-UEs associated with LWIP node and Non-LWIP-UEs being associated to standalone AP. Each associated UEs are generating application traffic (which is observed by varying the packet arrival rate). In all the experiments, the number of UEs associated with LWIP and standalone Wi-Fi AP are in the ratio 1:1. There are no hidden nodes in the network, hence RTS-CTS handshake is not enabled. Table 3 summarizes the simulation parameters used for evaluating the performance of NCF algorithms. The simulations are done using MATLAB based simulator. We have considered fairness index (FI) which can be written as

$$FI_i = \frac{Number\ of\ successful\ packets\ in\ i^{th}\ network}{Total\ Number\ of\ Successful\ packets}, \text{ where } i \in \{LWIP, Non-LWIP\}$$

For simplicity we have considered that packet arrival rates of LWIP and non-LWIP users are the same. Any proposed algorithm from the given setup can be called as fair if its FI lies near 0.5. One of the most important parameters for decision making is about counting collisions in the channel. In our work LWIP node estimates the number of collisions in the channel. A question arises on how collisions can be counted? It is well detailed in [36]. The authors have counted collisions in the channel by differentiating the actual collisions from the weak signals. For diagnosing collisions, the authors have used the error patterns within a physical-layer symbol. They has shown high accuracy in detecting the collisions as compared to the weak signals.

6.2. Performance of DOUTA

Figure 18 shows the variation in network throughput when DOUTA and Wi-Fi offload were used, and the load offered by each UE is varied from 100 to 700 pkts/sec. In both the cases DCF mechanism of Wi-Fi is employed. The variation is closely observed by increasing the UEs in the network from 10 to 30. In the case of Wi-Fi offload, each UE prefers to send data through Wi-Fi interface whenever Wi-Fi link is available (Wi-Fi Preferred Algorithm [32]) and follows DCF mechanism. DOUTA also follows DCF procedure, but it tends to control the uplink traffic when the offered load increases. In other words, DOUTA instructs each LWIP-UE the optimal fraction of traffic that has to be sent in uplink, which is obtained through optimization function, and allowing rest of the traffic to be sent through LTE interface. The optimal fraction of traffic that is sent in uplink has reduced the contention in the network, thereby reducing the time elapsed on collision which can be observed in Figure 19. In Figure 19, the x-axis is the offered load and y-axis represents time elapsed in the collision, simulation time is normalized to 10 seconds, it can be observed the time elapsed in collisions varies from 2 to 3 seconds out of 10 seconds in the saturated region. Also, Wi-Fi has improved the network throughput by 7% as compared to employing Wi-Fi offload. The time elapsed in the collisions has also reduced by 13%. This throughput improvement is achieved without incurring any additional signaling overhead in the core network.

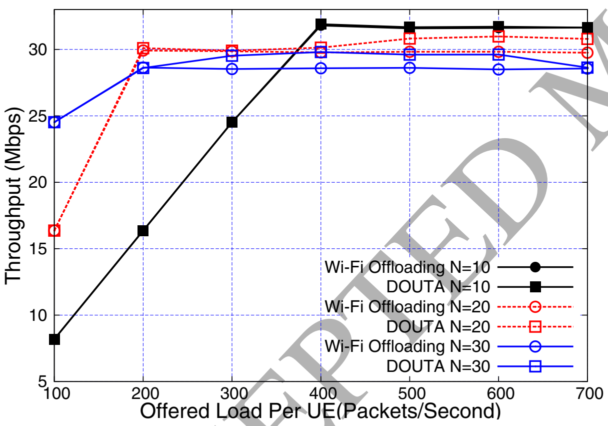


Figure 18: System Throughput - DCF vs DOUTA.

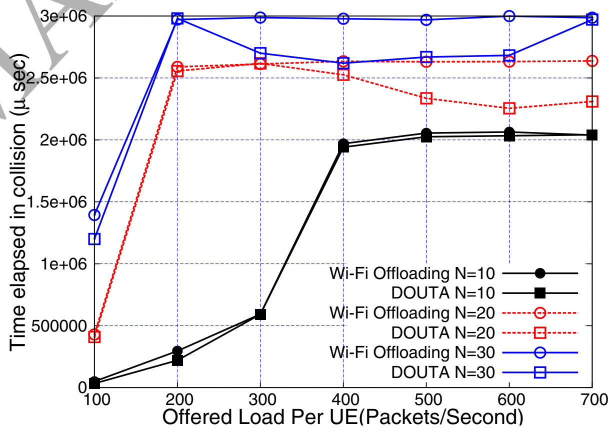


Figure 19: Time Elapsed in Collisions - DCF vs DOUTA.

6.3. Performance of FUND

Figure 21 shows the air time wasted in collisions. As the packet arrival rate (offered load) increases the number of collisions observed also gets increased in DCF mechanism. FUND has reduced the collisions by 50% as compared to regular DCF mechanism by coordinating the uplink transmission and by using fast channel access technique. Reduction in collisions has eventually lead to high throughput as shown in Figure 20. FUND ensures collisionless transmission among LWIP-UEs by sending the uplink schedule vector through LTE interface, which contains the transmission order for each UE. The greedy access to channel reduces the fairness among the users. Figure 22 shows fairness among UEs in terms of successful packet transmissions while using DCF and FUND algorithm. When DCF procedure is employed by LWIP-UEs and Non-LWIP-UEs, then 0.5 is their expected FI, which is clear from the plot. Shifting FI above 0.5 conveys that the algorithm is greedy and gives more opportunities for LWIP-UEs as compared to Non-LWIP-UEs. Even though FUND algorithm allows a biased utilization of resources benefiting LWIP-UEs, FUND algorithm ensures proportional FUND ON PERIOD and FUND OFF PERIOD based on the number of LWIP-UE and Non-LWIP-UEs. Eventually, the fraction of time given for each UE uplink transmission is equal in FUND algorithm. Hence it provides UE level fairness. FUND++ is a dynamic approach to improve the fairness of UEs in terms of successful packet transmissions. Nevertheless FUND is the most efficient of all NCF algorithms in terms of channel utilization.

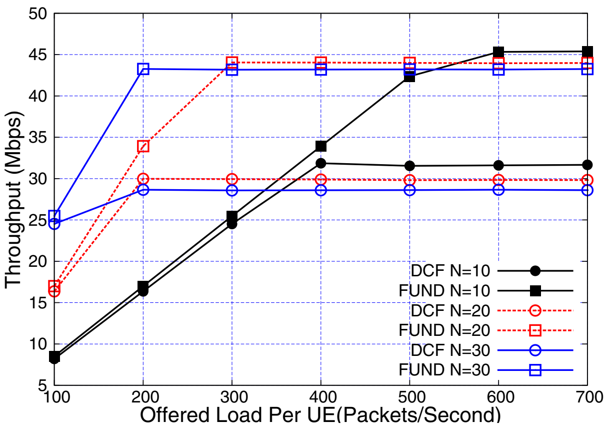


Figure 20: System Throughput - DCF vs FUND.

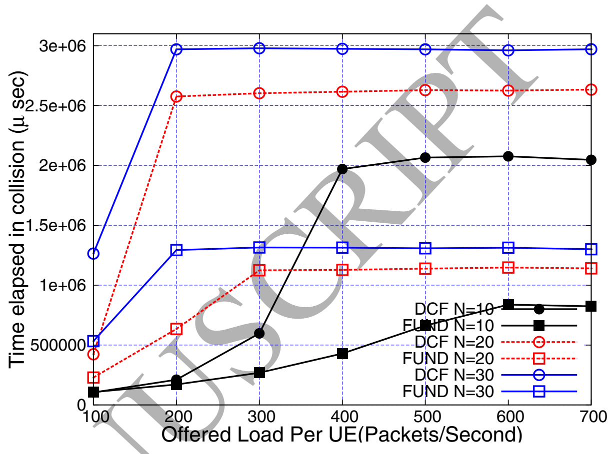


Figure 21: Time Elapsed in Collisions - DCF vs FUND.

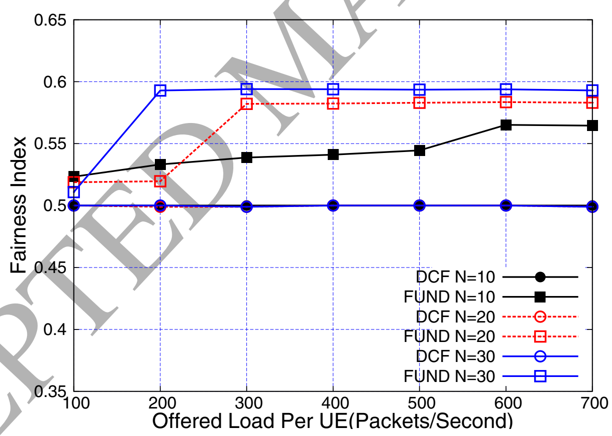


Figure 22: System Fairness - DCF vs FUND.

6.4. Performance of FUND++

FUND++ focuses ensuring fairness across LWIP and non LWIP users in the Wi-Fi channel. Fairness in such cases can be achieved by regulating the FUND cycle duration. Figure 25 shows the fairness among LWIP and non-LWIP users in case of FUND and FUND++. It can be observed that FUND++ is able to reach FI=0.5 which conveys that the system is fair. The throughput improvement of FUND++ is comparable with FUND, but FUND is always being the upper bound as shown in Figure 23. The time elapsed in collisions (Figure 24) is high in FUND++ as compared to FUND because the FUND++ ON PERIOD is lesser in FUND++ as compared to FUND ON PERIOD of FUND algorithm. As the time elapsed for transmission by Non-LWIP-UEs increases (FUND++ OFF PERIOD increases), and network throughput decreases. This is because, the time elapsed due to collisions increases, when DCF is employed with more number of non-LWIP-UEs. We can also observe that the FUND++ algorithm has extended the FUND++ OFF PERIOD by 8.8% more compared to FUND in order to ensure fairness to non-LWIP UEs.

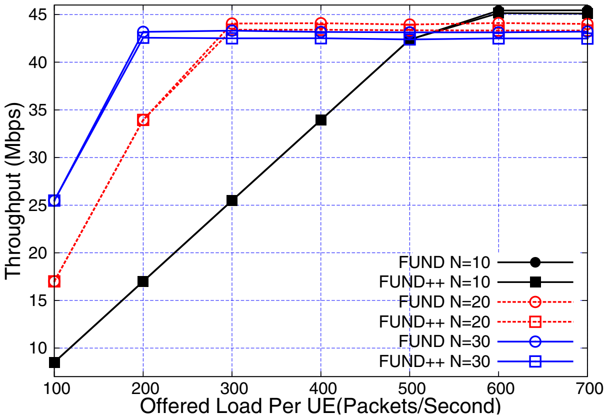


Figure 23: System Throughput - FUND vs FUND++.

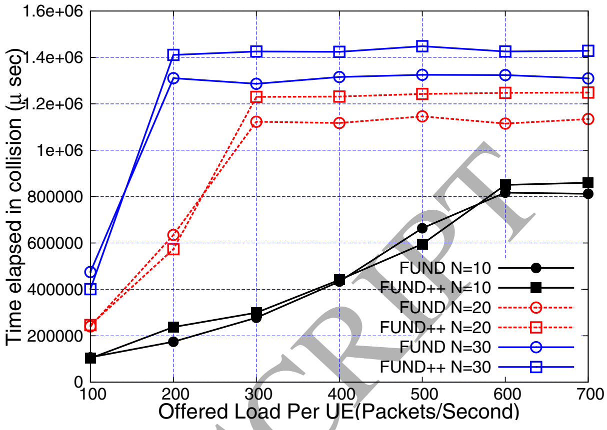


Figure 24: Time Elapsed in Collisions - FUND vs FUND++.

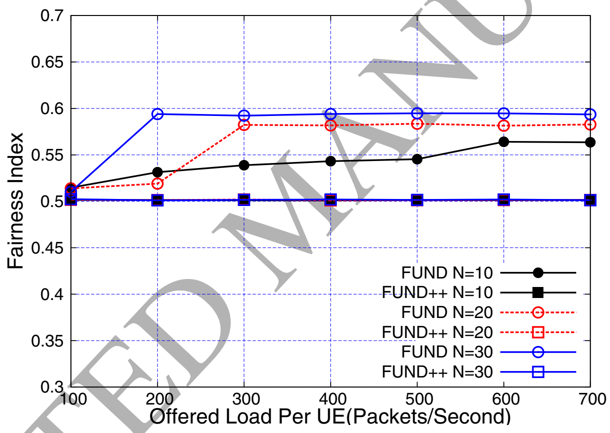


Figure 25: System Fairness - FUND vs FUND++.

6.5. Performance of E-UNWRAP

In this section, we present the evaluation of E-UNWRAP with different operation cycles (viz., variable and full operation).

6.5.1. Variable Operation

According to E-UNWRAP variable operation, during the virtual contention period, E-UNWRAP mechanism is followed, as detailed in section 4.4. In the remaining duration, it employs DCF mechanism. Scheduling the transmission in a predefined order has improved the network throughput. Figure 26 shows that when the number of users is more the network throughput of E-UNWRAP is better than DCF, in the saturated region. This improvement is well explained by a reduction in the fraction of the time elapsed in collisions. The time elapsed in collisions has reduced due to proper scheduling. Figure 27 shows that fraction of LWIP transmissions has been reduced in order to improve the overall network throughput, as the number of UEs participating in the transmissions increases the effective reduction in collisions of E-UNWRAP increases as compared to DCF. Figure 28 shows that LWIP-UEs have subdued their transmission opportunity to improve the overall network performance.

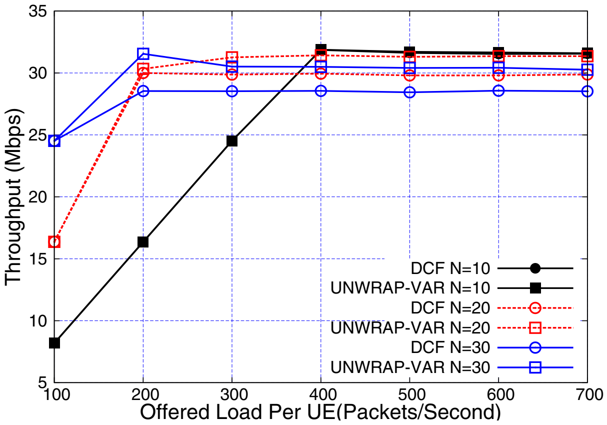


Figure 26: System Throughput - DCF vs UNWRAP-variable operation.

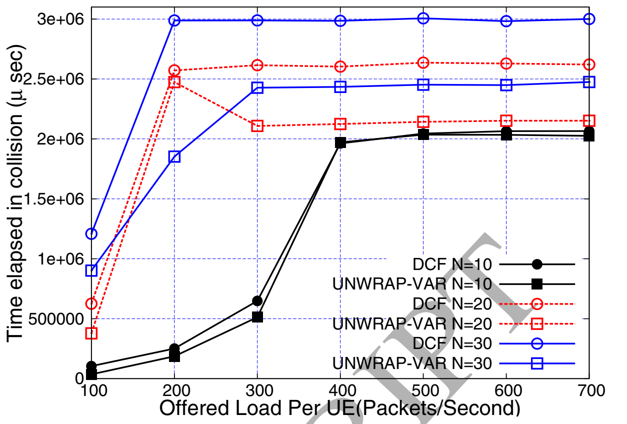


Figure 27: Time Elapsed in Collisions - DCF vs UNWRAP-variable operation.

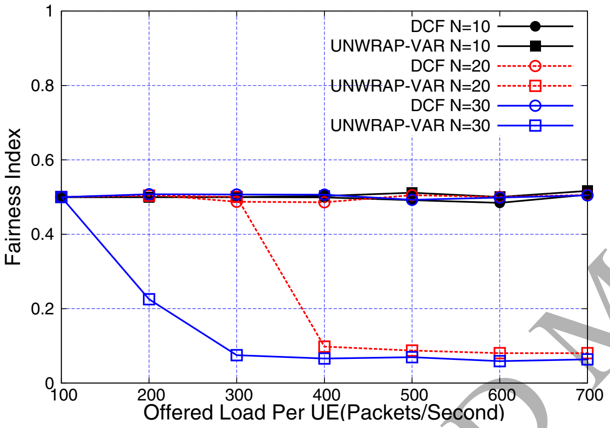


Figure 28: System Fairness - DCF vs UNWRAP-variable operation.

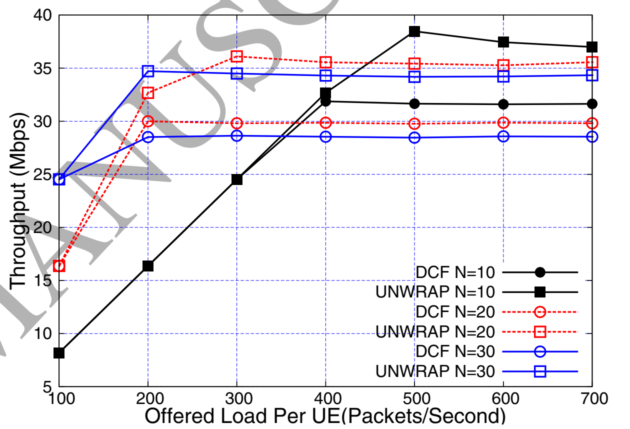


Figure 29: System Throughput - DCF vs E-UNWRAP - Full operation.

6.6. Full operation

In full operation, the VCP is spread over the entire duration, and the user contention window is regulated by contention window regulation module.

Figure 29 shows the significant improvement in the network throughput (21% increase) achieved by E-UNWRAP with full operation in comparison to DCF. This unleashes the power of LWIP in regulating the usage of Wi-Fi spectrum effectively. This phenomenon can be well explained using Figure 30. It shows the collisions among LWIP-UEs have been reduced greatly, thus resulting in the overall improvement in throughput. This is only feasible if Wi-Fi transmissions are coordinated by LTE. E-UNWRAP has not grabbed more opportunity. It is fair, Figure 31, shows that it even subdues its transmission opportunity to increase the opportunity to other Wi-Fi nodes in the network.

6.7. Performance evaluation of NCF algorithms in dense deployment scenario

In this section we compare the performance of proposed NCF algorithms with the state-of-the-art algorithms in the literature. We have conducted the experiment in a dense deployment scenario with multiple walls and floors where hidden-terminal problem arises. Also, we have profiled the performance of all the experiments by enabling RTS-CTS handshake. We have prefixed JS to NCF algorithms viz., JS-DOUTA, JS-FUND, JS-FUND++, and JS-UNWRAP, where Joint scheduler is employed on top of the proposed NCF algorithms.

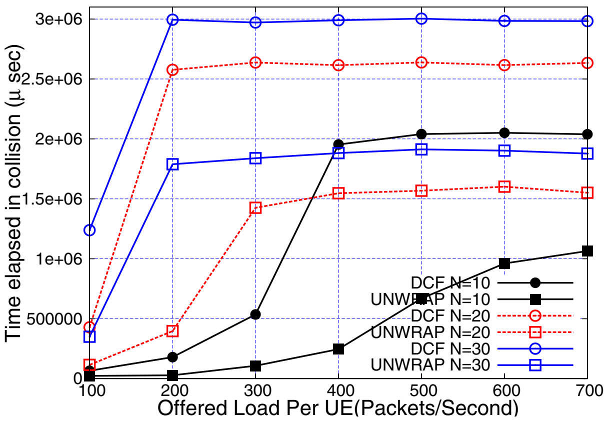


Figure 30: Time Elapsed in Collisions - DCF vs E-UNWRAP - Full operation).

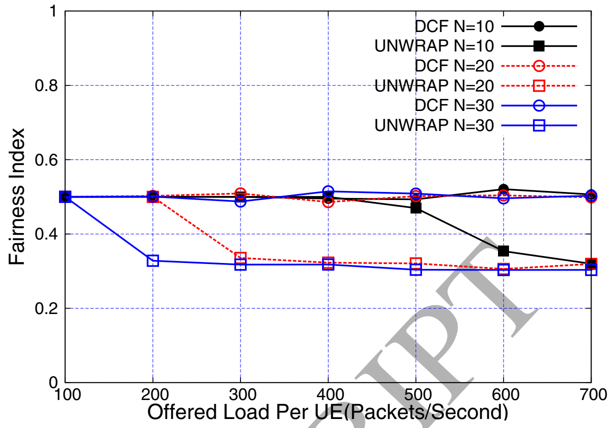


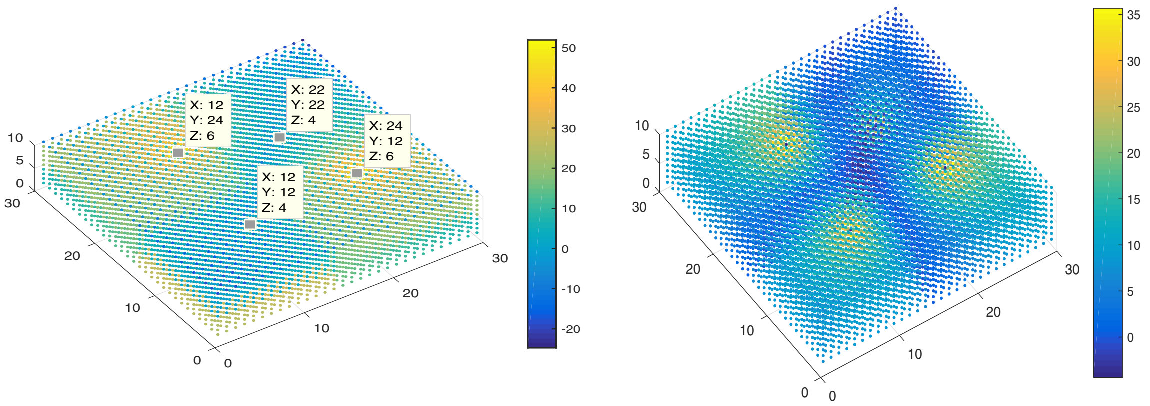
Figure 31: System Fairness - DCF vs E-UNWRAP - Full operation).

Table 4: Comparison of the proposed NCF algorithms.

Parameters	**DOUTA**	**FUND**	**FUND++**	**E-UNWRAP**
MAC changes	Not Required	Required	Required	Required
Fairness	Improves non-LWIP opportunities	Improves LWIP opportunities	Operates with Fairness	Improves non-LWIP opportunities
Throughput	Better than Wi-Fi offload by 7%	Better than DCF by 36%	Better than DCF by 23%	Better than DCF by 21%
Compatibility with existing UEs	Works Readily	Changes Required	Changes Required	Changes Required
Operation Type	Continuous	Interleaved with T_{ON}^{F}	Interleaved with T_{ON}^{F+}	Continuous in FULL operation
Type of Control	By controlling PSR	By controlling MAC operation	By controlling MAC operation	By controlling MAC operation
Time elapsed in collision	Reduced by 13% compared to DCF	Reduced by 56% compared to DCF	Reduced by 52% compared to DCF	Reduced by 33% compared to DCF

6.7.1. Experiment Scenario

Figure 32 shows the simulation scenario in which we have considered a two-storey building of dimensions 30 m × 30 m × 10 m having four LWIP nodes placed. The positions of LWIP nodes in the building are also marked in Figure 32. Path loss in this scenario is calculated by adhering to wall and floor losses recommended by 3GPP [37]. For creating a more challenging environment, we have considered LTE operating with reuse factor one and Wi-Fi operating in the same channel across all four APs. Figure 32 shows the SINR of LTE and Wi-Fi observed inside the building. The other important simulation parameters are shown in Table 5. We have compared the proposed NCF algorithms with existing 3GPP Rel. 12 based interworking technique (Rel-12) [38] and state-of-the-art α-optimal scheduler [39] to observe its performance benefits. Rel-12 technique makes a UE associate with LTE or Wi-Fi link of LWIP node based on the SINR observed on each link. The UE associates with the link having highest SINR. In case of α-optimal scheduler, each UE associates a set of flows through LTE uplink and Wi-Fi uplink based on the throughput achieved by that UE on each link. α-optimal scheduler steers the traffic dynamically across LTE and Wi-Fi links based on network load. Such steering is done with an objective to maximize the network throughput. When α=1, the scheduler does a proportionally fair split of the traffic across LTE and Wi-Fi links. The major difference between α-optimal scheduler and proposed JS-NCF algorithms is that the α-optimal scheduler efficiently steers the traffic across LTE and Wi-Fi links (only traffic steering), whereas JS-NCF algorithms improve the efficiency of Wi-Fi link by coordinating the uplink transmissions through LTE link.



(a) LTE SINR inside the building.

(b) Wi-Fi SINR inside the building.

Figure 32: SINR distribution of the building chosen for conducting experiment with 4 LWIP nodes in a two-storey building.

Table 5: Simulation Parameters

Parameter	**Value**
# of UEs, LWIP Nodes	140, 4
Max Tx power of LTE & Wi-Fi	23, 23 dBm
LTE path loss model	3GPP indoor path loss model [37]
Wi-Fi path loss model	ITU path loss model [40]
LTE MAC Scheduler	Proportional Fair Scheduler
UE position	Random
Wi-Fi Standard	IEEE 802.11n
Wi-Fi frequency and bandwidth	2.4 GHz, 20 MHz
LTE frequency and bandwidth	2.6 GHz, 10 MHz

6.7.2. Evaluation of network throughput for various loads

The total network throughput is measured in for JS-DOUTA, JS-FUND, JS-FUND++, JS-UNWRAP, Re-12 scheduler, and α-optimal scheduler by varying load on the network. The load variation is done by increasing number of uplink flows in the network. The average flow rate of each flow corresponds to 800 Kbps. Figure 33 plots aggregate throughput of LWIP network by varying traffic load from 400 flows to 800 flows. In Figure 33 the state-of-the-art α-optimal scheduler outperforms Rel-12 technique because, for a given load α-optimal scheduler dynamically steers the incoming traffic across LTE and Wi-Fi links, where as Rel-12 technique abides to transmit through one of the links that has the highest SINR. The problem of high contention is not resolved in case of both Rel-12 and α-optimal scheduler, but when the throughput of Wi-Fi gets saturated α-optimal scheduler splits the incoming traffic proportionally but Rel-12 does not change the link association. JS-DOUTA algorithm outperforms Rel-12 technique and α-optimal scheduler because JS-DOUTA allows optimal user traffic to be sent through Wi-Fi link which reduces the time elapsed in collisions. Similarly, JS-FUND and JS-FUND++ algorithms have outperformed the state-of-the-art scheduler by 14% and 12%, respectively, which is due to greedy transmission nature of these algorithms. But JS-FUND maintains the fairness at user level while JS-FUND++ maintains fairness at the network level. It is notable that all the NCF algorithms have outperformed Rel-12 technique by 13% on average. It can be clearly observed that when RTS-CTS is enabled, all the algorithms have improved

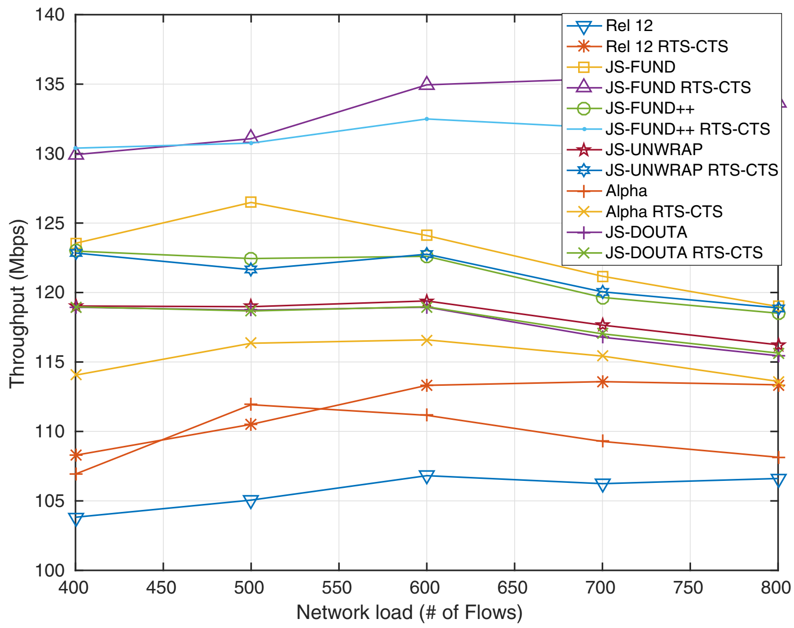


Figure 33: Variation in network throughput versus traffic load.

their network throughput by 5-18% as compared to Rel-12 technique. The throughput of the proposed JS-NCF algorithms has improved by 9% on average compared to the state-of-the-art α-optimal scheduler. The throughput improvement achieved by JS-NCF algorithms is due to their ability to reduce collisions in the Wi-Fi domain, which is achieved by coordinating the uplink transmissions with the help of LTE as the anchor. It is notable that introducing RTC-CTS mechanism to address hidden terminal problem in large network has improved the network throughput both in case of the state-of-the-art algorithm and the proposed JS-NCF algorithms.

6.7.3. Evaluation of user throughputs

Figures 34 and 35 show CDF of user throughputs without and with RTS-CTS mechanism for various algorithms. The CDF of user throughputs is shown for a fixed load of 800 flows in the network. All the JS-NCF algorithms outperform Rel-12 technique and α-optimal scheduler. When RTS-CTS mechanism is enabled, the throughput of all the users increase for all the algorithms. Figure 35 captures the throughput of individual users with RTS-CTS mechanism, where the collisions due to contention are greatly controlled. The α-optimal scheduler improves the user throughput by allocating resources proportionally across both LTE and Wi-Fi links. JS-NCF algorithms not only allocate fair resources across multiple users but also improve the throughput of the network by controlling the collisions efficiently.

7. Conclusions and Future work

In this work, we presented NCF algorithms with an objective of improving the Wi-Fi channel utilization. The developed algorithms are diverse in their objectives, layer of operation, and type of operation. We compared the proposed NCF algorithms with highly successful DCF mechanism of IEEE 802.11. Existence of a primary interface LTE in LWIP-UEs facilitate coordination in uplink transmission through contention based Wi-Fi channel, which results in an efficient Wi-Fi channel utilization. The developed NCF algorithms operate fairly with other nodes in the channel, some algorithms subdue their benefits in order to improve overall network performance. Using extensive simulation experiments, we observe that, the proposed NCF

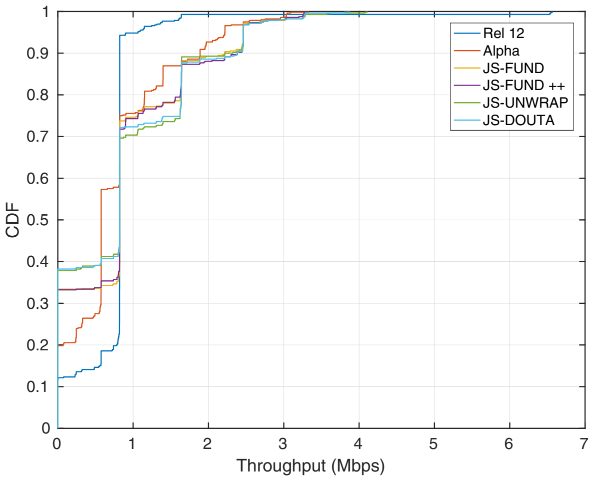


Figure 34: CDF of user throughputs without RTC-CTS.

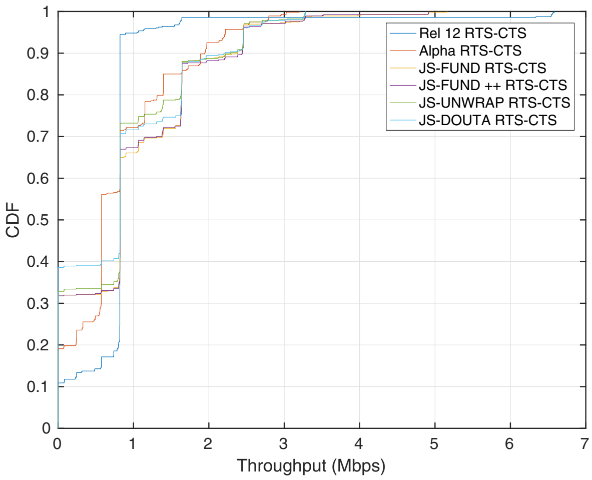


Figure 35: CDF of user throughputs with RTS-CTS.

algorithms have reduced collisions in Wi-Fi uplink by 13-56% and improved throughput by 7-36% as compared to Wi-Fi offload and DCF mechanism of Wi-Fi. We have also analytically modelled two of the NCF algorithms and shown its performance comparison with simulation results. An operator can use the NCF algorithm, DOUTA, if no modification should be needed at UE. If finer level of coordination at MAC layer is required, then FUND, FUND++ and E-UNWRAP can be preferred. The proposed algorithms will also work in LWA (PDCP level interworking architecture) with minor modifications. As a part of future work, we are implementing NCF algorithms in LWIP testbed [9] to study its performance in real time.

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