PRECISE: Power Aware Dynamic Traffic Steering in Tightly Coupled LTE Wi-Fi Networks

Thomas Valerrian Pasca S, Himank Gupta, Bheemarjuna Reddy Tamma and Antony Franklin A
Indian Institute of Technology Hyderabad, India
Email:[cs13p1002, cs16mtech01001, tbr, antony.franklin]@iith.ac.in

***Abstract*—LTE—Wi-Fi Radio Level Integration with IPsec Tunnel (LWIP) thrives as a complete solution to address the data requirement for telecom operators by effectively utilizing unlicensed spectrum. Co-located LWIP (C-LWIP) node couples Home eNodeB (HeNB) and Wi-Fi Access Point (AP) at radio protocol stack to enable a unified control decision over both LTE and Wi-Fi links. The challenges pertaining to small cells *viz.*, high co-tier interference and QoS provisioning can be effectively addressed by using LWIP. This paper proposes a novel *Power awaRE dynamiC traffIc StEering* (PRECISE) algorithm which regulates transmit powers of LTE and Wi-Fi of LWIP node in order to minimize interference across LWIP nodes in dense deployments. The PRECISE algorithm also does flow steering across LTE and Wi-Fi interfaces by employing Multi Attribute Decision Making (MADM) technique. It thrives on ensuring Guaranteed Bit Rate (GBR) flow requirements by dynamically controlling the transmit power across multiple LWIP nodes. Interference mitigation sub-problem and ensuring GBR sub-problem are formulated as Mixed Integer Non-Linear Programming (MINLP) problems. The proposed PRECISE algorithm improves the network throughput by 84% compared to 3GPP Rel-12 LTE Wi-Fi interworking and 48% compared to state-of-the-art α-optimal scheduler. It also has reduced the number of unsatisfied GBR flows by 35% as compared to α-optimal scheduler.**

I. INTRODUCTION

High penetration of multi-featured smartphones and tablets has lead to data explosion [1]. Limited by available spectrum for operation due to licensing requirements, it has become challenging for mobile network operators to address the ever growing data demand. One of the solutions to meet ever-growing data demand is to offload some of the cellular network traffic onto IEEE 802.11 based WLANs (Wi-Fi) which operate on the unlicensed spectrum. 3GPP has proposed various cellular-Wi-Fi interworking strategies from Rel.8 to Rel.12, which realize interworking between cellular and Wi-Fi networks through a gateway. Switching or offloading of downlink flows from cellular to Wi-Fi required changes to the flow table at the cellular/WLAN gateway. Fast switching and dynamic flow steering across cellular and Wi-Fi links are not feasible due to high signaling overhead and network delay involved in such operations. To overcome these challenges, 3GPP has proposed a finer level of interworking in Rel.13 [2]. The tighter level of interworking technologies include LTE Wi-Fi Aggregation (LWA) and LTE Wi-Fi Radio Level Integration with IPSec tunnel (LWIP). LWA realizes the aggregation at PDCP layer while LWIP realizes it at IP layer. LWIP architecture includes Small cell eNB (SeNB) and Wi-Fi AP integrated at their radio protocol stacks as shown in Figure 1 [3]. It includes a Link aggregation layer (LAL) over LTE and Wi-Fi radio protocol stacks for supporting flow steering across LTE and Wi-Fi links without any additional headers to packets. LWIP can be realized by co-located and non co-located deployments. In this paper, we investigate issues related to Co-located LWIP (C-LWIP) deployments.

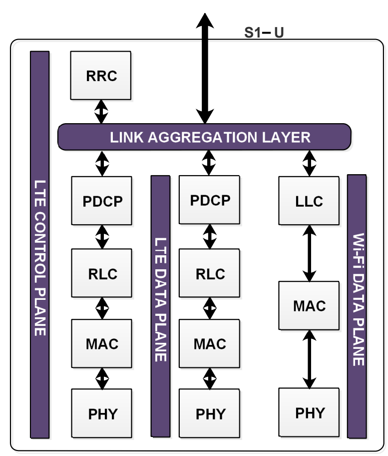

Fig. 1: Protocol stack of Co-located LWIP.

The challenges with small cell deployments include co-tier interference due to densification of small cells and QoS provisioning. Usage of orthogonal RATs (LTE and Wi-Fi) emerges as a solution to address this problem. The users located at the high interference zone of LTE can connect to Wi-Fi thereby reducing the effect of co-tier interference. Currently, LTE small cells and Wi-Fi APs are independently deployed, which makes an LTE user who is facing high interference difficult to find a suitable Wi-Fi AP to associate with for obtaining better

978-1-5386-3531-5/17/$31.00 © 2017 IEEE

service. The C-LWIP architecture ensures availability of Wi-Fi link for users even in the interference region, but C-LWIP deployment suffers from co-tier interference (for both LTE and Wi-Fi) when density of their deployment increases, and leads to coverage holes when the density decreases.

Another challenge is to ensure QoS for LWIP users, which corresponds to allocating sufficient radio resources for their guaranteed bit rate (GBR) flows. In a typical indoor scenario, the SINR received by a User Equipment (UE) is constrained by the number of obstacles and number of interfering LWIP nodes that exist in its vicinity. LTE scheduler such as ”Priority Set Scheduler” allocates more resources to the UEs with poor SINR in order to meet their GBR requirements. Such a QoS centric allocation adversely affects the overall system throughput.

II. Related Work

The existing solutions for interference mitigation include Inter-Cell Interference Coordination (ICIC) and eICIC [4]. These solutions employ frequency reuse and subframe muting to reduce interference in LTE networks. The offloading algorithm presented in [5] prioritizes the traffic with specific QoS requirement. The voice and video flows are sent through the cellular network while the elastic flows are sent through Wi-Fi. This approach ensures QoS of GBR flows, but it does not intend to maximize the utilization of network resources. In [6], to overcome poor availability and performance of the cellular network, the authors have used two key ideas viz., leveraging delay tolerance and fast switching from cellular to Wi-Fi to reduce the load on the cellular network. Initially, all flows are sent through Wi-Fi, if Wi-Fi is unable to transmit packets of a flow in a small time window (delay tolerance limit), then that flow is quickly switched to the cellular network. This solution focuses on maximizing the utilization of Wi-Fi, but it fails to maximize the overall system throughput.

In [7], the authors proposed an α-optimal scheduler in which scheduling across multiple RATs is formulated as an optimization problem. Steering the incoming traffic across different RATs viz., LTE and WLAN is done based on the value of α. For different values of α, the scheduler morphs its purpose as a proportional fair scheduler, maximum throughput scheduler, or maximize minimum rate scheduler. In [8], the authors proposed a ”water-filling” based interpretation for resource allocation across multiple RATs. The fraction of traffic sent over a RAT is proportional to the ratio of users peak capacity on that RAT and its throughput on the other RAT. The above mentioned schedulers enable efficient scheduling across both LTE and Wi-Fi simultaneously, but they do not aim to reduce interference in dense deployment scenarios.

To address the problems which exist with aforementioned works in the literature and to efficiently use the C-LWIP architecture, we propose a Power Aware Dynamic Traffic Steering (PRECISE) algorithm. The proposed PRECISE algorithm does efficient flow steering with intelligent power control to minimize interference and to ensure GBR requirements with improved system throughput.

III. Proposed Work

The PRECISE algorithm is designed with the following objectives: (i) Mitigation of co-tier interference in dense deployment of LWIP system, (ii) Meeting GBR requirements of the users including those experiencing poor SINR, and (iii) Dynamic steering of the flows across LTE and Wi-Fi links to maximize the system throughput. Algorithm 1 details the components and working of the PRECISE algorithm. Initially, the flow state information of all downlink flows is collected by a centralized decision making entity (for e.g., LWIP

Algorithm 1 Power awaRE dynamiC traffIc StEering

Input: Set of all flows in the system ($\mathcal{F}_i$), $i \in \{$flows 1,. . . ,k$\}$, SINR of UEs associated with C-LWIP node

for Every N ms **do**
  if $\mathcal{G}^s \geq 90\%$ **then** ▷ Trigger IM Phase
    $\Theta^{IM}(P_j^L, P_j^W)$
    Set Tx power obtained through optimization
  else ▷ Trigger GI Phase
    $\Theta^{GI}(P_j^L, P_j^W)$
    Set Tx power obtained through optimization
  end if
  $\mathcal{AI} \leftarrow$TOPSIS($\mathcal{F}_i$) ▷ Flow Steering
  if $\mathcal{L}^L > \mathcal{L}^W$ **then**
    if GBR flows unsatisfied **then**
      Steer set of unmet GBR flows (Φ_G) to Wi-Fi
    else
      Steer set of NGBR flows (Φ_{NG}) with high affinity index to Wi-Fi
    end if
  else
    if GBR flows unsatisfied **then**
      Steer set of unmet GBR flows (Φ_G) to LTE
    else
      Steer set of NGBR flows (Φ_{NG}) with high affinity index to LTE
    end if
  end if
end for

gateway). Note that this LWIP gateway assists only in regulating the transmit power of LWIP nodes. If requirements of GBR flows are met, then the algorithm aims to improve the system throughput by mitigating the co-interference by triggering Interference Mitigation (IM) phase. In this phase, optimal transmit power values are computed and set for LTE and Wi-Fi radios to reduce co-tier interference across interfering C-LWIP nodes. The IM phase is continued as long as QoS requirements of GBR flows are met. If GBR requirements of some of the flows are not met, then GBR Improvement (GI) phase is triggered in which the transmit powers of LTE and Wi-Fi interfaces of C-LWIP nodes are adjusted in order to meet the GBR requirements. $\mathcal{G}^s$ corresponds to percentage of GBR flows satisfied. Both IM and GI phases are followed by flow steering across LTE and Wi-Fi links in order to achieve their corresponding objectives. Flow steering involves ordering different flows based on their affinity to an interface. An i^{th} flow's affinity to an interface is given by its affinity index ($\mathcal{AI}_i$). If there exists unsatisfied GBR flows then a set of unmet GBR flows (Φ_G) are moved first to the lightly loaded interface of C-LWIP node. If GBR requirements are met, then a set of NGBR flows (Φ_{NG}) with high affinity are moved to the corresponding interface to maximize the throughput of the system. Φ_G is obtained by iteratively picking set of unmet GBR flows served in a heavily loaded link that can be accommodatable on the other link. How to accommodate a flow on a new link is discussed later in Section III-C. The power control function of PRECISE algorithm runs at LWIP gateway whereas the flow steering runs at C-LWIP node so that it can take independent and fast decision on steering of flows across LTE and Wi-Fi links.

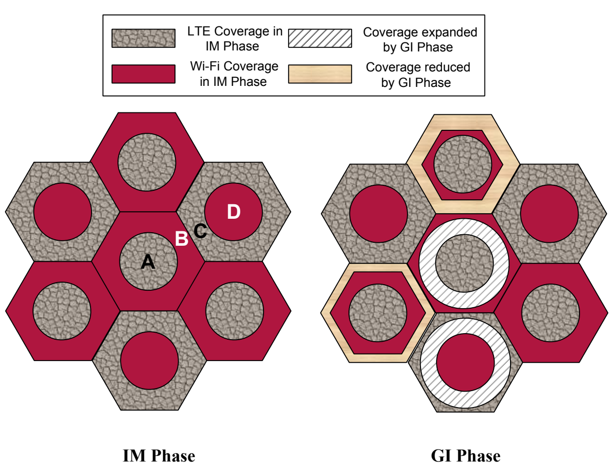

Fig. 2: Variation in coverage observed in different phases of PRECISE algorithm.

Figure 2 depicts the coverage pattern during IM and GI phases. It includes LTE operating on one licensed frequency band across all the cells and Wi-Fi using one unlicensed channel across all the cells. During IM phase, LTE and Wi-Fi coverages appear to cover the alternate cell edge regions in order to reduce co-tier interference (note that this figure is a closer approximation and it may vary based on user density and their positions in the network). In Figure 2, points 'A' and 'D' denote locations of two C-LWIP nodes where as 'B' and 'C' denote the regions of interest. When C-LWIP nodes at 'A' and 'D' transmit with same power, then the regions 'B' and 'C' suffer from high co-tier interference. IM phase is then triggered which reduces LTE co-tier interference in the regions 'B' and 'C' by reducing the transmit power of LTE in C-LWIP node 'A'. Similarly, Wi-Fi interference at regions 'B' and 'C' is reduced by reducing the Wi-Fi transmit power of C-LWIP node 'D'. During GI phase the edge of coverage region is either expanded or shrank based on the number of UEs with unmet GBR flows. Expansion or increase in transmit power on a link corresponds to improving bit rate for a UE with unmet GBR requirements. Reduction in coverage region corresponds to reducing interference for UEs associated with other C-LWIP nodes without degrading GBR guarantees of the current C-LWIP node.

A. Interference mitigation using orthogonal RATs (IM Phase)

We have formulated the interference mitigation sub-problem as a mixed integer non-linear programming (MINLP) problem with an objective of minimizing co-tier interference within a RAT. IM phase sets the optimal transmit powers to LTE and Wi-Fi interfaces of C-LWIP node. The SINR maximization of C-LWIP is formulated as follows.

$$Maxi.\ \Theta^{IM} = \sum_{i=1,j=1}^{U,B} \alpha_{i,j}^L \times SINR_i^L + \alpha_{i,j}^W \times SINR_i^W$$

s.t.

$$\sum_{j=1}^{B} \alpha_{i,j}^L \leq 1\ \forall i\ \ and\ \sum_{j=1}^{B} \alpha_{i,j}^W \leq 1\ \forall i$$

$$\alpha_{i,j}^L = \begin{cases} 1, & \text{if } SINR_i^L \geq Th_{LTE} \\ 0, & \text{otherwise} \end{cases}$$

$$\alpha_{i,j}^W = \begin{cases} 1, & \text{if } SINR_i^W \geq Th_{Wi-Fi} \\ 0, & \text{otherwise} \end{cases}$$

$$\alpha_{i,j}^L = \begin{cases} 0 \text{ or } 1, & \text{if } \alpha_{i,j}^W = 1 \\ 0, & \text{otherwise} \end{cases}$$

$$\alpha_{i,j}^W = \begin{cases} 0 \text{ or } 1, & \text{if } \alpha_{i,j}^L = 1 \\ 0, & \text{otherwise} \end{cases}$$

$$P_{min}^L \leq P_j^L \leq P_{max}^L;\ P_{min}^W \leq P_j^W \leq P_{max}^W$$

Θ^{IM} is the sum over LTE and Wi-Fi SINRs of users associated with LTE and Wi-Fi links of C-LWIP nodes. Here, P_j^L and P_j^W are the transmit powers of LTE and

Wi-Fi interfaces of j^{th} LWIP node, respectively. $\alpha_{i,j}^{L}$ is a binary variable which corresponds to association of i^{th} user with j^{th} C-LWIP node over LTE interface and $\alpha_{i,j}^{W}$ denotes the association of i^{th} user with j^{th} C-LWIP node over Wi-Fi interface. B and U denote the number of C-LWIP nodes and number of users in the system, respectively. This optimization problem (Θ^{IM}) can be solved using an MINLP solver.

B. GBR improvement using dynamic power control (GI Phase)

The objective of this sub-problem is to maximize the throughput of GBR flows. GI is formulated as an MINLP problem with an objective to improve the throughput for those UEs whose GBR requirements are not met. This can be achieved by maximizing the sum of weighted SINRs of those UEs.

$$Maximize\, \Theta^{GI} = \sum_{i=1,j=1}^{U,B} r_{i,j}^{L} \times SINR_i^L + r_{i,j}^{W} \times SINR_i^W$$

s.t.

$$\begin{cases} SINR_i^L - (\gamma \times \Theta(SINR_i^L)) \geq 0; \text{if } \Theta(SINR_i^L) \geq S_M \\ SINR_i^L - \Theta(SINR_i^L) \geq 0; otherwise \end{cases}$$

$$\begin{cases} SINR_i^W - \gamma \times \Theta(SINR_i^W) \geq 0; \text{if } \Theta(SINR_i^W) \geq S_M \\ SINR_i^W - \Theta(SINR_i^W) \geq 0; otherwise \end{cases}$$

$$P_{min}^L \leq P_j^L \leq P_{max}^L;\; P_{min}^W \leq P_j^W \leq P_{max}^L$$

Weight of UE depends on number of unmet GBR flows with that UE. The weight $r_{i,j}^{L}$ corresponds to fraction of unmet GBR flows of i^{th} UE associated with j^{th} C-LWIP node through LTE interface. $r_{i,j}^{L} = \frac{\vartheta_{i,j}}{\sum_i \vartheta_{i,j}}$, here $\vartheta_{i,j}$ corresponds to the number of unmet GBR flows of i^{th} UE associated with j^{th} C-LWIP node. $\Theta(SINR_i^L)$ and $\Theta(SINR_i^W)$ correspond to SINRs of LTE and Wi-Fi observed during the IM phase, respectively. γ denotes the tolerable fraction in reduction of SINR for the users who operate with the highest Modulation and Coding Scheme (MCS). S_M corresponds to the minimum SINR at which a UE gets the highest MCS.

C. Flow steering across LTE and Wi-Fi links

The PRECISE algorithm selects a flow to be steered from one interface to other using a multi-attribute decision making (MADM) technique called as Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) [9]. TOPSIS makes use of various decision making parameters (DMPs) from UEs such as LTE SINR, Wi-Fi SINR, and available bandwidths in LTE and Wi-Fi links. Link Aggregation Layer (LAL) of C-LWIP node gathers all these DMPs (refer Figure 1). TOPSIS chooses best suitable flow to be moved to an appropriate link based on these DMPs. The flow steering algorithm is executed once in every N ms.

Subroutine: TOPSIS for Ranking Flow Affinity

Input: Set of all flow ($\mathcal{F}_i$) parameters, Link to which flow affinity has to be obtained

1: Vector Normalization of all flow parameters $F_{i,j}$ where $i \in$ {flows 1,...,k}, $j \in$ {network parameters}
2: Apply given set of weights $w^T = \{w_1, \ldots, w_n\}$
3: $F_{i,j} \leftarrow F_{i,j} \times w_j$
4: Find A^+ (Positive ideal solution) and A^- (Negative ideal solution)
5: Find Positive ideal separation (S^+) and Negative Ideal separation (S^-)
6: Calculate C_i for each flow: $C_i \leftarrow \frac{Si^-}{Si^+ + Si^-}$
7: $\mathcal{AI} \leftarrow$ sort $\{C_i\}$ in descending order
8: Return the flow affinity index $\mathcal{AI}_i$ for every flow $\mathcal{F}_i$

TOPSIS: Subroutine TOPSIS [9] shows the procedure involved in prioritizing the flows. For every flow i, DMPs are obtained from the LAL of C-LWIP node. All these DMPs are normalized and appropriate decision making weights (w) are given to them. Following processing of DMPs, Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) are computed. PIS is a set of best values among all flows for each parameter while NIS is a set of worst values among all flows for each parameter. For example, PIS will contain the largest value in $SINR$ but the smallest value in packet error rate (PER). Relative Closeness (RC) is a metric which emphasizes how close a flow is to PIS or NIS. Affinity Index ($\mathcal{AI}_i$) of an i^{th} flow towards a specified interface is obtained by ranking them based on its RC. Flow with a large difference from NIS and less difference from PIS has high affinity for steering.

D. Obtaining Decision Making Parameters for TOPSIS

TOPSIS uses the following DMPs for decision making: load of LTE ($\mathcal{L}^L$), load of Wi-Fi ($\mathcal{L}^W$) and GBR_i requirements of i^{th} flow. Loads on both LTE and Wi-Fi links are calculated as follows:

$$\mathcal{L}^L = \frac{\sum_{i=1}^{N} uPRB_i}{tPRB \times N} \tag{1}$$

$$\mathcal{L}^W = \frac{\mathcal{BT}}{\mathcal{BT} + \mathcal{IT}} \tag{2}$$

Here, tPRB is the total number of physical resource blocks available in a Transmission Time Interval (TTI=1 ms in LTE). *uPRB* is the number of PRBs used for data transmission in a TTI. In Eqn (1), $\mathcal{L}^L$ is found as the ratio of total number of uPRB to the total number of available PRBs over N TTIs (we have set N=200 which corresponds to a Decision Making Interval - DMI). Eqn (2) is used to obtain load on Wi-Fi by estimating channel busy time over a total time of N ms. $\mathcal{BT}$ and $\mathcal{IT}$ correspond to busy and idle times of Wi-Fi channel, respectively.

In order to find that LTE can accommodate more flows, the cumulative throughput of all GBR flows is subtracted from the maximum achievable throughput. Available bandwidth in LTE ($\mathcal{A}^L$) can be obtained as follows.

$$\mathcal{A}^L = \mathcal{M}^L - \sum_{i=1}^{N} \mathcal{O}_i^L \tag{3}$$

Here, $\mathcal{M}^L$ denotes the maximum throughput that can be achieved by LTE under the given network conditions, given by $\mathcal{M}^L = BW \times log(1 + \Psi^L)$, where Ψ^L corresponds to average SINR of UE in LTE. $\mathcal{O}_i^L$ corresponds to the throughput observed by i^{th} user in LTE. Similarly, to estimate that Wi-Fi can accommodate more flows or not, current channel utilization by all GBR and NGBR flows (i.e., $\mathcal{L}^W$) is subtracted from the maximum channel utilization under the given network conditions.

$$\mathcal{A}^W = (\mathcal{MC}^W - \mathcal{L}^W) \times \mathcal{PD} \tag{4}$$

Here $\mathcal{MC}^W$ denotes the maximum channel utilization (network is fully loaded), $\mathcal{L}^W$ denotes the load on Wi-Fi and $\mathcal{PD}$ denotes the average physical layer data rate of Wi-Fi, which is given by,

$$\mathcal{PD} = BW \times log(1 + \Psi^W)$$

where Ψ^W corresponds to SINR of UE on Wi-Fi link.

IV. Simulation Setup and Performance Results

The performance of PRECISE algorithm is evaluated in a dense deployment scenario. We have compared the PRECISE algorithm with an existing Wi-Fi offload [6], [10], 3GPP Rel. 12 [11] and a state-of-the-art α-optimal scheduler [7] to observe its performance benefits. Wi-Fi offload algorithm prefers to use only Wi-Fi link whenever Wi-Fi is available and switches to LTE link on observing poor SINR in Wi-Fi. In 3GPP Rel. 12 solution, a UE associates with either LTE or Wi-Fi link of C-LWIP node. The UE prefers to associate with the link having higher SINR. The α-optimal scheduler associates a set of flows through LTE and Wi-Fi links based on throughput achieved by that UE in different RATs. When α=1, the scheduler does a proportionally fair split among the flows through LTE and Wi-Fi links. Figure 3 shows the simulation scenario where we have considered a building of dimensions 50 m $\times$ 50 m $\times$ 10 m having four C-LWIP nodes placed with a mean Euclidean distance between LWIP nodes as 20 meters. The positions of C-LWIP nodes in the building are shown in Figure 3. The building has two floors and a wall per every 10 meters. Path loss model includes wall and floor losses. For creating more challenging environment, we have considered LTE operating with reuse factor one and Wi-Fi operating in the same channel across all APs. The other important simulation parameters are shown in Table I. We have used Matlab based solver (*fmincon*) to solve the proposed MINLP problems.

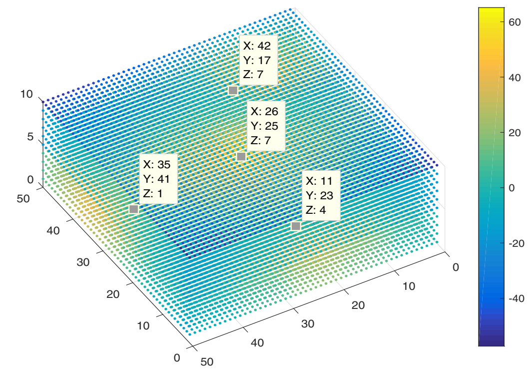

Fig. 3: SINR distribution 3D-map of the building chosen for conducting experiment with 4 C-LWIP nodes. The x,y, and z coordinates of C-LWIP nodes are also given in the map.

TABLE I: Simulation Parameters

Parameter	Value
# of UEs, LWIP Nodes	100, 4
Max Tx power of LTE & Wi-Fi	23, 20 dBm
LTE path loss model	3GPP indoor path loss model
Wi-Fi path loss model	ITU path loss model
LTE MAC Scheduler	Priority Set Scheduler (PSS)
UE position	Random
UE mobility model	Constant Position Mobility Model
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

A. SINR Distribution

The SINR distributions of UEs are observed in two cases (i) LWIP with fixed power (set to the maximum power) and (ii) LWIP power obtained from the PRECISE algorithm. Figure 4 shows CDF of SINR of UEs. It can be observed that PRECISE algorithm has improved SINR of UEs by 4 dB in both LTE and Wi-Fi links as compared to fixed power allocation. This improvement is achieved because PRECISE algorithm optimizes the transmit power of LTE and Wi-Fi links in order to reduce the co-tier interference across multiple LWIP nodes. This operation of PRECISE algorithm resembles fractional frequency reuse across different RATs.

B. Ensure GBR in the Network

PRECISE algorithm ensures data rate requirements of GBR flows and maximizes the throughput for NGBR flows thereby maximizing the entire network throughput. In this experiment UE traffic includes GBR and NGBR flows. GBR flows comprise of conversational voice (G.711) at 87.2 Kbps GBR, Video call (HD) at 1.2Mbps and Streaming Video at 1.2Mbps [12]. NGBR flows

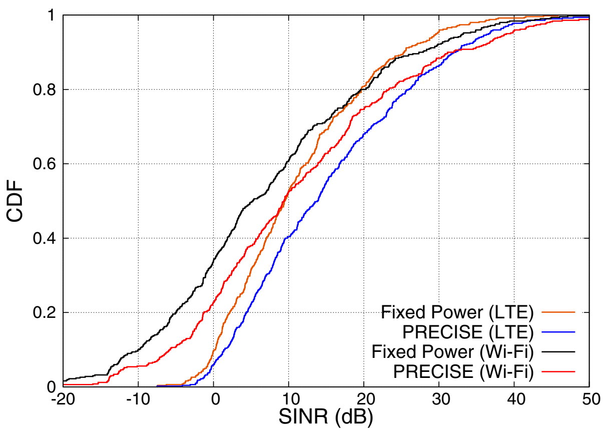

Fig. 4: CDF of UEs SINR.

include Sync apps and file downloads. Total number of downlink flows in the network at any instance follows Poisson distribution with mean varying from 300 to 8000 flows. Figure 5 is an instantaneous capture of throughput and number of unmet GBR flows. Data points are plotted for every 200 ms which corresponds to a DMI of PRECISE algorithm. The experiment is conducted for low, medium and high load conditions (load= 100, 300 and 600 flows), triggers are observed in all the cases. In case of load=100 flows, the number of GBR flows are low and they are satisfied. As the load increases, the number of unmet GBR flows increases. This triggers GI phase, which regulates the transmit power of LWIP nodes in order to reduce the number of unmet GBR flows. During GI phase the transmit power of LTE and Wi-Fi links are obtained by solving the optimization problem Θ^{GI}. In case of high load (load=600 flows), GI phase is triggered more than IM phase as the number of unmet GBR flows is very high.

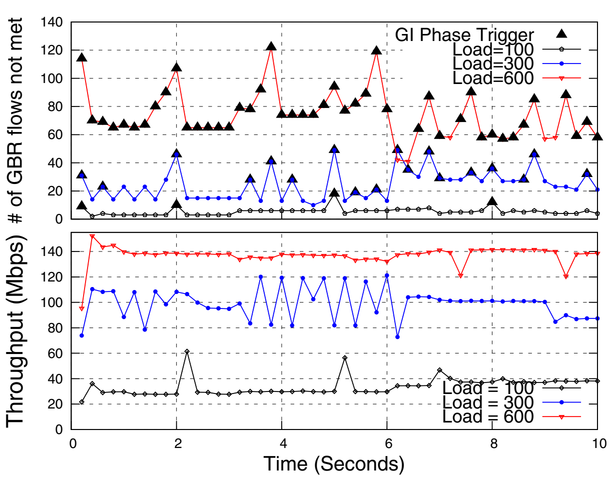

Fig. 5: Events triggered for varying load.

C. Different Phases of PRECISE Algorithm

To study different phases of PRECISE algorithm, we have conducted four different experiments. Across each experiment, the mean number of flows in LWIP network

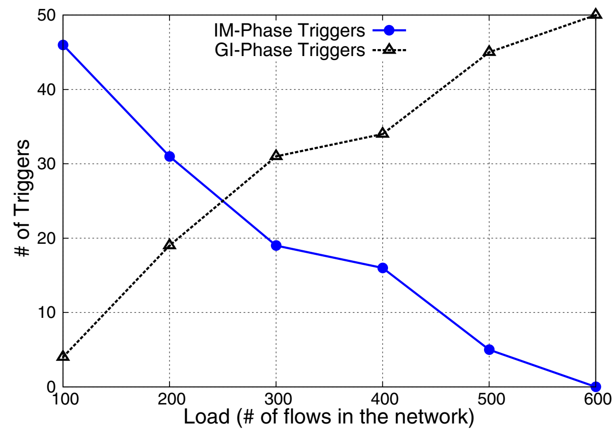

Fig. 6: Triggers for different threshold.

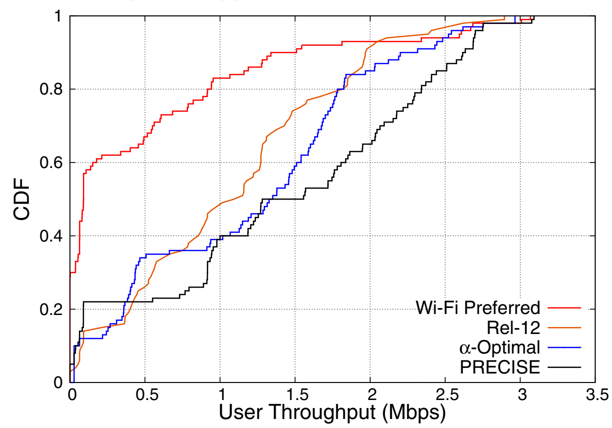

Fig. 7: CDF of UEs throughput.

is varied from 100 to 600. We have counted the number of IM triggers and GI triggers observed for different loads. Figure 6 shows the number of times IM and GI phases are triggered. As the load in the network (the number of flows) increases from 100 to 600, the number of GBR flows unsatisfied increases. In order to reduce the number of unmet GBR flows, GI phase is triggers accordingly.

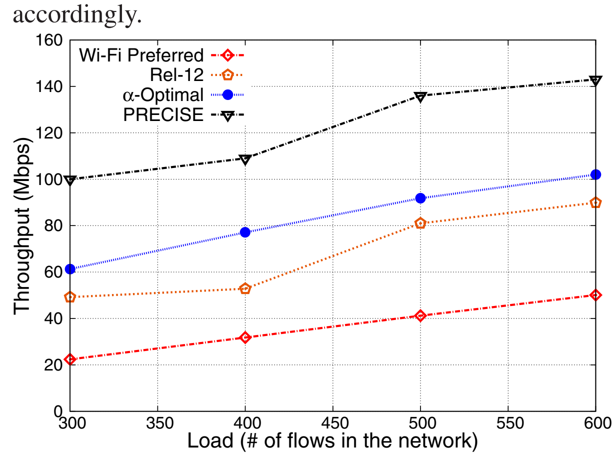

Fig. 8: Throughput for different load.

D. Throughput Analysis

Performances of different algorithms are compared with PRECISE algorithm. Figure 7 shows CDF of UEs throughput observed for a fixed load (load = 600 flows) when different algorithms are employed. In case of Wi-Fi preferred algorithm, UE throughput is low because a UE that is associated with LWIP node strictly confines to use Wi-Fi resource even when both LTE and Wi-Fi SINRs are high. The UE prefers to use LTE only when Wi-Fi SINR is lesser than a threshold which leads to inefficient resource utilization. Rel-12 allows the UE to choose and associate the flow to the link with better SINR. Hence the UE throughput has improved significantly compared to Wi-Fi preferred algorithm. α-optimal scheduler distributes the flows of a UE proportionally across LTE and Wi-Fi links based on the throughput achieved by that UE on each RAT (observed over each DMI). In the case of PRECISE algorithm not only the flow steering across LTE and Wi-Fi links are done, but also the efficient power regulation has lead to improved user throughput. Figure 8 shows the throughput achieved by varying the load, for different algorithms. As the load increases throughput of the network increases significantly in case of PRECISE compared to other algorithms because of efficient flow routing and power regulation. PRECISE algorithm has improved the network throughput by 48% as compared to the α-optimal scheduler. PRECISE algorithm has outperformed 3GPP Rel-12 based LTE Wi-Fi interworking by 84%. α-optimal thrives to maximize the throughput of all the UEs in the network hence it indulges in steering the flows with high data requirement on to the best interface. PRECISE algorithm also considers the type of traffic (GBR, NGBR) involved in order to maximize the GBR satisfaction in high load case. Figure 9 captures the fraction of unmet GBR flows in the network when different algorithms are employed. PRECISE algorithm minimizes the unmet GBR flows compared to other algorithms because of its ability to pick GBR flows first and steer to the best interface in order to satisfy their requirements. PRECISE algorithm has reduced the number of GBR flows unmet by 35% as compared to α-optimal scheduler.

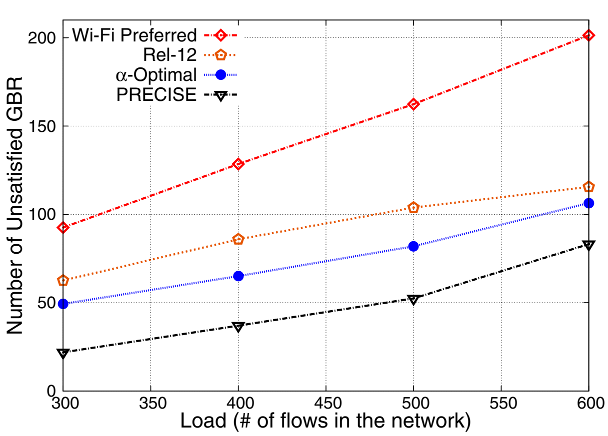

Fig. 9: Unsatisfied GBR.

V. Conclusions

The standardization of co-located LWIP has enabled sophisticated control over LTE and Wi-Fi RATs. We have proposed a downlink steering algorithm, PRECISE, with an objective to ensure QoS and to maximizing throughput in co-located LWIP deployment scenario. The PRECISE algorithm employs power control to reduce interference in dense deployment scenario and improves the performance of GBR flows. It also dynamic steers the flows across LTE and Wi-Fi links using MADM technique, which associates a flow through the most affine interface in order to improve the network throughput. The PRECISE algorithm has outperformed the throughput of state-of-the-art α-optimal scheduler by 48% and 3GPP Rel-12 LTE Wi-Fi interworking by 84%. PRECISE algorithm has reduced the number of unmet GBRs compared to other existing algorithms; notably it has reduced unmet GBR flows by 35% as compared to α-optimal scheduler. As a part of future work, the PRECISE algorithm can be further improved by considering traffic steering based on battery level of UEs.

VI. Acknowledgment

This work was supported by the project ”Converged Cloud Communication Technologies”, MeitY, Govt. of India. We thank Mukesh Kumar Giluka for his contribution in this work.

References

[1] Cisco. (2017) Visual Networking Index: Global Mobile Data Traffic Forecast Update. [Online]. Available: https://goo.gl/zY4nKI

[2] 3GPP, “LTE-WLAN Aggregation and RAN Controlled LTE-WLAN Interworking,” Tech. Rep. 36.300, 2016.

[3] S. Thomas *et al.*, “Architectural Challenges and Solutions for Collocated LWIP - A Network Layer Perspective,” in *2017 Twenty Third National Conference on Communication (NCC)*, March 2017, pp. 1–6.

[4] S. Deb *et al.*, “Algorithms for eICIC in LTE HetNets,” *IEEE/ACM Trans. on Net.*, vol. 22, no. 1, pp. 137–150, 2014.

[5] J.-H. Lee *et al.*, “Host-based distributed mobility management: Example of traffic offloading,” in *IEEE CCNC*, Jan 2013, pp. 637–640.

[6] K. Lee *et al.*, “Mobile Data Offloading: How Much Can Wi-Fi Deliver?” *IEEE/ACM Trans. on Net.*, vol. 21, no. 2, pp. 536–550, April 2013.

[7] S. Singh *et al.*, “Optimal traffic aggregation in multi-RAT heterogeneous wireless networks,” in *IEEE, ICC*, May 2016, pp. 626–631.

[8] ——, “Proportional Fair Traffic Splitting and Aggregation in Heterogeneous Wireless Networks,” *IEEE Communications Letters*, vol. 20, no. 5, pp. 1010–1013, May 2016.

[9] Y.-J. Lai, T.-Y. Liu, and C.-L. Hwang, “Topsis for MADM,” *European Journal of Operational Research*, vol. 76, no. 3, pp. 486–500, 1994.

[10] 5GAmericas. (2015, Nov) Whitepaper on LTE Aggregation and Unlicensed spectrum. [Online]. Available: http://goo.gl/4yHPhH

[11] 3GPP, “LTE/WLAN Radio Interworking,” Tech. Rep. 37.834, 2013.

[12] Skype. (2017) How much bandwidth does Skype need? [Online]. Available: https://goo.gl/KYCZ5V