Aggregating LTE and Wi-Fi: Fairness and Split-Scheduling

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***Abstract*—People are seeking solutions in diverse directions to cope with mobile data explosion and resource scarcity in mobile cellular networks. Of many candidate approaches, smart aggregation of LTE and Wi-Fi radios is a promising solution that bonds heterogeneous links to meet a mobile terminal's available bandwidth need. Motivated by the existence of a significant number of carrier-operated Wi-Fi APs, we propose a mechanism, called LTE-W, of efficiently utilizing LTE and Wi-Fi links only with the minimum changes of eNodeBs, LTE backhaul networks, and mobile terminals. Our mechanism has the following two key components: (i) mode selection and (ii) bearer-split scheduling. In the mode selection, LTE-W internally decides who should be served by either of LTE or LTE-Wi-Fi aggregation considering intra-cell fairness rather than just following users' intention of aggregation. For the users decided to be offered the aggregation service, we choose a bearer (roughly defined a set of flows with a similar QoS in LTE) as a basic unit of aggregation and propose a smart intra-bearer scheduling algorithm that splits a bearer's traffic into LTE and Wi-Fi links, considering the tuning of TCP flows that take two heterogeneous wireless links. We evaluate our mechanism using the NS-3 with LENA, and compare it to a transport-level aggregation mechanism, MPTCP, demonstrating that LTE-W significantly improves MPTCP, e.g., up to 75% in terms of Jain's fairness index.**

I. Introduction

To cope with mobile data explosion [1], one of the promising solutions from the perspective of mobile network operators (MNOs) is to intelligently utilize multiple access radios in an aggregated manner. The idea is that when there does not exist a single radio access technology (RAT) that offers sufficient bandwidth to meet an application's requirement (e.g., users at the cell edge), two or more RATs are merged so that the application is able to experience a scaled-up capacity [2], [3]. In fact, it is expected to be the key ingredient of the next-generation 5G wireless to efficiently use heterogeneous wireless networks in an integrated manner [4]. Two candidate RATs to aggregate are LTE and Wi-Fi, due to their popularity in the state-of-the-art mobile devices, which is also the focus of this paper.

There exists an extensive array of research and development efforts both in the research and commercial domains, where a variety of approaches are taken at different layers (see the related work in Section II) and their unique pros and cons exist. A lot of research efforts on opportunistically using Wi-Fi APs mostly for delay-tolerant applications have been made in the name of Wi-Fi offloading, e.g., [5], [6]. Other notable examples to aggregate LTE and Wi-Fi, rather than opportunistically using one of them, include MPTCP (Multi Path TCP) at the transport layer [7]–[9]. This paper is motivated by the fact that a significant portion of Wi-Fi APs are being deployed by MNOs[1], referred to as MNO-operated Wi-Fi, enabling many mobile users to be under the coverage of both LTE and Wi-Fi. This may provide more opportunities to MNOs to tightly optimize the aggregation of LTE and Wi-Fi links at the link-level for higher efficiency, but without much change of the current LTE architecture.

We summarize our contributions in what follows:

(a) Fairness, split-scheduling, and TCP: Unconditionally providing the aggregation service to all aggregation-requested users may lead to serious unfairness, hurting the system-level QoS and suboptimally utilizing the system resource. For example, the aggregation service would be much more beneficial to the users at the cell edges than the users close to an eNodeB. Also, in splitting the packets inside a bearer (which is the basic unit of aggregation, as discussed later) served by two highly heterogeneous links, LTE and Wi-Fi, we need to consider the compatibility of such splitting mechanism with TCP, since TCP's protocol features are highly sensitive to out-of-order packets and other incoming packet stream patterns. In this paper, we take a time-scale separation approach that we first decide a *mode* of a bearer (i.e., either of LTE-only or LTW-W mode), whenever a new bearer is created, using the solution of an utility maximization problem that formulate the (intra-cell) fairness. We prove that our proposed mode selection algorithm outputs the optimal solution. This intra-cell fairness provisioning is the major gain coming from a link-level aggregation, forming the key difference from MPTCP. In MPTCP, LTE and Wi-Fi subflows would achieve the throughputs depending on available path-bandwidths (a LTE path and another Wi-Fi path), often ignoring intra-cell fairness (see Section IV). Once the modes of all bearers are decided, eNodeB then performs split-scheduling that strips the incoming packets of a LTE-W bearer into two links, so that TCP flows inside the bearer experience good throughput. This "infrequent" decision of a bearer mode allows our design to separately focus on the fairness and TCP performance, thereby leading to a simple, yet efficient design of a link-

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[1]For example, KT, which is one of the biggest three MNOs in South Korea, have already about 200 million APs [10].

level aggregation service.

(b) Architecture design: We propose an architectural design, called *LTE-W,* that aims at achieving the key features mentioned above, as depicted in Fig. 1. The key direction of our design is to achieve our goal with the minimum change of the current LTE implementation, e.g., a simple software upgrade. To that end, we use a bearer (a group of flows with a similar QoS defined in LTE [11]) as a basic aggregation unit in order to minimize the eNodeB modification [12], [13] as well as avoid high complexity per-flow based processing. In LTE, the PDCP layer is responsible for handling bearers, and thus our bearer split-scheduling is also proposed to be implemented at the PDCP layer. We also propose a modification of Wi-Fi AP MAC architecture (that are MNO-operated) to employ per-bearer queueing (i.e., separate queues for LTE-W bearers, and also possible by a simple software upgrade), so that the bearer-splitting function at eNodeB is operated in a more predictable manner. This per-bearer queueing enables the system to provide the predictable Wi-Fi throughput, which is importantly used in our mode selection decision module, as well as to sustain more stable behavior of TCP flows than that with only FIFO queueing.

(c) NS-3 LENA implementation and evaluation: We implement our LTE-W design based on extending NS-3 LENA, which is publicly available in [14], [15]. We compare the performance of LTE-W with MPTCP under various scenarios. Our evaluations show that TCP flows inside a LTE-W bearer achieve stable throughputs, and more importantly, LTE-W outperforms MPTCP in terms of the system-wide Jain's fairness index by 75%, and verify that our proposed bearer split mechanism achieves high link utilization.

II. Related Work

One of smartly exploiting LTE and Wi-Fi links is to adaptively select one of those, being categorized into network-driven [16]–[19] and user-driven [2], [3] approaches. For example, the issue of deciding who should use which interface mode is formulated by an NP-hard optimization problem, where a greedy-like algorithm [18] or a low-complexity distributed algorithm [19] is proposed. As an array of closely related work to this paper, there exist various proposals on aggregating LTE and Wi-Fi links. In the International Telecommunication Union's (ITU) Plenipotentiary Conference 2014 in Busan, Samsung demonstrated Download Booster on Galaxy S5 as a bandwidth aggregation in the application layer and SK shows a demonstration of the commercial deployment of Multipath TCP (MPTCP) [7]–[9]. MPTCP utilizes multiple physical *paths* simultaneously to improve throughput and resilience, but lacking in providing the intra-cell fairness (see Section IV for details). In 2015 Mobile World Congress at Barcelona, KT demonstrates the LTE-H (LTE-HetNet) using Samsung's LTE base station and Wi-Fi AP, and Qualcomm's modem chip for mobile devices based on LTE PDCP layer bandwidth aggregation.

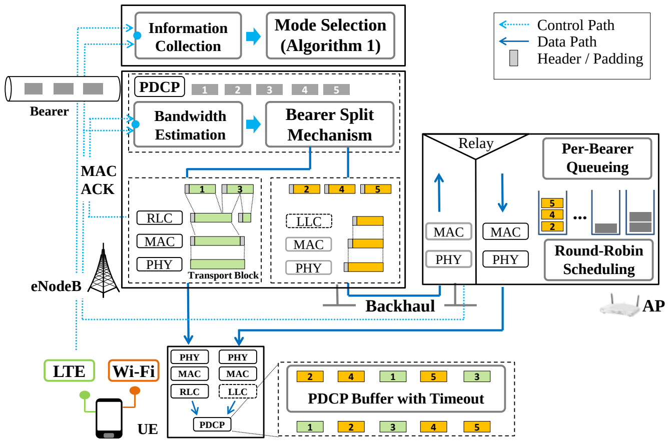


Fig. 1: LTE-W Architecture Overview

III. LTE-W Design

A. LTE Background

Bearer. A bearer, which is a unit of traffic management, is a tunnel connection between User Equipment (UE) and Packet-data-network GateWay (PGW), where multiple flows are grouped in a bearer based on the degree of QoS provided by the Policy and Charging Rules Function (PCRF) [11]. Throughout the initial certification processes, the default bearer is established. When a UE requests a service which requires higher Quality of Service (QoS), then a dedicated bearer is established on demand. Depending on the QoS, each dedicated bearer is classified as a Guaranteed Bit Rate (GBR) bearer and a Non-GBR bearer. In this paper, we support LTE-W services only for Non-GBR bearers to support a kind of buffered data services except for a default bearer, and GBR bearers for fixed bit rate applications (e.g., VoIP) or streaming is not supported by LTE-W.

LTE user plane protocol stack. User plane protocol stack in LTE has four commonly related layers in eNodeB and UE: Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC), and PHY. PDCP is responsible mainly for IP header compression and ciphering, and supports lossless mobility in case of inter-eNodeB handovers and provides integrity protection to higher layer control protocols. RLC supports data segmentation and concatenation to fit the size required by the MAC (mostly transport block size), and performs Automatic Repeat reQuest (ARQ). Indeed, RLC has three modes for data transmission: Transparent Mode (TM), Unacknowledged Mode (UM), and Acknowledged Mode (AM). The main functions of MAC are Hybrid-ARQ (HARQ) and reporting of scheduling information. We refer the readers to [20], [21] for more details.

B. LTE-W operation overview

Modes. We consider a scenario that a UE, who are under the coverage of both LTE and Wi-Fi, has three options to choose in her smartphone as follows: **M1.** Wi-Fi only, **M2.** LTE-only, and **M3.** LTE-W. Both **M1** and **M2** are the modes that are available at smart devices in the current market. The mode **M3** are added due to our LTE-W service. From the perspective of a LTE-W service provider, the major target to be considered is **M2** and **M3**, where the UEs choosing **M1** are treated as exogenous ones. Note that we consider the case where, even if a UE chooses the LTE-W mode, she is *not* guaranteed to be served by both LTE and Wi-Fi, which is determined by the operator. The operator decides this based on the result coming from its mode selection module (see Section III-C).

Operating procedures. We now describe a summary of LTE-W operation procedures, using the architecture overview in Fig. 1. As an initial procedure, an eNodeB manages the basic information on the UEs and the MNO-operated APs under its cell coverage (e.g., MAC/IP addresses and SSID, etc).

(a) *UE's choice of mode:* Whenever each UE expresses and often changes her choice out of three possible modes, it is reported to the eNodeB, and the RRC layer of the eNodeB records the *bearer-information,* such as the mode preference, bearer ID, LTE and Wi-Fi throughputs (that are estimated when each UE will be connected). See Section III-C for how to estimate LTE and W-Fi throughputs.

(b) *Mode selection and bearer split-scheduling:* Using the bearer-information, the eNodeB performs mode selection in RRC layer and bear split-scheduling in PDCP layer. Note that there exist a variety of ways of where to perform mode selection, e.g., MME (Mobility Management Entity) or some centralized server in the managed LTE infrastructure [4]. The role of bearer split-scheduling is to strip the incoming PDCP PDUs in a LTE-W bearer over directly LTE link or Wi-Fi link (by forwarding the PDUs to the AP that serves the corresponding UE).

In the rest of this section, we describe two key components of LTE-W, (i) mode selection in Section III-C and (ii) bearer split-scheduling in Section III-D. We assume that each eNodeB and AP is connected by a high-speed backhaul link, which holds for most of MNOs' infrastructure.

C. Mode Selection

Formulation. We now describe our mode selection algorithm, called **ModeSel**, which runs whenever a new bearer is created. For ease of exposition, we consider a system as presented next when a new bearer is created: In a cell there exist m Wi-Fi APs and one eNodeB, and let M and N be sets of Wi-Fi APs and UEs. Let J be the maximum number of bearers that a UE can open[2]. We use the notation (i, j) be the j-th bearer of UE i. We abuse the notation to mean that M, N, and J are the sets of the corresponding items. Let $(b_{ij} : i \in N, j \in J)$ be the 0-1 matrix, where $b_{ij} = 1$ when the bearer j is opened at UE i, and 0 otherwise. Suppose that each UE i expresses her preference of LTE-W, denoted by p_i, where $p_i = 1$ (resp. $p_i = 0$) when she chooses LTE-W (resp. LTE-only), and let $\boldsymbol{p} = (p_i : i \in N)$. Then, given $\boldsymbol{p}$, the entire bearers can be expressed as a union of two disjoint sets $B_0 = \{(i, j) \mid p_i = 0, b_{ij} = 1\}$ and $B_1 = \{(i, j) \mid p_i = 1, b_{ij} = 1\}$, i.e., B_1 is the set of all bearers that are *eligible* to be served by both LTE and Wi-Fi, and B_0 is the set of all bearers that are excluded from the LTE-W aggregation service.

[2]In LTE-A, $J = 8$ [22].

Let $\boldsymbol{x} := (x_i^k : i \in N, k \in M)$ be the physical association vector of UEs, where $x_i^k = 1$ when UE i is associated with AP $k \in M$. We specially use the superscript 0 to refer to eNodeB, so $x_i^0 = 1$ when associated with LTE. We assume that each UE is always associated with the eNodeB, but may not have Wi-Fi connection. Thus, it is clear that $1 \le \sum_{k=0}^m x_i^k \le 2$ for all $i \in N$. Let $(L_{ij} : i \in N, j \in J)$ and $(W_{ij} : i \in N, j \in J)$ be the given vectors of the throughputs of LTE and Wi-Fi links of each bearer (i, j) when it is served by purely either of LTE and Wi-Fi under the considered setup, where $L_{ij} = 0$ (resp. $W_{ij} = 0$) when $b_{ij} = 0$ (resp. $b_{ij} = 0$ or $x_i^k = 0$ for all $k \in M$).

We consider the following optimization problem that solves the following:

$$\textbf{OPT:} \quad \max \sum_{i,j} U(\gamma_{ij}), \tag{1}$$

$$\text{subject to} \quad \lambda_{ij} \in \{0, 1\}, \quad \forall i \in N,\ \forall j \in J, \tag{2}$$

$$\lambda_{ij} = 0 \quad \forall j \in J, \text{ if } p_i = 0, \tag{3}$$

$$\gamma_{ij} = \begin{cases} L_{ij} & \text{if } (i, j) \in B_0, \\ L_{ij} + \lambda_{ij} \cdot W_{ij} & \text{if } (i, j) \in B_1, \end{cases} \tag{4}$$

$$\text{given} \quad L_{ij}, W_{ij},\ \forall i \in N,\ \forall j \in J, \quad \boldsymbol{p} \tag{5}$$

where $U(\cdot)$ is a utility function that satisfies the standard conditions in literature, i.e., concavity, differentiability, and monotonicity. One can consider the famous $\alpha-$fair utility function [23]: $U(\gamma_{ij}) = \gamma_{ij}^{1-\alpha}/(1 - \alpha)$ for $\alpha \ne 1, 0 \le \alpha$, and $U(\gamma_{ij}) = \log(\gamma_{ij})$ for $\alpha = 1$. The $\alpha-$fair utility function is related to the well-known fairness, such as proportional fairness ($\alpha = 1$), and max-min fairness ($\alpha \to \infty$). The variable $\lambda_{ij} \in \{0, 1\}$ represents whether the bearer (i, j) is served by both LTE and Wi-Fi ($\lambda_{ij} = 1$) or not ($\lambda_{ij} = 0$). The constraint (3) means that LTE-W service is not provided to the UE that does not want it. In the constraint (4), γ_{ij} corresponds to the actual throughput of the bearer (i, j) after who gets the LTE-W service is decided.

Optimal algorithm and analysis. To develop an algorithm that solves **OPT**, we first decompose it from the perspective of each Wi-Fi AP k, for which we let B_1^k be the set of all bearers of UE (choosing the LTE-W service) that are associated with AP $k \in M$, i.e., $B_1^k = \{(i, j) \mid p_i = 1, b_{ij} = 1, x_i^k = 1\}$. **OPT** can be decomposed into the following:

$$\begin{aligned} &\max \sum_{i,j} U(\gamma_{ij}) \\ &= \max \left[\sum_{(i,j)\in B_0} U(\gamma_{ij}) + \sum_{(i,j)\in B_1} U(\gamma_{ij}) \right] \\ &= \sum_{(i,j)\in B_0} U(\gamma_{ij}) + \sum_{k\in M} \left[\max \sum_{(i,j)\in B_1^k} U(\gamma_{ij}) \right]. \end{aligned} \tag{6}$$

From this decomposition, to solve **OPT**, it suffices that each AP k finds the optimal λ_{ij} for its associating UEs.

We now describe our algorithm, which we call **ModeSel**,

Algorithm 1: ModeSel

1: **INPUT**
U : Utility function,
$\boldsymbol{p} = (p_i : i \in N)$ LTE-W preference vector,
$(C^k : k \in M)$: capacity of AP k,
$(L_{ij} : i \in N, j \in J)$: Bearer LTE throughput,
2: **OUTPUT** $\boldsymbol{\Lambda} = (\lambda_{ij} : i \in N, j \in J)$

3: **Initialization:** $\boldsymbol{\Lambda} = \boldsymbol{0}$
4: **for** AP $k \in M$ **do**
5: Sort the bearers $(i, j) \in B_1^k$ in ascending order of L_{ij}.
6: **for** $n \in [1 : |B_1^k|]$ **do**
7: Select n bearers in B_1^k at the front of the sorted set.
8: $U_n = \sum_{\text{selected } n \text{ bearers}} U(L_{ij} + \Delta(n, C^k))$
9: **end for**
10: $n^\star = \text{argmax}_n U_n$
11: Set $\lambda_{ij} = 1$ for the bearers (i, j) that achieves $n^\star$
11: **end for**

in **Algorithm 1**.

In **ModeSel**, based on the decomposition in (6), for each AP k, we select which UE should be served by LTE-W. In Lines 4-5, for each AP k, the LTE throughputs of UEs associated with AP k are sorted in ascending order. For each n with $1 \leq n \leq |B_1^k|$, we select n bearers that has smallest LTE throughputs (Line 7), and calculate the total utility U_n of the sum of LTE throughputs and Wi-Fi throughputs, denoted by $\Delta(n, C^k)$, if the selected n bearers are also served over Wi-Fi (Line 8), we choose $n^\star$ that maximizes U_n. Finally, we decide to serve the bearers (i, j) that outputs $n^\star$ (Line 10). **ModeSel** has the worst-case $O(MJ^2N^2)$ time complexity, because B_1^k has the maximum size NJ, where recall that J is the maximum number of bearers, $JN \log JN$ is the complexity for sorting.

Per-bearer queueing. The term $\Delta(n, C^k)$, which corresponds to the Wi-Fi throughput for each bearer if n bearers are served by an AP, depends on the designer of LTE-W, in particular, in relation to how to treat LTE-W bearers in Wi-Fi AP. In our design, we propose the rule, called *per-bearer queueing* that each bearer with the LTE-W service is assigned a separate queue and all other normal flows are served in a FIFO queue. Thus, under this per-bearer queueing,

$$\Delta(n, C^k) \quad = \quad \frac{C^k}{n+1}. \tag{7}$$

We believe that this queueing policy is plausible, because Wi-Fi APs in this paper are operated by MNOs, and they try to maximize their revenue to provide a better QoS to the LTE-subscribing users who make monthly payment. It is typical that Wi-Fi services provided by a MNO are additional, often used just to obtain more market share in the competition with other MNOs. This per-bearer queueing is also beneficial in the bearer split-scheduling in Section III-D, contributing to predictable throughput estimation, as demonstrated in Section IV.

LTE throughput measurement: In practice, it is reported that over 70% of bearers contains only one TCP flow, and almost 50% of flows are shorter than 5.0 sec [24]. As we consider the patterns of mobile phone users, a flow is persistently transmitted in bearer for long time including only one flow. Thus, in our mechanism, we estimate the LTE throughput in a fixed time less than 5.0 sec (in simulation we consider 3.0 sec). These measured LTE throughputs for each bearer used as L_{ij} in **ModeSel**.

Optimality analysis. **OPT** is an integer program, which is in many cases NP-hard. However, as stated in Theorem 1, **OPT** outputs an optimal solution in polynomial time.

Theorem 1. *Under the per-bearer queueing policy at APs,* **ModeSel** *outputs an optimal solution of* **OPT**.

Proof. Since $(L_{ij} : i \in N, j \in J)$ is given and APs are not coupled (due to our assumption that each UE is associated with one AP), it is sufficient to solve the following per-AP optimization:

$$\textbf{Per-AP OPT:} \qquad \max \sum_{(i,j) \in B_1^k} U(\gamma_{ij}).$$

In this proof, we assume that we focus on an arbitrary AP k. We will prove that U_{n^*} is larger than or equal to the total utility for any other combinations of UEs in B_1^k, for which for any given n, we will prove that the total utility for the n smallest LTE throughput bearers exceeds that for any n selection of bearers.

For a given n, let $G_n = \{g_1, g_2, \ldots, g_n\}$ be the set of LTE throughputs of n-smallest bearers, and consider an arbitrary set $S_n = \{s_1, s_2, \ldots, s_n\}$ of n LTE throughputs of any n bearers. Without loss of generality, $g_i \leq g_j$ and $s_i \leq s_j$ for all $i < j \leq n$. Let $A = G_n \cap S_n$, and $|A| = a$, where let

$$G'_n = G_n \setminus A = \{g'_1, g'_2, \cdots, g'_{n-a}\},$$
$$S'_n = S_n \setminus A = \{s'_1, s'_2, \cdots, s'_{n-a}\},$$

Due to the convexity of $U(\cdot)$, it is easy to check that for any $1 \leq j \leq n - a$,

$$\Big(U(g'_j + \Delta(n, C^k)) - U(g'_j)\Big) - \Big(U(s'_j + \Delta(n, C^k)) - U(s'_j)\Big) \geq 0, \tag{8}$$

where $\Delta(n, C^k)$ is defined in (7). Then, the total utilities of G_n and S_n when served by LTE-W service are compared by:

$$\begin{aligned} &T(A, n) + T(S', n) + \sum_{i=1}^{n-a} U(g'_i) \\ &\leq T(A, n) + T(S', n) + \sum_{i=1}^{n-a} U(g'_i) \\ &+ \sum_{i=1}^{n-a} \Big[(U(g'_i + \Delta(n, C^k)) - U(g'_i)) - (U(s'_i + \Delta(n, C^k)) \\ &- U(s'_i)) \Big] \quad = \quad T(A, n) + T(G', n) + \sum_{i=1}^{n-a} U(s'_i), \end{aligned}$$

where $T(S', n) = \sum_{i=1}^{n-a} U(s'_i + \Delta(n, C^k))$, and similarly

$T(G', n)$. Therefore, the total utility of G_n is larger than that of S_n for a fixed number of queues $1 \leq n \leq |B_1|$. This completes the proof. □

D. Bearer Split-Scheduling

Key issues and challenges. We first discuss the key issues and challenges when we design a scheduling algorithm that splits the packets of a LTE-W bearer.

- *TCP throughput:* Suppose that a scheduler knows the per-bearer throughputs for LTE and Wi-Fi links a priori, say x_L and x_W, respectively, and consider a simple packet-reception rate based transport protocol, e.g., UDP. Then, a split-scheduling that splits the incoming packets to eNodeB as a ratio of x_L and x_W is enough. The challenge comes from the fact that most of Internet applications use TCP which has very complex protocol behaviors. In particular, TCP is highly sensitive to out-of-order packets, which may result in retransmission timeouts, leading to a large collapse of Congestion Window (CWND) and thus very low throughput. A vanilla approach to completely remove packet ordering is to per-flow link scheduling, i.e., directing a TCP flow inside a bearer to a single link, LTE or Wi-Fi. However, this scheduling is clearly undesirable, due to its low link utilization as well as the cost of per-flow processing in eNodeB. Thus, it is necessary to devise a split-scheduling algorithm that minimizes out-of-order packets as well as maximizes link utilization.
- *Tracking network variations:* Another issue is that even x_L and x_W are the values that may be hard to be stably given, since the network and channel conditions are highly time-varying and they also significantly depend on the underlying MAC layer behaviors. For example, MAC-layer scheduling in eNobeB achieving some fairness is highly vendor-specific. Thus, there is a need of efficiently estimating x_L and x_W with a low-cost mechanism.

Our design: In our design, we employ a delay-based split-scheduling based on a smart measurement-based bandwidth estimation. We also augment our design by installing a resequencing buffer at the UE PDCP layer to compensate for the imperfect handling of our delay-based split-scheduling and bandwidth estimation. We now elaborate each components next.

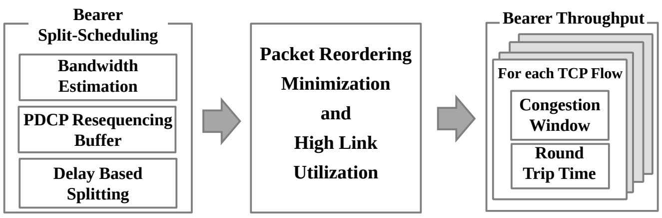


Fig. 2: Overview of bearer split-scheduling

Split-scheduling algorithm: Delay-based. We propose a split-scheduling that is based on the delay estimation of two links, LTE and Wi-Fi. The basic idea is simple: for an incoming PDCP PDU, we schedule it at the link having a smaller delay, where the term "delay" corresponds to the time from when the eNodeB transmits a packet at PDCP layer to when a UE receives it at its PDCP layer. Split-scheduling utilizes the estimated available bandwidth of a given link. We first describe the bearer split-scheduling algorithm, called **BSplit**, in **Algorithm 2**.

Algorithm 2: BSplit

INPUT For $i \in \{L, W\}$,
  B_i : Link i estimated available bandwidth,
  S_i : Total number of unacked PDUs over link i,
  C_i : Additional delay of link i.

for each incoming PDCP PDU p **do**
  Compute D_i for each link i as follows:
  $D_i = (S_i + \text{size}(\mathrm{p}))/B_i + C_i$.
  $i^\star = \text{argmin}_{i \in \{L,W\}} D_i$.
  $S_{i^\star} = S_{i^\star} + \text{size}(\mathrm{p})$.
  Schedule p to link $i^\star$.
end for

For each incoming PDCP PDU p, let $\hat{D}_i$ be the delay we are interested in, which can be approximated by:

$$\hat{D}_i \approx D_i = (S_i + \text{size}(\mathrm{p}))/B_i + C_i,$$

where C_i is the delay for processing and propagation, and B_i is the estimated available bandwidth (whose detail will be discussed shortly), and $S_i + \text{size}(\mathrm{p})$ is the amount of queued bytes over link i. In **BSplit**, the incoming PDCP PDU is scheduled at a link that shows smaller D_i. To measure S_i, we employ a method of counting unAcked Packet Data Units (PDUs) at the PDCP layer[3], which corresponds to the total size of PDUs in the intermediate queues (i.e., eNodeB RLC queue or AP MAC queue), packets on-the-fly, and the packets in the resequencing buffer (see the discussion later). This design is based on the fact that queueing and transmission delays are inversely proportional to a link available bandwidth, and although we consider C_i, it is typical that the processing and propagation delays are an order-of-magnitude smaller than queueing delay [24]. Since our split-scheduling **Bsplit** schedules the incoming PDCP PDU based on delay, out-of-order packets can be significantly reduced, which holds as long as the estimated available bandwidth becomes correct.

Link utilization. Recall that, as mentioned earlier, a splitting algorithm may be successful at minimizing out-of order packets at the high cost of link utilization. There exists a tradeoff between high link utilization and the degree of packet out-of-ordering, which is more serious when more heterogeneity for C_i appears. However, in practice, C_i is negligible compared to the delay due to the packets in the pipe as well as in the queue. Then, we can easily check that

$$\triangle S_L : \triangle S_W = B_L : B_W,$$

where $\triangle S_i$ denotes the the increament of pumped-in unAcked PDUs on link i, i.e., the transmission ratio is the same as

[3]The LTE standard requires an ack for each PDCP PDU.

the bandwidth ratio, as demonstrated in our microbenchmark result Fig. 3, where the available bandwidths for LTE and Wi-Fi are set to be 6Mbps and 4Mbps, respectively. We observe that link utilization is almost 1, and also **BSplit** achieves the sending rates for two links with the same ratio of available throughputs even over short time-scales.

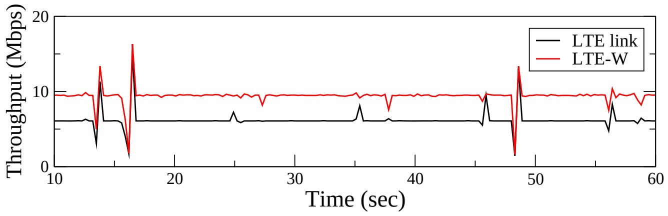


Fig. 3: Instantaneous throughput of total LTE-W and LTE link

Measurement-based bandwidth estimation. To run **BSplit**, it remains to get the information of B_i, where our goal is to track time-varying B_i well. The possible fluctuation of B_i is due to time-varying channel conditions as well as TCP's protocol features such as ack clocking and window-based flow control. In our design, we employ a measurement based method as explained in the following steps:

S1. The eNodeB records the information of each n^{th} PDCP PDU of each bearer and sends it directly through LTE or Wi-Fi.

S2. For a received packet on UE, LTE RLC layer ack or Wi-Fi MAC layer ack are generated and sent back to the eNodeB or the associating AP.

S3. The eNodeB PDCP layer collects these acks coming from either of RLC acks in LTE or Wi-Fi MAC, and then records the D_i^n, and decrements the S_i^n by the number of perfectly acked or dropped PDUs.

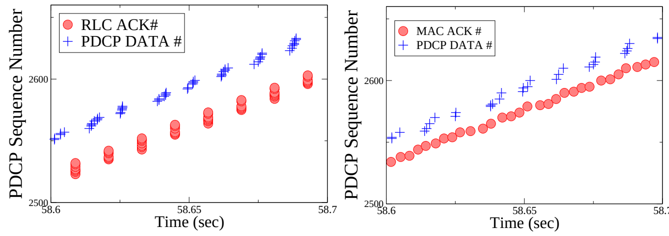
S4. Finally, the estimated B_i is computed by, using two n^{th} and m^{th} PDCP PDUs as follows:

$$B_i = \frac{S_i^m - S_i^n}{D_i^m - D_i^n},$$

where B_i is updated with its exponential moving average, and we choose a different policy of choosing m and n for LTE and Wi-Fi due to the difference in acking the packets in both links.

As demonstrated in Fig. 4, LTE RLC Acknowledged Mode provides concatenation and segmentation thus sends acks in a cumulative manner, but Wi-Fi MAC ack is transmitted whenever there exists a successful data transmission. Thus, in choosing m and n, for estimating B_L in LTE, we use the last ack of simultaneously received acks, including relatively short time in a queue, but for estimating B_W in Wi-Fi, we simply use adjacent acks such as $m = n + 1$.

Further tuning: PDCP resequencing buffer. Despite our design of **Bsplit** that aims at minimizing the number of out-of-order packets, due to the random features of wireless channels and highly dynamic external flows in Wi-Fi and possible imperfectness in estimating the available bandwidths for two links, there are some cases when LTE-W does not provide enough gains to UEs. For this reason, we install additional



(a) LTE (b) Wi-Fi

Fig. 4: Different ack transmission patterns: LTE and Wi-Fi.

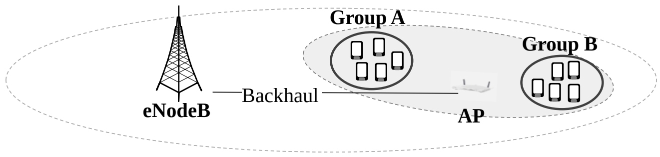


Fig. 5: Simulation node setup: 10 LTE-W UEs, `Group A` (5 UEs) and `Group B` (5 UEs)

safety device, which is a resequencing buffer at each UE to correct the order of the incoming packets. One of the crucial parameters in the design of the resequencing buffer is the timer T when a packet in the buffer is pushed up to TCP. As T grows, we can increase the chance of correctly ordering out-of-order packets, which, however, also increases RTT, resulting in the decrease of TCP throughput. In our design, we choose $T = 100$ msec from our various simulation experiments.

IV. Performance Evaluation

We show our simulation results that are focused on evaluating our mode selection and bearer split-scheduling. Our simulation codes were written based on extending NS-3 LENA [14], which an open source implementing LTE and EPC [14], [15].

A. Setup

Simulation environments. Fig. 5 shows the node setup in the simulation, where we consider a heterogeneous network that a eNB is connected to a MNO-operated AP. In our setup, ten UEs choose to utilize LTE-W, placed in two different geographical places (each five UEs), marked as `Group A` and `Group B`. We assume that each UE has one dedicated bearer consisting of a flow (based on the measurements [24]) and tries to download a content with an infinite size from a remote server. We let all the TCP acks to be transmitted only through LTE due to stability and reliability.

TABLE I: Simulation parameters

Parameter	Value
LTE / Wi-Fi configuation	20 MHz TDD / 48 Mbps
Mode of RLC layer	Acknowledge Mode
LTE / Wi-Fi scheduler	Proportional fair / Round-robin
LTE pathloss model	OkumuraHata
Wi-Fi pathloss model	ITU UMa/UMi
PDCP Buffer Timeout	100ms
TCP Version	New Reno
Simulation time	100 sec

Comparison. We compare the performance in terms of fairness and TCP throughput of LTE-W with MPTCP which is a well-known transport-level bandwidth aggregation. For MPTCP, among the several proposed versions, we consider the Linked Increases Algorithm (LIA) [25], available as a public open-source code [26]. We modify this code compatible to the LTE/Wi-Fi systems. Different from the LTE-W, since all UEs could utilize MPTCP outside of MNO's administrative domain, the way of allocating network resources may be different from the MNOs' targeted fairness, as demonstrated in our evaluation results.

B. Results

MPTCP and LTE-W. Table II shows the average per-group and total throughputs of MPTCP and LTE-W UEs, where we observe that LTE-W has a large total throughput than MPTCP, implying the efficiency of network resources. More importantly, LTE-W offers more bandwidths to the UEs of Group B, which are located at the cell edge, whereas too much bandwidth is allocated to the users at the cell center. More detailed analysis will be provided hereafter, by focusing on the issue of fairness.

TABLE II: Average throughput of MPTCP and LTE-W

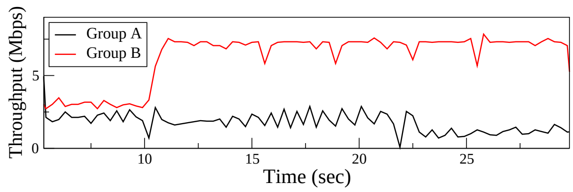
		`Group A`	`Group B`	All
LTE-W	LTE	3.8522	1.7777	2.8150
($\alpha = 1$)	Wi-Fi	0.0	2.8590	1.4295
	Total	3.8522	4.6367	4.2445
MPTCP	LTE	3.0724	0.3730	1.7227
	Wi-Fi	2.8592	0.7643	1.8117
	Total	5.9316	1.1373	3.5345

Fairness of MPTCP and LTE-W. We first investigate the per-bearer fairness of both protocols, MPTCP and LTE-W, whose results are summarized in Table III. We vary the fairness parameter α in the α-fair utility functions, where we observe that the utilities for all tested α of LTE-W outperform MPTCP. When we see the fourth column "who gets LTE-W?", in our LTE-W, only a part of the entire UEs are decided to get both LTE and Wi-Fi, because our mode selection leads to assigning priority to UEs having smaller LTE throughput to maximize the increment of the network utility (e.g., UEs located at the cell edge). This trend is slightly different across different values of α in that more LTE-W users in `Group A` are selected as the LTE-W mode for larger α, since α increases, the utility gain and the slope of utility function decreases, so that the mode selection algorithm chooses a larger number of UEs for both LTE and Wi-Fi. Figs. 6(a) and 6(b) depict the instantaneous throughputs for two cases, $\alpha = 1$ and $\alpha = 10$. The instantaneous throughputs of LTE-W UEs in `Group B` increase due to the addition of Wi-Fi, while the throughputs of UEs in `Group A` do not change. But, $\alpha = 10$, instantaneous throughputs of LTE-W UEs in both groups increase.

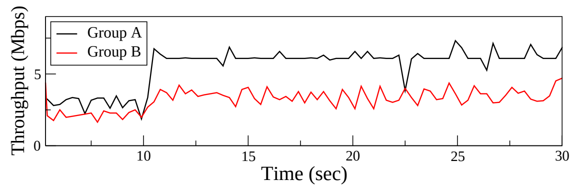
$\circ$ *Jain's fairness index:* Fig. 7(a) shows the Jain's fairness index of LTE-only, MPTCP and LTE-W UEs, where by definition the index ranges over the interval [0,1]. LTE-W outperforms by 15%, and MPTCP by 75%. This implies that unconditional providing of the aggregation service to all UEs, as in MPTCP, causes serious unfairness.

TABLE III: Utility comparison: LTE-W and MPTCP

α	MPTCP	LTE-W	Who gets both LTE and Wi-Fi?
0.01	35.0981	42.2563	`Group B` (5)
0.1	33.1660	40.7972	`Group B` (5)
1	0.9457	14.4131	`Group B` (5)
10	-4.66E+12	-4.20E-6	`Groups A` (1), `B` (5)
100	-3.60E+147	-1.16E-55	`Groups A` (3), `B` (5)



(a) Instantaneous throughput of each LTE-only UE `Group A` and LTE-W UE `Group B` ($\alpha = 1$)



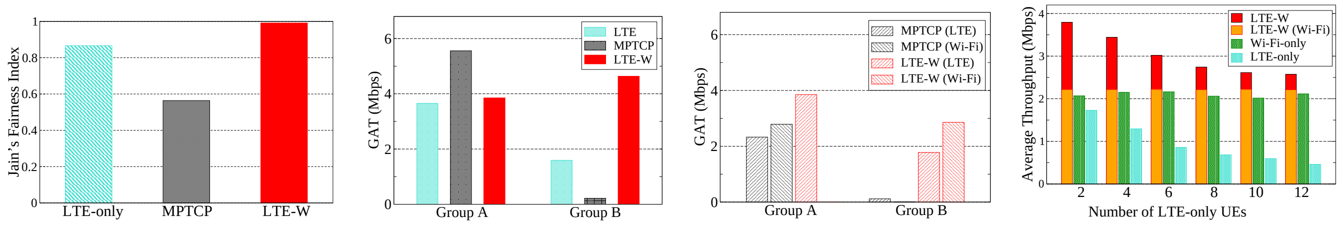
(b) Instantaneous throughput of each LTE-W UE in `Group A` and `Group B` ($\alpha = 10$)

Fig. 6: Instantaneous throughputs

$\circ$ *GAT of* `Group A` *and* `Group B`*:* We confirm this by looking at what happens in each group, where we plot geometric average of UE throughputs (GAT[4]) for $\alpha = 1$, shown in Fig. 7(b). Due to our distance setting from the eNodeB, the GAT of LTE-only UEs in `Group A` is two times larger than that of `Group B`, and LTE-W UEs achieves higher GAT than LTE-only UEs for all cases. However, GAT of MPTCP in `Group B` is even lower than that of LTE-only UE, as also seen Fig. 7(c), i.e., bandwidth concentration on `Group A`. However, LTE-W UEs in `Group B` receives higher GAT than those in `Group A`, thanks to our mode selection. Moreover, LTE-W UEs in `Group B` achieves high utilization of LTE/Wi-Fi links, since GAT from LTE resource is almost the same as the GAT of LTE-only UEs in `Group B`.

High link utilization and TCP performance. As illustrated in Fig. 7(d), LTE-W achieves the high link utilization as the number of LTE-only UEs increases from 2 to 12 for a fixed number of LTE-W and Wi-Fi-only UEs. This is verified that the sum of throughputs of Wi-Fi only and LTE only is almost the same as the total LTE-W throughput, implying that our **BSplit** works well for TCP. Note that bearer split-scheduling operates on a bearer basis that contains a multiple of TCP flows. Thus, one may wonder about the individual TCP performance, and the fairness among them. Figs. 8(a) and 8(b) shows the traces of CWNDs for the cases when a bearer contains 2 and 4 flows, respectively. We observe that they stably follow the standard behavior of TCP's CWND,

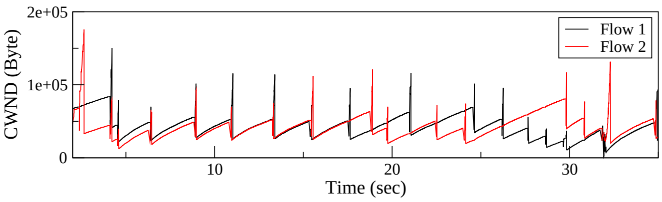
[4]For a set of numbers $\{x_i\}_{i=1}^N$, GAT = $(\prod_{i=1}^N x_i)^{1/N}$



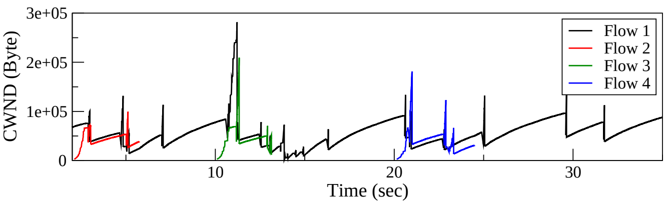
(a) Jain's fairness index of LTE-only, MPTCP and LTE-W UEs (b) GAT of LTE, MPTCP LTE-W for each Groups A and B (c) GAT from each LTE and Wi-Fi (d) GAT of LTE-only, Wi-Fi-only, and LTE-W

Fig. 7: Fairness comparison: LTE-W and MPTCP.

and there is no starvation for a specific flow.



(a) CWND of LTE-W for a two-flow bearer.



(b) CWND of LTE-W for a four-flow bearer.

Fig. 8: CWND traces for a bearer containing multiple TCP flows.

V. Conclusion

Adaptive bandwidth aggregation is a promising solution to cope with scarcity of mobile network capacity and high bandwidth-hungry applications. In this paper, we proposed a link-level LTE/Wi-Fi bandwidth aggregation, called LTE-W. As two key modules, we proposed mode selection and bearer split-scheduling that smartly considers per-bearer fairness and efficiently merge LTE and Wi-Fi links to achieve good TCP performance and link utilization. LTE-W is implemented at the NS-3 LENA platform, and evaluated in terms of fairness and TCP performance with comparison to a transport-level bandwidth aggregation, MPTCP.

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