Design and Implementation of LTE RRM with Switched LWA Policies

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***Abstract*—LTE-WLAN aggregation (LWA) combines the radio resources of LTE and WLAN, which takes the advantage of Wi-Fi's high availability and indoor coverage to provide better usage of both WLAN and LTE. In this mechanism, it is essential that the network should intelligently switch a Data Radio Bearer (DRB) to utilize either LTE or Wi-Fi. This paper implements the Radio Resource Management layer (RRM) for LWA and proposes two types of the switched LWA policies: the guaranteed bandwidth and the equal sharing policies. We measure the delay times of the LWA procedures, which indicate that the switched LWA policies can be implemented at the RRM with negligible overhead. We conduct emulation, simulation and analytic analysis to evaluate the performance of the switched LWA policies. The beauty of the LWA policies is that the performance is not affected by the DRB holding time distribution. Our study indicates that switched LWA can effectively reduce the blocking probability of the LWA's DRBs.**

***Index Terms*—Data Radio Bearer (DRB), Long-Term Evolution (LTE), LTE-WLAN aggregation (LWA), Radio Resource Management (RRM), switched LWA**

I. Introduction

MOBILE data traffic has been dramatically increased, and the telecom operators are seeking solutions to provide higher bandwidth, wider coverage and better Quality of Service (QoS) with low development cost. Several advanced technologies have been proposed to aggregate multiple Long-Term Evolution (LTE) carriers, and different Radio Access Technologies (RATs) are used to provide extra bandwidth. For example, carrier aggregation can group up to 5 discontinuous LTE component carriers to extend the bandwidth by 5 times [1, 2, 3]. Apart from LTE bandwidth aggregation, inter-RAT aggregation or offloading is another cost-effective solution to increase bandwidth. For example, WLAN is often used by telecom operators to supplement the bandwidth need of existing mobile infrastructures. LTE-WLAN aggregation (LWA) combines the radio resources of both LTE and WLAN [4, 5], which takes the advantage of Wi-Fi's high availability and indoor coverage to provide better usage for both WLAN and LTE.

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A. *LWA Architecture of ITRI*

Two LWA deployment scenarios to interface the eNB and a WLAN entity are defined: co-located and non-collocated [5]. The non-collocated scenario is out of the scope of this paper and the reader is referred to [10, 11, 12, 13, 14] for the details. Our implementation at the Industrial Technology Research Institute (ITRI) follows the co-located scenario where an internal backhaul is used to connect the eNB and a Wi-Fi AP. An advantage of this scenario is that the eNB can directly connect to an existing Wi-Fi AP without any modification to the AP. Fig. 1 depicts the collocated LWA system. Following 3GPP R13, the current version of LWA supports downlink transmission for WLAN, and both uplink and downlink transmissions for LTE.

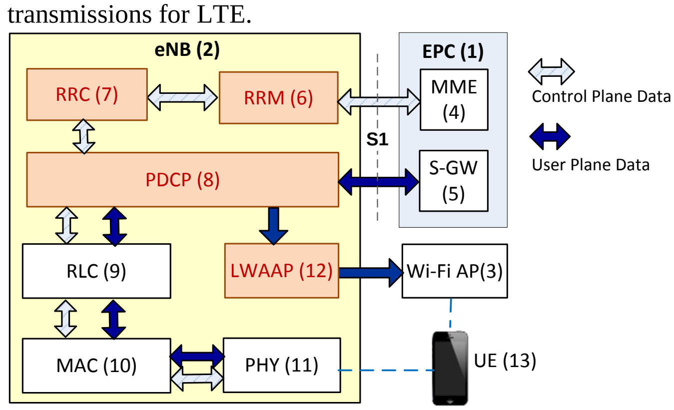


Fig. 1. ITIR's LWA system.

The ITRI eNB (Fig. 1 (2)) is connected to the EPC (Fig. 1 (1)) by the S1 interface, where the control plane data are delivered between the MME (Fig. 1 (4)) and the Radio Resource Management layer (RRM; Fig. 1 (6)). The user plane data are delivered between the S-GW (Fig. 1 (5)) and the Packet Data Convergence Protocol layer (PDCP; Fig. 1 (8)).

The eNB is connected to a Wi-Fi AP (Fig. 1 (3)) through an Ethernet cable. In the eNB, the RRM is in charge of LWA related procedures [5]. The Radio Resource Control (RRC; Fig. 1 (7)) is responsible for encoding and decoding the RRC messages [15], and serves as the bridge to forward internal control messages between the RRM and the PDCP. Extra RRC information elements (IEs) and the RRC

WLANConnectionStatusReport message are defined to support WLAN detection, LWA activation/deactivation and WLAN status report.

The PDCP is responsible for delivering the PDCP protocol data unit (PDU) [16], and the downlink data sent from the EPC are delivered through either LTE or WLAN based on the rules set at the PDCP. To support LWA, the PDCP extends the packet sequence number (SN) to 18 bits for better out-of-sequence packet detection, and adds a PDCP control PDU called "LWA status report". This PDU is sent from a UE to the eNB to indicate the downlink packet delivery status of a LWA bearer. The parameters include the first missing PDCP SN (FMS), the highest received PDCP SN on WLAN (HRW), and the number of missing PDUs (NMP) [16]. The PDCP uses this LWA status report together with the PDCP status report to decide the optimal ratio of packet transmission between LTE and WLAN.

The Radio Link Control (RLC; Fig. 1 (9)), the Medium Access Control (MAC; Fig. 1 (10)) and the Physical Layer (PHY; Fig. 1 (11)) handle the LTE data. The LWA Adaptation Protocol (LWAAP; Fig. 1 (12)) identifies the LWA bearers of the LWAAP service data units (SDUs) and sends these SDUs to the Wi-Fi AP [17, 5]. The LWAAP appends a one-byte header to each PDCP PDU to produce the corresponding LWAAP PDU. The appended LWAAP header consists of data radio bearer (DRB) identity. This identity indicates the DRB of the LWAAP PDU. Then the eNB forwards the LWAAP packets to the Wi-Fi AP over the Ethernet. The destination address field and the EtherType of the Ethernet packets are set as the Wi-Fi MAC address of the UE (Fig. 1 (13)) and the "LWA EtherType" (which is 0x9E65). The LWA EtherType is used to identify the received LWA packets at the UE side. The Wi-Fi AP forwards the LWA packets to the UE over WLAN based on the UE's Wi-Fi MAC address.

B. *Recent LWA Deployments*

LWA trials have been conducted [6]. Kojima et al. reported peak throughput of 260 Mb/s (64.8 Mb/s for LTE and 300 Mb/s for Wi-Fi) [7]. Korea Telecom reported peak throughput of 600 Mb/s (150 Mb/s for LTE and 450 Mb/s for Wi-Fi) [8]. The ITRI and MediaTek (MTK) in Taiwan have collaborated to develop the TDD LWA technology, and the prototype (Fig. 2) was demonstrated in the Mobile World Congress (MWC) 2016 with the peak throughput of 400Mb/s (100Mb/s for LTE and 300 Mb/s for Wi-Fi) [9]. ITRI has pushed the peak throughput of LWA to 412 Mb/s without carrier aggregation (104 Mb/s for LTE and 312 Mb/s for Wi-Fi) for a single UE. With carrier aggregation, the peak throughput is 450Mb/s. In an enhanced version, the peak throughput of the eNB is 900Mb/s, where the eNB transmits 200Mb/s LTE data to a UE by carrier aggregation and transmits 700Mb/s data to a PC via a Wi-Fi AP. Both the UE and the PC can receive data without packet loss under the target bit rates.

This paper reports the LWA development of the eNB at ITRI and proposes several switched LWA policies. The paper is organized as follows. Section II describes ITRI's RRM design at the eNB. Section III elaborates on ITRI's implementation of

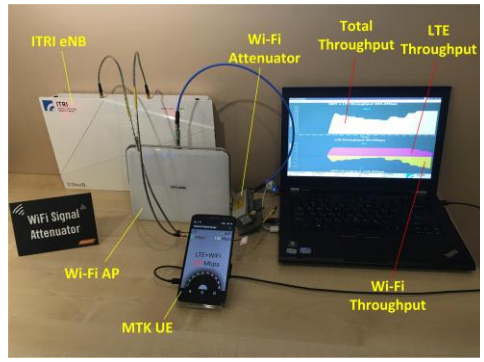


Fig. 2. The prototype of the ITRI LWA demonstrated in MWC 2016.

LWA procedures and their time complexities. Section IV proposes switched LWA policies that utilize the switched data radio bearer mechanism to accommodate more admission requests. We conduct measurements, emulation, simulation and analytic analysis to investigate the performance of the ITRI's implementation.

II. ITRI's RRM

Fig. 3 depicts the functional block diagram of ITRI's RRM (Fig. 3 (1)), which consists of four major parts: the UE Control (Fig. 3 (2)), the RRM database (Fig. 3 (3)), the Interface entity (Fig. 3 (4)) and the Cell Control. The Cell Control is in charge of the base station related functions such as the management of broadcast messages and the inter-cell interface coordination. Details of the Cell Control are out of the scope of this paper, and will not be elaborated further. The UE Control is responsible for the UE related functions such as radio bearer management and mobility management. These functions will be given in this section.

The ITRI's RRM includes a database (Fig. 3 (3)) to be accessed by all entities in the UE Control. For each UE, the database maintains a UE context to record the UE capability, the UE's current state, ongoing procedures and the established radio bearer configurations. The context also includes the LWA related configurations and information such as the associated Wi-Fi AP and the received WLAN measurement reports. Besides the 3GPP defined information, the database in ITRI's implementation maintains a Wi-Fi list for every LWA capable UE. For a Wi-Fi AP included in the measurement report, if this Wi-Fi AP is collocated with the eNB, then when the UE sends the report to the eNB, the AP's Basic Service Set Identifier (BSSID) is saved in the Wi-Fi list of the UE. The Wi-Fi lists are used for LWA load balancing to be described in Section IV.

The Radio Resource (RR) manager (Fig. 3 (10)) is responsible for LTE and WLAN radio resource management based on the information stored in the database. The RR manager provides the following services to other UE Control entities: available resource inquiry, resource allocation request, resource allocation modification request, radio resource release indication, and available radio resource indication (for the LWA entity only). The Interface entity (Fig. 3 (4)) allows the RRM to interact with the RRC (Fig. 3 (5)) and the MME (Fig. 3 (6)). This entity maps the incoming external messages into the internal events and dispatches them to the UE manager (Fig. 3

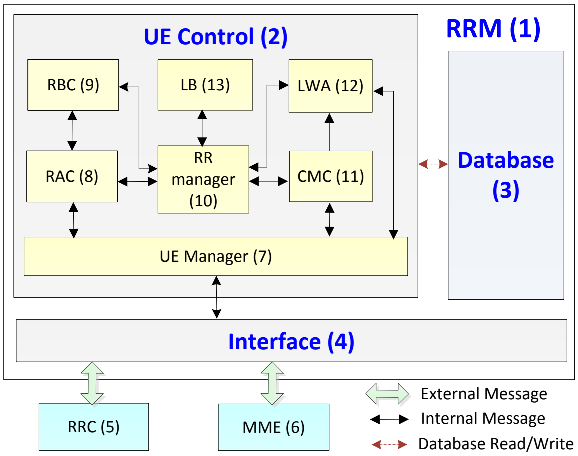


Fig. 3. Functional block diagram of ITRI's RRM.

(7)). It also packs an outgoing message with the proper format according to the destination of the message. With the Interface entity, we can modularize the ITRI RRM such that the RRM can be ported for different RRC and MME implementations. Upon receipt of an event from the Interface entity, the UE manager invokes the corresponding procedure based on the UE's state recorded in the database. To balance against the radio resource utilization and the QoS of the in-progress radio bearers, the Radio Admission Control (RAC; Fig. 3 (8)) interacts with the RR manager to decide if new radio bearers should be established according to their QoS requirements and the available resources in LTE/WLAN.

The Radio Bearer Control (RBC; Fig. 3 (9)) establishes the DRBs based on their radio bearer configurations after they are admitted by the RAC. The RBC interacts with the RR manager to maintain the radio bearers at the change of the radio resource situation caused by mobility or other reasons, and releases the radio resources at session termination, handover or at other occasions.

To support UE's mobility, the Connection Mobility Control (CMC) entity (Fig. 3 (11)) requests the UE to perform radio resource measurements and report the measurement results to be used in handover. In addition to the measurements of LTE carrier frequencies, the WLAN frequency measurements are also required if the UE supports LWA. The measurement configuration set by the CMC includes the measurement objects and reporting configurations. The LTE measurement object is a single Evolved Universal Terrestrial Radio Access (E-UTRA) carrier frequency. The WLAN measurement object consists of a set of WLAN identifiers (e.g. BSSIDs) and optionally a set of WLAN frequencies. The reporting configuration consists of reporting criterion (e.g. single event or periodical reporting) and the report format. This measurement configuration is maintained in the UE context. The CMC is responsible for making the LTE handover decisions according to the received E-UTRA measurement reports. For WLAN measurement results, the CMC simply forwards the reports to the LWA entity. In other words, the CMC does not handle the LTE-WLAN handover issue.

The LWA entity (Fig. 3 (12)) handles the WLAN measurement reports and controls the downlink data path to a LWA capable UE. Specifically, the LWA entity executes the LWA related procedures including LWA activation, mobility and deactivation. These procedures are initiated according to the WLAN measurement reports. Details of LWA procedures will be described in Section III.

3GPP defines the load balancing function to mitigate uneven distribution of the traffic load over multiple cells [5]. Load balancing can also be achieved by switching a DRB between LTE and WLAN, or splitting a DRB between LTE and WLAN with an appropriate ratio. In ITRI's implementation, split bearer assignment decision is made at the PDCP. The ratio of transmission between LTE and WLAN can be dynamically determined based on the PDCP and the LWA status reports sent from the UE. Since the PDCP is responsible for handling these reports in the ITRI implementation, the split DRB policy is exercised at the PDCP, which will be addressed in a separate paper. On the other hand, switched bearers are assigned at the RRM based on the WLAN measurement results provided in the RRC MeasurementReport messages. This paper will focus on switched DRB policy where every DRB is either assigned to LTE or WLAN, but not both. ITRI's RRM implements the Load Balancing (LB) entity (Fig. 3 (13)), which re-distributes the LTE and the WLAN radio resources when the RAC accepts a radio bearer request and when the RBC modifies the radio bearers. An example of load balancing algorithms is repacking that dynamically switches a DRB between the LTE eNB and a Wi-Fi AP [18, 19]. The RR manager may invoke repacking when LTE resource is insufficient to accommodate a data radio bearer request. The details will be elaborated in Section IV.

III. Performance of ITRI's LWA Procedures

This section measures the delays of LWA procedures based on the ITRI's RRM described in Section II. The "pure" LTE UE attachment is modified to accommodate WLAN, and the eNB is responsible for configuring the WLAN measurements for a UE. Upon receipt of the WLAN measurement configuration, the UE performs WLAN measurement to detect the statuses of the nearby Wi-Fi APs. Based on the WLAN measurement report, the eNB may conduct LWA activation, mobility or deactivation. Details of the LWA procedures can be found in 3GPP R13 [5, 15]. We conduct experiments to measure the elapsed times of the major steps in these procedures. Every experiment is repeated 50 times to obtain stable results. Our experiments indicate that the standard deviations for these elapsed times are small, which shows good stability of ITRI's implementation.

A. UE Attachment

In the UE attachment, the RAC in the RRM (Fig. 3 (8)) instructs the RR manager (Fig. 3 (10)) to check if there is sufficient LTE radio resource for the E-RAB setup request. If so, the eNB obtains the UE capability from the UE. The RRM of the eNB saves the UE capability in the RRM database (Fig. 3 (3)) and forwards it to the MME. The LWA parameters in the UE capability include the lwa-r13 parameter and UE's Wi-Fi MAC address. The lwa-r13 parameter indicates if the UE supports LWA. If so, based on the default settings of LWA

DRB and UE capability information accessed from the RRM database, the RBC (Fig. 3 (9)) prepares the DRB configuration for LWA, which includes the selection of proper PDCP configuration such as enabling extended PDCP SN and the PDCP status report. This configuration is used to instruct the UE to set the DRB type as "LWA". Then the UE manager (Fig. 3 (7)) reports the E-RAB setup status to the MME.

We have conducted experiments to measure the T1 delay of UE attachment (the delay for 4 message exchanges between when the ITRI RRM issues the RRC message "UECapabilityEnquiry" and when the UE reports "RRCConnectionReconfigurationComplete"). The histogram shown in Fig. 4 indicates that the expected T1 is 205ms and its standard deviation is 6.9.

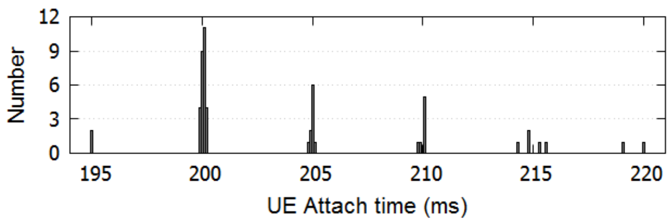


Fig. 4. The T1 histogram for UE attachment.

B. *WLAN Measurement*

In ITRI's RRM, immediately after the UE attachment, another RRCConnectionReconfiguration and Complete message pair is exchanged to configure WLAN measurement, which includes the WLAN measurement object and measurement report. The WLAN measurement object contains information of the Wi-Fi APs that can be connected to the UE. The information includes Wi-Fi AP's BSSID, band (2.4GHz or 5GHz) and channels. The measurement report configuration specifies the report criteria and additional WLAN AP information request (e.g. channel utilization). The default WLAN measurement configuration is stored in the RRM database. The CMC (Fig. 3 (11)) prepares the WLAN measurement configuration based on the default measurement configuration, and then requests the UE to perform WLAN measurement. The UE conducts WLAN measurement in the background. When an event is detected by the UE through the measurement, a MeasResultWLAN report is sent to the LWA entity (Fig. 3 (12)) of the eNB through the UE manager and the CMC. The most important elements in the measurement report are the WLAN identity and its Received Signal Strength Indicator (RSSI). The LWA entity checks the WLAN identity to see if this Wi-Fi AP connects to the eNB. If not, the information is dropped. Otherwise, the parameters (WLAN identity and its RSSI) are used by the LWA entity to trigger LWA activation (Event W1), mobility (to change Wi-Fi AP; Event W2), or LWA deactivation (Event W3). After LWA is activated, the RRM of the eNB selects the network (either LTE or WLAN) to transfer the data to the UE.

We have conducted experiments to measure the T2 delay for the WLAN measurement configuration. The histogram shown in Fig. 5 indicates that the expected T2 is 40ms and its standard deviation is 2.993.

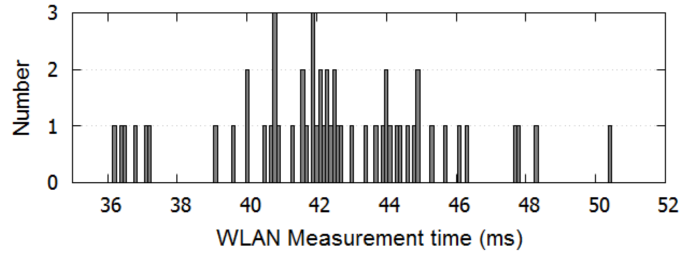


Fig. 5. The T2 histogram for WLAN measurement.

C. *LWA Activation*

Fig. 6 illustrates the message flow for LWA activation. When the UE detects that a Wi-Fi AP's RSSI is larger than a threshold THR_1, it sends the MeasurementReport message to the eNB to report Event W1 (Message C.1 in Fig. 6). The LWA entity activates LWA by requesting the UE to associate with a Wi-Fi (Message C.2). After replying to the eNB (Message C.3), the UE conducts WLAN association with the Wi-Fi AP (Procedure C.4). In ITRI's implementation, the eNB always configures the UE to send the WLANConnectionStatusReport message to the eNB after the UE has successfully connected to WLAN (Message C.5). Upon receipt of Message C.5, the LWA entity sends the available radio resource indication (for WLAN) to the RR manager. The RR manager checks if the associated Wi-Fi AP has sufficient radio resource. If so, the LWA entity requests the PDCP (Fig. 1 (8)) to switch the data path from LTE to WLAN based on one of the policies described in Section IV.

We have conducted experiments to measure the T3 delay for LWA activation. The histogram shown in Fig. 6 indicates that the expected T3 is 487.8ms and its standard deviation is 4.64. Note that both T1 and T3 involve two message-pair exchanges. Since T3 includes WLAN association delay, $T3 > T1$.

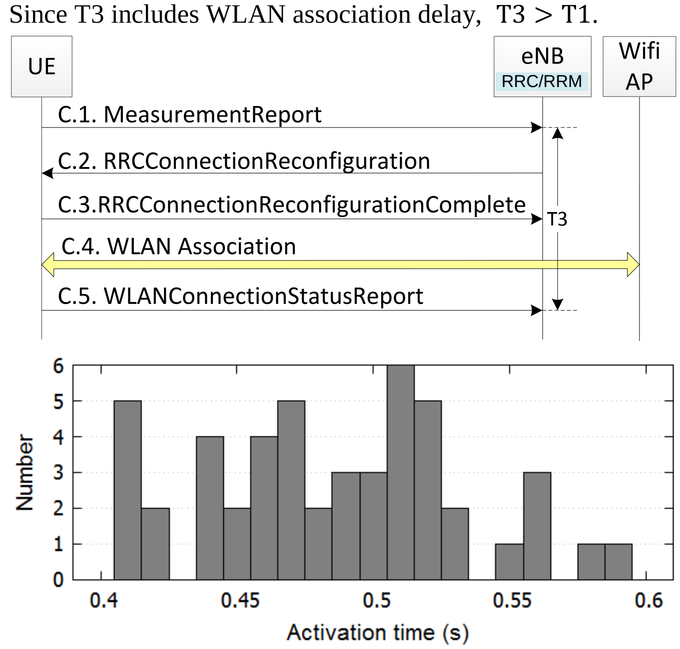


Fig. 6. Message flow for LWA activation and the T3 histogram.

D. *LWA Mobility*

Denote the Wi-Fi AP connected to the UE as the source AP (AP1). If the UE moves from the source AP to a new AP, then the new AP is called the target AP (AP2). When the UE detects that the RSSI of AP1 is smaller than a threshold THR_2, and the

RSSI of AP2 is larger than a threshold THR_3, it sends the MeasurementReport message to inform the eNB of Event W2 (Message D.1 in Fig. 7). Then the LWA entity requests the RR manager to check if there are available radio resources in both AP2 and LTE. If so, the LWA entity sends radio resource modification request to the RR manager, which instructs the PDCP to temporarily switch the data path from WLAN to LTE. The LWA entity then commands the UE to perform WLAN mobility through the RRCConnectionReconfiguration message (Message D.2). This message requests the UE to release the Wi-Fi connection to AP1, and establish the connection to AP2. After sending the RRCConnectionReconfiguration Complete message to the eNB (Message D.3), the UE starts disassociating from AP1 and associating to AP2 (Procedure D.4). After the UE has successfully associated to AP2, it sends the WLANConnectionStatusReport message with the successful cause to notify the eNB that Wi-Fi AP change procedure is complete (Message D.5). Like the action taken for Message C.5, the LWA entity may request the PDCP to switch the data path from LTE to WLAN based on a policy described in Section IV. In our implementation, THR_1 >THR_3 because the RSSI of the serving AP may decrease fast for a moving UE. Hence we need to move the UE to a target AP as soon as possible even if the RSSI of the target AP (which is larger than THR_3) is not as good as THR_1. The delay from D.1 to D.5 is basically the same as that for T3.

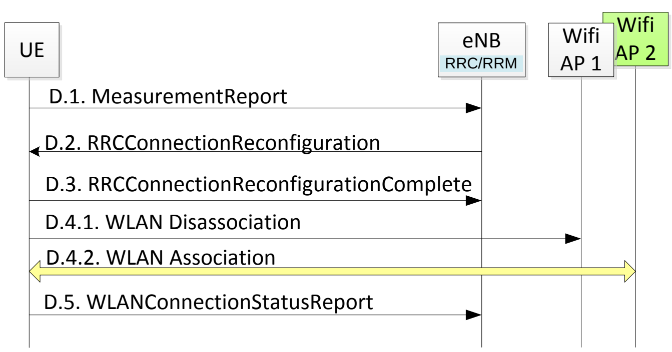


Fig. 7. Message flow for WLAN mobility.

E. *LWA Deactivation*

When the UE detects that the source AP's RSSI is smaller than a threshold THR_4, it sends the MeasurementReport message to the eNB to report Event W3 (Message E.1 in Fig. 8). Then the LWA entity instructs the RR manager to check if there are available LTE radio resources. If so, the LWA entity sends radio resource modification request to the RR manager, which commands the PDCP to detach the data path from WLAN. Then the LWA entity deactivates LWA through the RRCConnectionReconfiguration and Complete message pair exchanged (Messages E.2 and E.3). After that, the LWA entity sends radio resource unavailable indication (for WLAN) to the RR manager to indicate that the UE can only use LTE resource. In our implementation, THR_2 >THR_4 to maintain the WLAN connection as long as possible. The eNB releases the WLAN connection if no WLAN mobility target is found. We have conducted experiments to measure the T4 delay (the delay from E.1 to E.3). The histogram shown in Fig. 8 indicates that the expected T4 is 41ms and its standard deviation is 3.2. Note that T4 is slightly longer than T2 due to the extra Measurement report message exchange.

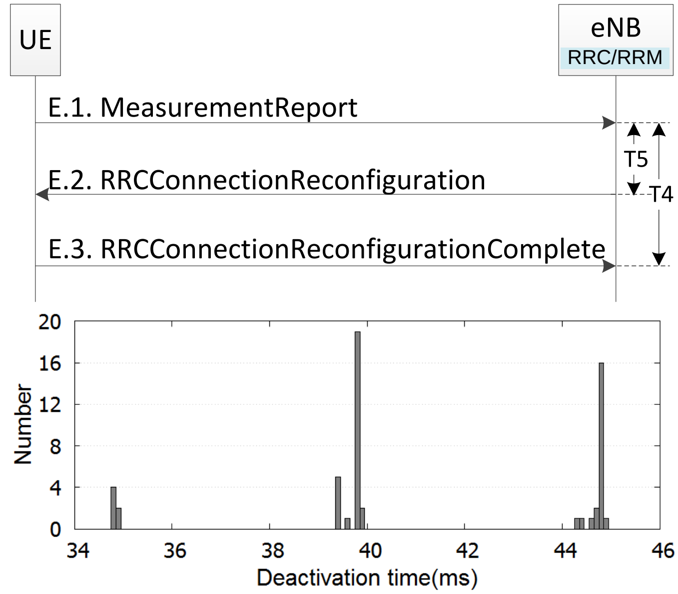


Fig. 8. Message flow for LWA deactivation and the T4 histogram.

IV. The Switched LWA Policies

The delay times of the LWA procedures measured in the previous section indicate that the switched LWA policies can be implemented at the RRM with negligible overhead. In ITRI's implementation, switched bearer assignment decision is made at the LB entity of the RRM. When the RRM assigns the DRBs, it is important to minimize the blocking (outage) probability. Therefore, exercising a sophisticated switched LWA policy is essential. Two types of policies can be exercised at the LB entity to decide the bandwidth and the network assigned to a switched DRB. In the guaranteed bandwidth policy, every DRB is guaranteed a minimum bandwidth. Without loss of generality, we assume that an eNB covers K Wi-Fi APs. For $1 \leq k \leq K$, let W and W_k be the bandwidths of the eNB and AP k respectively. Assume that $W = 150$ Mb/s and $W_k = 300$ Mb/s. If every DRB is guaranteed a minimum bandwidth w, then the eNB and AP k can support up to $M = \frac{W}{\mathrm{w}}$ and $M_k = \frac{W_k}{\mathrm{w}}$ DRBs, respectively. In this policy, a DRB request may be rejected. On the other hand, in the equal sharing policy, the bandwidth W (W_k) is equally shared by all DRBs, and a DRB request is always accepted [20]. Note that the sharing policy should not be exercised for saturated DRB traffic. We propose several switched LWA policies for DRB assignment of ITRI's eNB. These policies are addressed in the following subsections. Although both LTE and WLAN data streams pass through the eNB, for the description purpose, we say that a DRB is handled by the eNB if its data are delivered through LTE, and is handled by a Wi-Fi AP if it is delivered through WLAN. We will use queueing models for the analytic analysis in this section. Specifically, we use K+1 queues where queue k represents AP k (for $1 \leq k \leq K$), and queue K+1 represents the eNB. These queues are connected with different topologies for different policies.

A. *The AP-first Policy*

AP-first is a guaranteed bandwidth policy, which is typically used by the mobile operators. In this policy, when a DRB arrives at AP k, the LB entity first attempts to assign the incoming DRB to AP k. If M_k DRBs are already assigned to AP k, the LB entity tries to assign the new DRB to the eNB. If M DRBs are already assigned to the eNB, then the incoming DRB request is blocked (rejected).

Let the DRBs arriving at Wi-Fi AP k be a Poisson process with the rate λ_k and the DRB holding times have an arbitrary distribution with the mean $1/\mu$, then the DRB traffic to AP k is $\rho_k = \lambda_k / \mu$. When we say "a UE requests a DRB in the radio coverage of a Wi-Fi AP", it does not imply that the DRB is handled by the AP. Instead, it means that the UE engaged in the DRB is residing in the radio coverage of the Wi-Fi AP. This DRB is either handled by the Wi-Fi AP or the eNB. Let random variable I_k be the number of DRBs whose UEs reside in the radio coverage of AP k at the steady state. If $I_k \leq M_k$, then these DRBs are handled by AP k. If $I_k > M_k$, then M_k DRBs are handled by AP k, and $I_k - M_k$ DRBs are handled by the eNB. Clearly, for the AP-first policy, $I_k - M_k \leq M$.

Let $p_{A,k}$ be the probability that a DRB arriving at AP k is rejected in the AP-first policy. This blocking probability can be derived by modeling the AP-first policy as a two-stage queueing system (i.e. K M/G/M_k/M_k queues representing the APs at the first stage and one M/G/M/M queue representing the eNB at the second stage). Let $p_{b,k}$ be the probability that an incoming DRB request cannot be accommodated at AP k ($1 \leq k \leq K$). From [21]

$$p_{b,k} = B(\rho_k, M_k) = \left(\frac{\rho_k^{M_k}}{M_k!}\right)\left(\sum_{i=0}^{M_k}\frac{\rho_k^i}{i!}\right)^{-1} \quad (1)$$

For $K \geq 2$, if the second-stage queue exists, the DRB requests rejected at the first-stage queue k will overflow to the second-stage queue with the arrival rate $p_{b,k}\lambda_k$, and the net arrival rate of the second-stage queue is $\lambda = \sum_{k=1}^{K} p_{b,k}\lambda_k$. These merged arrivals to the eNB can be approximated as a Poisson process. Then similar to (1), the blocking probability $p_{b,K+1}$ for the eNB is

$$p_{b,K+1} = B\left(\sum_{k=1}^{K} p_{b,k}\rho_k, M\right)$$

and the blocking probability $p_{A,k}$ for the DRBs arriving at AP k in the AP-first policy is

$$\begin{aligned} p_{A,k} &= p_{b,k}p_{b,K+1} \\ &= B(\rho_k, M_k)B\left(\sum_{n=1}^{K} B(\rho_n, M_n)\rho_n, M\right) \quad \text{for } K \geq 2 \quad (2) \end{aligned}$$

For K=1, when the rejected DRB requests at AP1 overflow to the eNB, these requests arriving at queue K+1 (=2) may not form a Poisson process. For this case, we can merge the queues for AP1 and the eNB into one queue that accommodates $M_1 + M$ DRB arrivals at a time, and

$$p_{A,1} = B(\rho_1, M_1 + M) \quad \text{for } K = 1 \quad (3)$$

B. Repacking on Demand: The Implementation

Repacking is a guaranteed bandwidth policy, which was proposed for two-tier mobile network (see [19] and the references therein). Repacking improves the AP-first policy by creating more opportunities to admit a DRB request. The idea of repacking is to transfer the DRBs served at the eNB back to the APs.

For $1 \leq n \neq k \leq K$, a repacking DRB candidate at AP n satisfies two conditions: the DRB (whose UE resides at the radio coverage of AP n) is served at the eNB, and AP n has free capacity to accommodate this DRB. When the AP-first policy fails to accept an incoming DRB request of AP k, the LB entity checks the WLAN list in the RRM database to see if the eNB serves a DRB of AP n, and AP n is serving less than M_n DRBs. If so, the RRM transfers the DRB to AP n, and the incoming DRB of AP k can be served at the eNB. Depending on the time when repacking is exercised, two repacking schemes have been proposed. In always repacking, the RRM always moves a DRB (if exists) in the eNB to the corresponding AP as soon as a DRB is completed at that AP. Always repacking keeps maximum available DRB capacity in the eNB at the cost of higher repacking rate. Unlike always repacking, repacking on demand (RoD) does not immediately perform repacking when a DRB in an AP is completed. Instead, repacking is exercised only when it is necessary (i.e., when the AP-first policy fails to accept an incoming DRB).

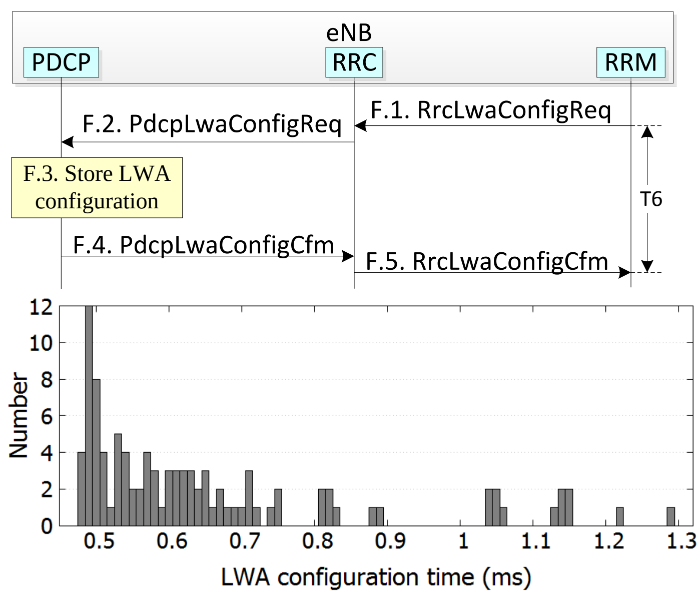


Fig. 9. The LWA configuration message flow and the histogram for T6.

To implement repacking, the LB entity needs to switch the DRBs from LTE to WLAN. In ITRI's implementation, this task is achieved by the interaction between the RRM, the RRC and the PDCP. As illustrated in Fig. 9, the LB entity of the RRM sends RrcLwaConfigReq (Message F.1) to the RRC. The RRC then sends PdcpLwaConfigReq (Message F.2) to the PDCP. These messages request the PDCP to change the LWA configuration. The PDCP conducts Procedure F.3 to store the new LWA configuration that switches the DRB from LTE to WLAN. The PDCP then directs all downlink packets of the DRB to the WLAN, and replies PdcpLwaConfigCfm (Message

F.4) to the RRC. The RRC returns RrcLwaConfigCfm (Message F.5) to the LB entity of the RRM to complete the repacking task. We have conducted experiments to measure the T6 delay (the delay from F.1 to F.5). The histogram shown in Fig. 9 indicates that the expected T6 is 0.65532ms and its standard deviation is 0.199.

Note that repacking incurs significant handover signaling overhead in a two-tier mobile network. For example, about 200 ms was reported for handover due to repacking [18]. On the other hand, as compared with other LWA procedures, the time complexity of repacking shown in Fig. 9 is negligible in ITRI's LWA implementation.

C. Repacking on Demand: The Performance

Interesting enough, Hung and Lin [19] proved that RoD has the same blocking probability as always repacking. As compared with always repacking, RoD significantly reduces the numbers of repacking. Therefore, we consider RoD in ITRI's implementation. The blocking probability $p_{R,k}$ for AP k in RoD can be derived following the work in [19]. We first derive the probability $\pi(\rho_{k,}i)$ that $I_k = i$ with traffic ρ_k. Suppose that $M \to \infty$. If the DRB arrivals to AP k form a Poisson process and the DRB holding times have an arbitrary distribution, then from [22] the number of DRBs in AP k can be modeled by an M/G/∞ queue, and $\pi(\rho_{k,}i)$ can be expressed as

$$\pi(\rho_{k,}i) = \left(\frac{\rho_k^i}{i!}\right) e^{-\rho_k} \tag{4}$$

Since $p_{R,k}$ is the same for both always repacking and RoD, it suffices to model always repacking. We design a stochastic process for always repacking where a state is defined as a vector $\mathbf{I} = [i_1, i_2, \dots, i_K]$ that represents the numbers $I_k = i_k$ of outstanding DRBs arriving at AP k for $1 \le k \le K$. Assume that $M \to \infty$, then the state space for this unrestricted LWA system is

$$S_\infty = \{\mathbf{I} = [i_1, i_2, \dots, i_k, \dots, i_K] | I_k = i_k \ge 0, 1 \le k \le K\}.$$

Let $\Pr[\mathbf{I}]$ be the probability that state $\mathbf{I}$ occurs. Since the probability for $I_k = i$ is expressed in (4), we have $\Pr[\mathbf{I}] = \Pr[\mathbf{I} = [i_1, i_2, \dots, i_K]] = \Pi_{1 \le k \le K} \pi(\rho_{k,}i_k)$. For $1 \le k \le K$, let $p_k(j)$ be the probability that j DRBs of AP k are served by the eNB. Then from (4), we have

$$p_k(0) = \sum_{m=0}^{M_k} \pi(\rho_{k,}m) \quad \text{and}$$
$$p_k(j) = \pi(\rho_{k,}M_k + j) \quad \text{for } j > 0 \tag{5}$$

Let $p_k^+(j)$ be the probability that j DRBs of APs 1, 2,…, k (where $k \le K$) are served by the eNB. Then

$$p_1^+(j) = p_1(j) \quad \text{and}$$
$$p_k^+(j) = \sum_{l=0}^{j} p_{k-1}^+(l) p_k(j-l) \quad \text{for } k > 1 \tag{6}$$

Note that (6) can be recursively computed by using (5). If $M < \infty$, then the states that may occur in the LWA system is $\mathbf{S} = \{\mathbf{I} = [i_1, i_2, \dots, i_K] | \sum_{k=1}^{K} \max(i_k - M_k, 0) \le M\}$. From (6) the probability $\Pr[\mathbf{S}]$ is

$$\Pr[\mathbf{S}] = \sum_{m=0}^{M} p_K^+(m) \tag{7}$$

Let $\boldsymbol{S_1} = \{\mathbf{I} = [i_1, i_2, \dots, i_K] | \sum_{k=1}^{K} \max(i_k - M_k, 0) = M\}$. In $\boldsymbol{S_1}$, the eNB serves exact M DRBs. From (6), we have

$$\Pr[\boldsymbol{S_1}] = p_K^+(M) \tag{8}$$

For $1 \le k \le K$, let $\boldsymbol{S_{2,k}} = \{\mathbf{I} = [i_1, i_2, \dots, i_k, \dots, i_K] | 0 \le i_k < M_k\}$ and $\overline{\boldsymbol{S}}_{\boldsymbol{2,k}} = \{\mathbf{I} = [i_1, i_2, \dots, i_k, \dots, i_K] | i_k \ge M_k\}$. In $\boldsymbol{S_{2,k}}$, all outstanding DRBs at AP k are served by this AP, and it can accommodate the next incoming DRB. We have

$$\Pr[\boldsymbol{S_{2,k}}] = \sum_{m=0}^{M_k-1} \pi(\rho_{k,}m) \tag{9}$$

Now we consider an incoming DRB request of AP K. Let

$$\boldsymbol{S_{3,K}} = \{\mathbf{I} = [i_1, i_2, \dots, i_K] | \sum_{k=1}^{K-1} \max(i_k - M_k, 0) = M\}.$$

In $\boldsymbol{S_{3,K}}$, exact M DRBs of APs 1,.., K-1 (excluding the DRBs of AP K) are served by the eNB. Similar to (8), we have

$$\Pr[\boldsymbol{S_{3,K}}] = p_{K-1}^+(M) \tag{10}$$

For $1 \le k \le K$, let $\boldsymbol{S_{3,k}} = \{\mathbf{I} = [i_1, \dots, i_k, \dots, i_K] | \sum_{1 \le n \ne k \le K} \max(i_n - M_n, 0) = M\}$. By rearranging the indexes of the APs, it is obvious that $\Pr[\boldsymbol{S_{3,k}}]$ can be expressed as (10) if we replace AP K by AP k.

Consider the LWA system with Poisson DRB arrivals and general holding time distribution. Under the condition that M is finite (i.e., $\mathbf{S}$ is the sample space), the equilibrium probabilities $\Pr[\boldsymbol{S_1}|\mathbf{S}]$, $\Pr[\boldsymbol{S_{2,k}}|\mathbf{S}]$ and $\Pr[\boldsymbol{S_{3,k}}|\mathbf{S}]$ for $\mathbf{I} \in \mathbf{S}$ are expressed as [19]

$$\Pr[\boldsymbol{S_1}|\mathbf{S}] = \frac{\Pr[\boldsymbol{S_1}]}{\Pr[\mathbf{S}]},$$
$$\Pr[\boldsymbol{S_{2,k}}|\mathbf{S}] = \frac{\Pr[\boldsymbol{S_{2,k}}]}{\Pr[\mathbf{S}]}, \text{and}$$
$$\Pr[\boldsymbol{S_{3,k}}|\mathbf{S}] = \frac{\Pr[\boldsymbol{S_{3,k}}]}{\Pr[\mathbf{S}]} \tag{11}$$

Equations (11) are independent of the DRB holding time distribution, and are only affected by the means of the holding times.

In always repacking, an incoming DRB at AP k is rejected if AP k already serves M_k DRBs and the eNB is occupied by M DRBs. This situation occurs when the LWA system is at any state $\mathbf{I} \in \overline{\boldsymbol{S}}_{\boldsymbol{2,k}} \cap \boldsymbol{S_1}$, and the probability is

$$p_{R,k} = \Pr[\overline{\boldsymbol{S}}_{\boldsymbol{2,k}} \cap \boldsymbol{S_1}|\mathbf{S}] = \Pr[\boldsymbol{S_1}|\mathbf{S}] - \Pr[\boldsymbol{S_{2,k}} \cap \boldsymbol{S_1}|\mathbf{S}] \tag{12}$$

For any state in $\boldsymbol{S_{2,k}}$, no DRB of AP k is served at the eNB, and we have $\boldsymbol{S_{2,k}} \cap \boldsymbol{S_1} = \boldsymbol{S_{2,k}} \cap \boldsymbol{S_{3,k}}$. Since $\boldsymbol{S_{2,k}}$ and $\boldsymbol{S_{3,k}}$ are independent, we have $\Pr[\boldsymbol{S_{2,k}} \cap \boldsymbol{S_{3,k}}|\mathbf{S}] = \Pr[\boldsymbol{S_{2,k}}|\mathbf{S}] \Pr[\boldsymbol{S_{3,k}}|\mathbf{S}]$. Therefore, (12) is re-written as

$$p_{R,k} = \Pr[\boldsymbol{S_1}|\mathbf{S}] - \Pr[\boldsymbol{S_{2,k}}|\mathbf{S}] \Pr[\boldsymbol{S_{3,k}}|\mathbf{S}] \tag{13}$$

From (11), (13) is re-written as

$$p_{R,k} = \frac{\Pr[\boldsymbol{S_1}]-\Pr[\boldsymbol{S_{2,k}}]\Pr[\boldsymbol{S_{3,k}}]}{\Pr[\mathbf{S}]} \quad (14)$$

and (14) can be computed by (7)-(10). For K=1, $\Pr[\boldsymbol{S_1}] = p_1^+(M) = \pi(\rho_{1,}M_1 + j)$, $\Pr[\boldsymbol{S_{3,1}}] = 0$, $\Pr[\mathbf{S}] = \sum_{m=0}^{M} p_1^+(m)$ $= \sum_{m=0}^{M_1+M} \pi(\rho_{1,}m)$, and (14) is the same as (3). That is, $p_{R,1} = p_{A,1}$. In other words, RoD is the same as the AP-first policy for K=1.

D. The Equal-Sharing Policy for AP

Unlike the guaranteed bandwidth policies that may reject incoming DRB request, equal sharing accommodates all DRB request by degrading the bandwidth enjoyed by every DRB at an AP. Equal sharing was first proposed by Jeng and Lin [20] for GPRS. Implementing this policy in GPRS incurs some costs. For the LWA implementation of ITRI, this policy can be exercised with negligible cost by executing the procedure described in Fig. 9. In our implementation, a DRB request arriving at AP k is first assigned to the eNB with the minimum bandwidth w. If the eNB is not available, then the request is assigned to AP k with the equal sharing policy. In this approach, AP k follows the equal sharing policy. On the other hand, the eNB still guarantees the minimum bandwidth for a DRB, which is preferred by the mobile operators.

The performance of equal sharing for APs can be modeled as a two-stage queuing system, where the placement of the servers at the two stages reverses that of the AP-first policy. That is, the first stage has an M/G/M/M queue for the eNB. The second stage has K M/G/∞ queues for AP k where $1 \le k \le K$. Let $p_{b,K+1}$ be the probability that a DRB request cannot be served at the eNB. Following (1), we have $p_{b,K+1} = B(\sum_{k=1}^{K} \rho_{k,}, M)$. The DRBs of AP k that cannot be served at the eNB will overflow to AP k with the rate $p_{b,K+1}\lambda_k$. From (4), $\pi(p_{b,K+1}\rho_{k,}, i)$ is the probability that there are i DRBs accommodated by AP k. Let $\Theta_k w$ be the portion of AP k's bandwidth assigned to a DRB, where $0 < \Theta_k \le 1$. Then a DRB enjoys w of AP k's bandwidth (i.e., Θ_k=1) with the probability $\sum_{i=0}^{M_k} \pi(p_{b,K+1}\rho_{k,}, i)$, and is assigned $\frac{M_k w}{M_k+i}$ of the bandwidth (i.e., Θ_k=$\frac{M_k}{M_k+i}$) with the probability $\pi(p_{b,K+1}\rho_{k,}, i + M_k)$. The average bandwidth assigned to a DRB can be indicated by $\mathrm{E}[\Theta_k]w$, where

$$\mathrm{E}[\Theta_k] = \sum_{i=0}^{M_k} \pi(p_{b,K+1}\rho_{k,}, i) + \sum_{i=1}^{\infty} \left(\frac{M_k}{M_k+i}\right) \pi(p_{b,K+1}\rho_{k,}, i + M_k) \quad (15)$$

V. Numerical Examples

To evaluate the performance of switched LWA, we consider a baseline LTE/WLAN system (abbreviated as the baseline system) that does not support switched LWA policies. In this baseline system, the LTE and the WLAN resources are separately managed, where a UE decides the usage of LTE and WLAN for its DRBs, and connects them to LTE and WLAN directly. In other words, the eNB and the Wi-Fi APs only see the DRB requests sent to them, and cannot switch the DRBs between LTE and WLAN. The baseline system is modeled as follows. The DRB requests arriving at AP k are independently sent to the eNB or AP k by the UE. Therefore, the eNB and the K APs can be modeled as K+1 independent queues. Consider the DRB requests arriving at AP k. Assume that through random decisions of the UEs, $\alpha\rho_k$ of the traffic load are assigned to AP k and $(1-\alpha)\rho_k$ of the traffic load are assigned to the eNB. Therefore, the blocking probability $p_{b,k}$ for the DRBs processed at AP k and the blocking probability $p_{b,K+1}$ for the DRBs processed at the eNB are

$$p_{b,k} = B(\alpha\rho_{k,}M_k) \text{ and } p_{b,K+1} = B(\textstyle\sum_{k=1}^{K}(1-\alpha)\rho_{k,} M) \quad (16)$$

From (16), the blocking probability $p_{B,k}$ for a DRB arriving at AP k (and is processed either at AP k or the eNB) is

$$\begin{aligned} p_{B,k} &= \alpha p_{b,k} + (1-\alpha)p_{b,K+1} \\ &= \alpha B(\alpha\rho_{k,}M_k) + (1-\alpha)B(\textstyle\sum_{k=1}^{K}(1-\alpha)\rho_{k,} M) \end{aligned} \quad (17)$$

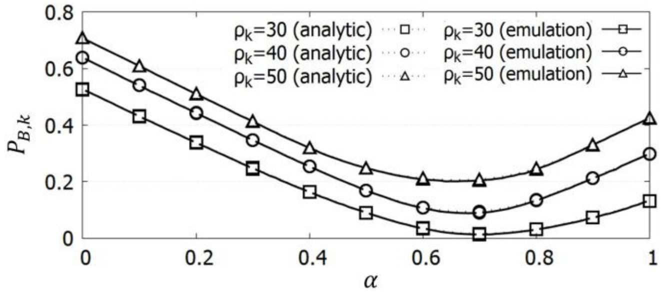
Since the UEs decide whether the DRB requests go to LTE or WLAN, the α parameter cannot be controlled. We make a favorable assumption for the baseline system that the UEs are “smart” enough to select the optimal value for the α parameter. We compare the switched LWA policies and the “optimal” baseline LWA system by the analytic models derived in the previous section and (17). Note that the only assumption made in our analytic models is Poisson arrivals. This widely made assumption in telecom traffic engineering is general and fits the behavior of real traffic. The DRB holding times have general distribution. The beauty of the LWA policies is that the performance is not affected by the DRB holding time distribution. These analytic models are validated against the emulation and the event-driven simulations. The event-driven simulation model follows the same approach used in [19, 23, 24, 25, 18]. In the emulation, the ITRI RRM actually generates the DRB connections to the UEs covered by three Wi-Fi APs overlapped with the eNB. The “TP-Link Archer C9” Wi-Fi APs are used and the UEs are engineering handsets powered by MTK (Helio X10 chipset). The LWA system parameters are summarized in Table 1.

Table 1. LWA System Parameters.

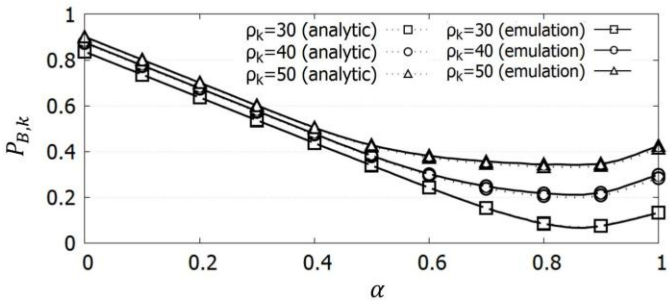
Parameter	Description
Carrier Frequency	2.3 GHz (LTE), 5G Hz (WLAN 802.11ac)
Bandwidth	20MHz (LTE), 80MHz (WLAN)
LTE output power	24 dBm
LTE mode	TDD band 40; Non-CA
LTE MCS	28
WLAN Channel	36-44

Fig. 10 plots $p_{B,k}$ against α and $\rho_{k,}$, where K=1 and 3. The solid curves represent the emulation results and the dashed curves represent the analytic results. The figure indicates that the analytic model is consistent with the emulation. Similarly, Fig. 11 (b) indicates that the analytic $\mathrm{E}[\Theta_k]$ values (the dashed curves) and the emulation results (the solid curves) are consistent. For other switched LWA policies, the analytic analysis and emulation results are consistent, and the details are omitted.

Fig. 10 indicates that optimal α values exist, which are different for different sets of parameters. The figure shows that $p_{B,k}$ for the optimal α is better than that of the random selected α by 90.49% for K=1, and 79.25% for K=3. In the remainder of this section, we consider optimal α to favor the performance of the baseline system.

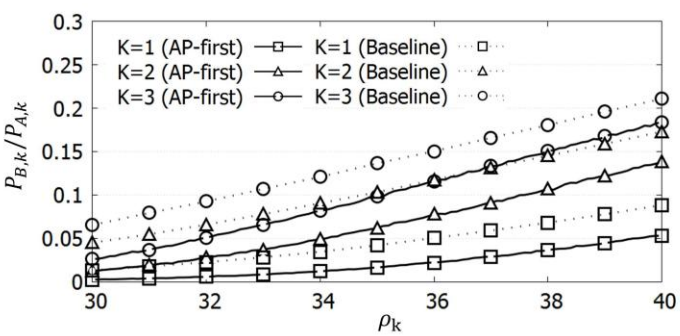


(a) K=1

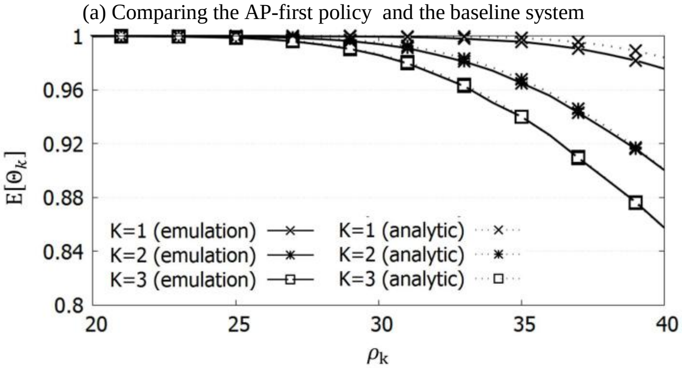


(b) K=3

Fig. 10. Effects of α and ρ_k on $p_{B,k}$ ($M_k = 30, M = 15$).



(a) Comparing the AP-first policy and the baseline system



(b) The equal sharing performance

Fig. 11. Effects of ρ_k and K on $p_{A,k}, p_{B,k}$ and $\mathrm{E}[\Theta_k]$ ($M_k = 30, M = 15$).

Fig. 11 (a) plots $p_{B,k}$ and $p_{A,k}$ against α and ρ_k, where $M_k = 30,$ and $M = 15$. The figure indicates that the AP-first policy outperforms the baseline system by 40.13%-82.18% for K=1, 19.93%-71.92% for K=2, and 12.85%-60.03% for K=3. Fig. 11 (b) plots $\mathrm{E}[\Theta_k]$ against ρ_k and K. The figure indicates that for $\rho_k \leq 20$, $\mathrm{E}[\Theta_k] = 1$. By increasing ρ_k from 20 to 40, $\mathrm{E}[\Theta_k]$ decreases by around 2% (K=1), 10% (K=2), and 12% (K=3). These results indicate that equal sharing can accommodate all DRB requests by slightly reducing the bandwidth of each DRB.

Fig. 12 plots $p_{R,k}$ and $p_{A,k}$ against α and ρ_k, where $M_k = 30$, and $M = 15$. The figure indicates that the RoD outperforms the AP-first policy by 8.76%-29.58% for K=2 and 9.9%-36.64% for K=3.

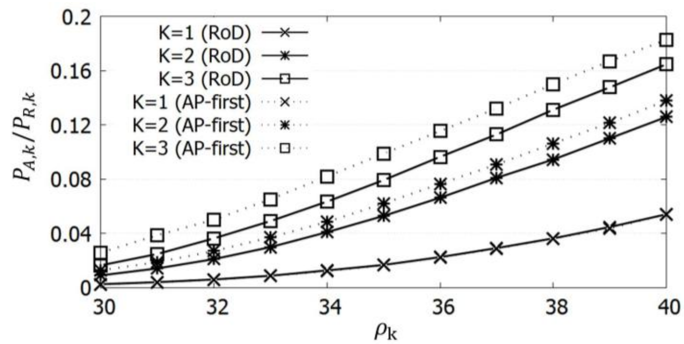


Fig. 12. Effects of ρ_k and K on $p_{A,k}, p_{R,k}$.

To conclude, the AP-first policy significantly outperforms the optimal baseline system, and the RoD outperforms the AP-first policy.

VI. Conclusions

This paper proposed a RRM implementation for LWA. We described the ITRI's LWA architecture and measured the delay times of the LWA procedures. The measurements indicate that ITRI's implementation has the time complexity with low variances. We proposed two types of switched LWA policies: the guaranteed bandwidth and the equal sharing policies. We showed that the switched LWA policies can be implemented at the ITRI's RRM with negligible overhead. We then conducted emulation, simulation and analytic analysis to evaluate the performance of the switched LWA policies. Our study indicates that switched LWA can effectively enhance the DRB admission of the LWA as compared with a LWA system that does not exercise any switched LWA policy. The beauty of the LWA policies is that the DRBs' blocking probability is not affected by the DRB holding time distribution.

In the future, we will explore more switched LWA policies for different application scenarios. For example, equal sharing can be exercised among the eNB and the APs, or repacking can be implemented with equal sharing. We will also study split DRB policies exercised at the PDCP. We are implementing WLAN uplink transmission based on 3GPP R14, and will consider the issues for the LWA uplink transmission. We will also investigate inter-cell load balancing with 200 commercial LWA eNBs.

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