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Date: 11 August 2016  
To: Liaison Coordinator, 3GPP  
Requested distribution to: Satoshi Nagata, Chairman of 3GPP TSG RAN WG1  
From: Wi-Fi Alliance  
RE: Response to Liaison Statement on coexistence simulation results for DL only LAA

Dear Liaison Coordinator,

Wi-Fi Alliance requests that the attached report be distributed to the Chair of the 3GPP TSG RAN WG1, as a response to the 3GPP liaison statement on coexistence simulation.

Best Regards,

Tina Hanzlik  
Wi-Fi Alliance Staff

Date: 12 August 2016

To: 3GPP TSG RAN WG1

From: Wi-Fi Alliance

RE: Response to Liaison Statement on coexistence simulation results for DL only  
LAA

This document has been prepared to address questions raised by 3GPP liaison statement R1-161396, which provides questions about simulation results originally presented in Wi-Fi Alliance contribution R1-156621. Simulation results of 3GPP scenarios for Rel. 13 LBT coexistence performance were contributed to 3GPP RAN1 for the November 2015 meeting, and provided several performance observations. The simulations were conducted with the ns-3 discrete-event system simulator, which was extended in 2015 for closer alignment with the methodology described in 3GPP TR36.889.

This document is organized as follows. Section 1 is a response to the liaison statement questions asked in R1-161396. Section 2 summarizes changes made to the ns-3 simulator, and how such changes affect the results presented in R1-156621.

## Section 1. Responses to liaison questions

**Question 1:** What is the reason not to utilize ITU channel model for system simulations? In order to be able to compare and better understand the results, it would be highly beneficial to provide at least one set of results that follow the 3GPP methodology.

When the simulation effort was originally chartered, the intent was to apply it to both future 3GPP and IEEE 802.11ax standardization efforts. Once the decision was later taken to focus on a 3GPP contribution, other areas of alignment with TR36.889 were prioritized above replacing the channel model. However, the ITU InH model is now supported in the latest version. In general, the simulator was aligned to TR36.889 methodology as much as time and resources permitted. Since R1-156621 was published, additional work (described in Section 2.1) was performed on the simulator to further improve the alignment. Updated results provided in Section 2 contain the following improvements:

- Use of the ITU InH indoor propagation path loss and shadowing model
- More efficient scheduler interaction with the channel access mechanism, allowing channel reservation signals to be significantly reduced
- Changes to TCP initial congestion window (increased from 1 segment to 10 segments) and to TCP segment size (increased from 536 to 1448 bytes) to allow for faster initial window growth and more efficient use of channel reservations
- Configuration of MIMO for LAA nodes (SISO was used in R1-156621)
- Changes to various LBT parameters agreed at December 2015 plenary
- Changes to how control signals are sent on licensed and unlicensed channels, including Discovery Reference Signals on the unlicensed channel
- Addition of a voice application designed to collect statistics corresponding to TR36.889 outage criteria
- The underlying ns-3 base simulator was upgraded from version 3.23 to the current ns-3 mainline (just before version 3.26 release), which brings improvements to the ns-3 802.11n Wi-Fi model and a refactored TCP congestion control implementation.

**Question 2:** What is the LAA rate control algorithm and why was LAA peak throughput limited to 40 Mbps? For the given assumptions, LAA can support rates up to 150 Mbps in the unlicensed spectrum.

LAA rate control is the same as in LTE; it assigns the maximum MCS that allows the target BLER of 10%. MCS selection is adapted based on the actual PHY layer performance, according to the received CQI feedback.

LTE can support rates approaching 150 Mbps in this 20 MHz scenario using 2x2 MIMO, 64 QAM code rate. However, R1-156621 showed peak rates of around 37 Mbps for FTP.

There were several reasons for this: i) use of LAA SISO instead of LAA MIMO, ii) idle times enforced by CCA algorithm, and iii) idle times due to reservations.

For the first issue, during the time that a MIMO abstraction was under development for the Wi-Fi models, we configured the LAA mode to SISO, for an equal comparison. We later enabled MIMO for Wi-Fi but did not add MIMO back for LAA when preparing R1-156621; this was an oversight on our part. Enabling MIMO will roughly double the observed peak rate, but not approach 150 Mb/s, due to idle times enforced by CCA algorithm and reservation signals.

Specifically, idle times result from the use of reservation signals and the need to idle for at least one subframe after a TXOP concludes, to allow other nodes to contend. The ns-3 implementation does not support partial subframes, so LAA transmission bursts start and end at the subframe boundary. When the channel is released by a node at the subframe boundary, other nodes will contend and win the access e.g. after not less than the minimum LBT interval (43 us). In this case, the node will need to reserve the channel until at least at the end of following subframe boundary (this is what happens in the current implementation; in the experiments of R1-156621, the reservation was even longer). In the experiments for R1-156621, a maximum TXOP of 4 msec was considered. The maximum rate is bounded by a factor of 4/5 (4 msec on, 1 msec off) even when there is no contention. However, we also made use of a conservative scheduler, which started scheduling data only after the channel was won, thus requiring a long reservation signal (at least 2 msec) that consumed also a large portion of the 4 msec TXOP, meaning that each TXOP could perhaps allow transmission of either one or two subframes worth of data.

Current simulations using 2x2 MIMO, an optimistic scheduler and a larger (8 msec) TXOP are able to achieve higher FTP data rates, peaking instead at around 133 Mb/s.

**Question 3:** Given that both LAA and Wi-Fi have identical channel access mechanisms, is the limitation to peak throughput to 40 Mbps the main reason for higher channel occupancy by LAA or was there some other reason?

LAA and Wi-Fi have similar but not identical access mechanisms, with some differences in backoff algorithm and TXOP limits, and the use of reservation signals to align on subframe boundaries. Differences in time occupancy of the channel are also affected by the amount of control data on the channel (such as DRS signals vs. beacons). As discussed above, in R1-156621, the simulations made use of a conservative scheduler that requested channel access from the LBT access manager before scheduling the data, and if granted, incurred a 2 msec reservation signal before data was actually sent in a future TTI. For file transfers, the reservation signal can be somewhat amortized across a long TXOP. However, for more intermittent packets like TCP handshake and low data rate, constant bit rate traffic, the channel occupancy for a small amount of data can be relatively large. For current results, the improved efficiency of the implementation

(optimistic scheduler, use of longer TXOPs) has decreased the difference in channel occupancy time between LAA and Wi-Fi.

**Question 4:** What is the reason for large number of TCP timeouts, given the same unlicensed spectrum access mechanism for LAA and Wi-Fi and in addition, given the ability of LAA to transmit TCP ACKs on licensed spectrum without any delay?

As explained in R1-156621 section 3.2, the channel occupancy due to the scheduler and reservation signal design was quite high for this scenario, ranging from 60% to 83%. As a result, many flows incurred drops for which they were not able to recover without taking a TCP timeout, due to the congestion on the link. The TCP ACKs were returned on a licensed channel and did not contribute to the timeouts; the forward losses caused the timeouts. In summary, despite the specification of a similar access mechanism, the way that it was implemented for LAA due to LTE implementation constraints resulted in a highly unequal proportion of time required for LAA to send TCP flows.

**Observation 1:** It should be assumed that LAA is utilized to offload bulk traffic to unlicensed spectrum with resource utilization is efficient. Low bit rate low latency traffic, where meeting QoS is critical and buffering is not feasible, would be routed to licensed spectrum. LTE has standardized mechanisms how to meet desired QoS on air interface and core network.

**Question 5:** Could Wi-Fi Alliance/CTTC provide corresponding simulation results modelling low bit rate low latency Wi-Fi services against LAA bulk traffic offload?

Since the 3GPP contribution was written, a voice application corresponding to the specification in TR36.889 has been added, and the simulator was instrumented to track latency statistics and outage occurrences, according to TR36.889 outage criteria of 98%ile latency greater than 50 msec. The voice application replaces FTP on two nodes in the operator B (Wi-Fi) network, and sends packets classified as access category AC\_VO. In general, when using the FTP and TCP traffic models in our current code and a FTP lambda value of 2.5, the low latency application performance is slightly worse in the Step 2 network (the configuration that corresponds to LAA bulk traffic offload), in terms of packets lost and latency, but latencies and losses do not exceed the threshold criteria defined for outage conditions. For example, in the base FTP configuration described further in Section 2, the 98%ile latency for the two voice flows in the Step 1 Wi-Fi network is 3.3 msec, while for LAA it ranges from 4.7 to 5.5 msec depending on the energy detection threshold used. For TCP, the 98%ile latency for Wi-Fi Step 1 network is 3.9 msec, while for LAA it ranges from 5.5 to 6.0 msec. CDF plots for voice latency statistics are provided in Section 2.

**Question 6:** Could Wi-Fi Alliance/CTTC provide further information on the ns-3 release number used for the simulations referenced in [2], so that experts in 3GPP could analyse and reproduce the results?

The ns-3 code used in these simulations is not yet in the mainline ns-3 repository but in a separate branch that is tracking the mainline. The URL for the Mercurial repository is <http://code.nsnam.org/laa/ns-3-lbt>. A wiki page describing how to reproduce results in these documents is maintained at <https://www.nsnam.org/wiki/LAA-WiFi-Coexistence>, and instructions are also provided in README files in the code. The simulations corresponding to R1-156621 are mostly aligned with revision 18 of the repository referenced above, with the additional modification of a maximum LBT TXOP of 4 msec. The simulations corresponding to the revised results in this document can be reproduced by using revision 66 of the same repository.

**Question 7:** A 2ms MAC-to-PHY delay is mentioned in the LBT modelling section of the evaluation assumptions in [2]. It is RAN1's opinion that the MAC-to-PHY delay should not impact the unlicensed band channel occupancy.

Is the MAC-to-PHY delay in the evaluations applied after trying to contend for the channel (and channel reservation is assumed for the corresponding duration before the useful data packet transmission)?

Yes, in R1-156621, the delay occurs after trying to contend for the channel. This is the main reason for the long reservation and high channel occupancy incurred in the channel. When the eNB is granted access, it starts scheduling the data, which will reach the air 2 msec afterwards.

After discussion with different vendors, we later aligned with the RAN1 view of not having this implementation delay impact the channel occupancy. Current results are not affected by this implementation choice, as the data is scheduled in advance and the channel is requested only if the data is already available for transmission.

## 2. Comparison of current results with previously reported results

### 2.1 Changes to ns-3 simulator since R1-156621

ns-3 software for LBT is maintained in a public Mercurial repository located at <http://code.nsnam.org/laa/ns-3-lbt>. The version of this repository that aligns most closely with R1-156621 is revision 18:ee4c3f5f6064 (Sunday Nov 29, 2015).

The following changes were made since the simulator version used in R1-156621:

#### 1) Scheduler interaction with category 4 LBT algorithm

One area of the LBT specification that leaves room for implementation is the way in which the physical layer sends a reservation signal to reserve the channel. Since transmissions must occur on subframe boundaries (in our implementation), but the CCA algorithm may operate asynchronously to such boundaries, there will be occasions where the LBT node gains access but has to wait until the subframe boundary to start transmission. There is also a 2 msec delay (MAC to PHY delay) that occurs from the time that data is scheduled in the MAC (frame #n) and when the transmission can occur (frame #(n+2)). In our original implementation, we generated a reservation signal between frame #n and #(n+2), resulting in an inefficient use of the channel. In other words, the LBT implementation waited for a transmit opportunity (TXOP), and once obtained, performed scheduling, generated a reservation for 2 msec, and then started transmission. This implementation, while strictly conformant, caused inefficient use of the channel for bursty data (too much channel usage due to reservation signals).

After discussion with some vendors, we undertook a different implementation whereby the channel access request is deferred until data is already scheduled and ready for imminent transmission on next subframe. This results in a much shorter reservation signal and more efficient use of the channel.

The ns-3 LBT simulator still provides the choice of either the first (implementation 1) or second (implementation 2) options, but the default is the second option.

#### 2) TCP parameters

R1-156621 used default ns-3 TCP parameters of 536 byte segment size and initial congestion window of one segment. Some comments on this configuration suggested that better coexistence results would be obtained if the TCP initial congestion window was set to 10 and the segment size set to 1440. We therefore have changed these defaults.

#### 3) LAA MIMO configuration

R1-156621 used an LAA SISO configuration, yielding maximum throughputs for the configuration of about 40 Mb/s for FTP. This configuration was due to earlier comparisons with Wi-Fi before ns-3 Wi-Fi models had a MIMO capability. Around the time of the R1-156621 contribution, the Wi-Fi was upgraded to MIMO, but the LAA was left as SISO. In the current code, we support the default ns-3 2x2 MIMO abstraction, with both spatial and transmission diversity, and up to MCS 28.

#### 4) Changes to various parameters agreed at December plenary

The finalization of 3GPP resulted in agreements to update a number of parameters and LBT algorithms, including the initial and extended CCA defer at 43 microseconds, the LAA CCA slot time of 9 microseconds, the energy detection threshold as tunable around the -72 dBm level, the maximum TXOP duration of 8 msec, the update of the contention window based on a hybrid ARQ (HARQ) feedback rule, and the maximum size of the contention window equal to 63.

#### 5) Modeling of control signals

After consultation with vendors, we made some changes to how control signals are modeled in ns-3. Discovery Reference Signal (DRS) signals are sent during the so called Discovery Signal Measurement Timing Configuration (DMTC) window (6 msec between subframe 0 and 5), with a tunable periodicity of 40/80/160 msec. The periodicity defaults in our tests to 80 msec. DRS transmission is subject to a priority LBT with a fixed defer period of 25 msec. If data is scheduled during the DMTC window, DRS is embedded with data, otherwise it is sent alone without data, and modeled as a transmission occupying 1 msec. The system information (MIB/SIB1) is channeled through the PCell.

6) support of ITU InH indoor model for path loss and shadowing, according to TR36.814, replacing the IEEE 802.11ax indoor channel model.

7) addition of a voice application designed to gather statistics corresponding to TR36.889 outage definitions.

#### 8) underlying ns-3 changes

The R1-156621 simulation models were built on a baseline ns-3 release of ns-3.23. The current simulation models have been ported to ns-3.25, with the Wi-Fi code ported further to the current ns-3 development mainline (which is just prior to the upcoming ns-3.26 release). This port includes improvements to the underlying ns-3 802.11n model (the underlying LTE model is largely unchanged). In addition, the ns-3.25 release contains a refactored TCP congestion control implementation based on the Linux architecture.

## 2.2 FTP results

The following results are reprinted from R1-156621 (Figures 2-1 and 2-2), and then followed by updated simulation results in Figures 2-3 and 2-4. These runs evaluated performance of a 0.5

MB file transfer with an FTP Model 1 application process ( $\lambda=2.5$ ), run over a UDP protocol. The link layer of LAA is RLC-UM. In all runs, the Wi-Fi energy detection threshold is -62 dBm, while the LAA energy detection threshold was varied between -62 dBm and -82 dBm (in the contribution, only the -62 dBm and -82 dBm cases were plotted). We observed in the original contribution that lowering the LAA ED threshold to -82 dBm benefits Wi-Fi performance, especially in terms of latency, but does not allow the Wi-Fi network to recover and achieve the same performance as the Wi-Fi over Wi-Fi case. The reason is that the substituted Wi-Fi network occupies the channel during roughly 4.5% of time at this traffic load, while the LAA network occupies the channel during 12% of time, which increases the probability of Wi-Fi to defer more and to collide with signals received below the -62 dB threshold.

### 2.2.1 R1-156621 results

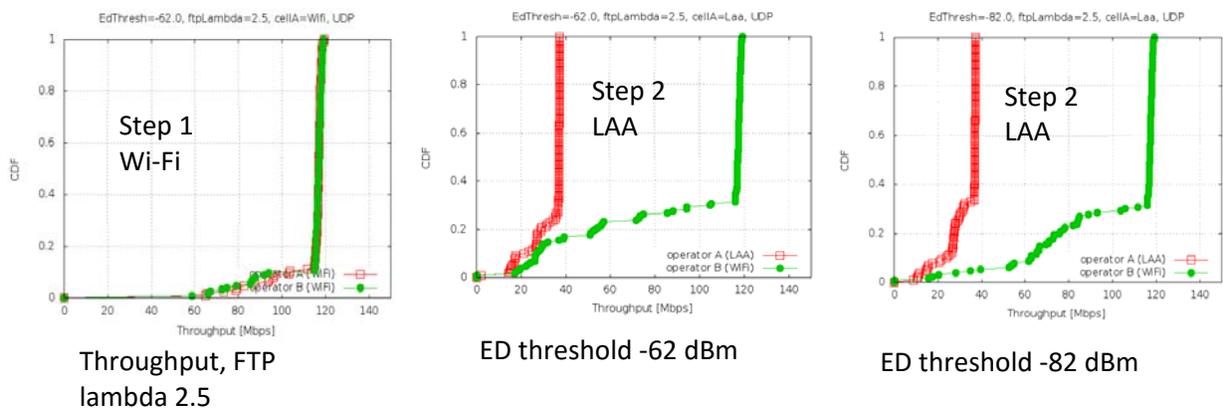


Figure 2-1 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over UDP (Figure 3-1 of R1-156621).

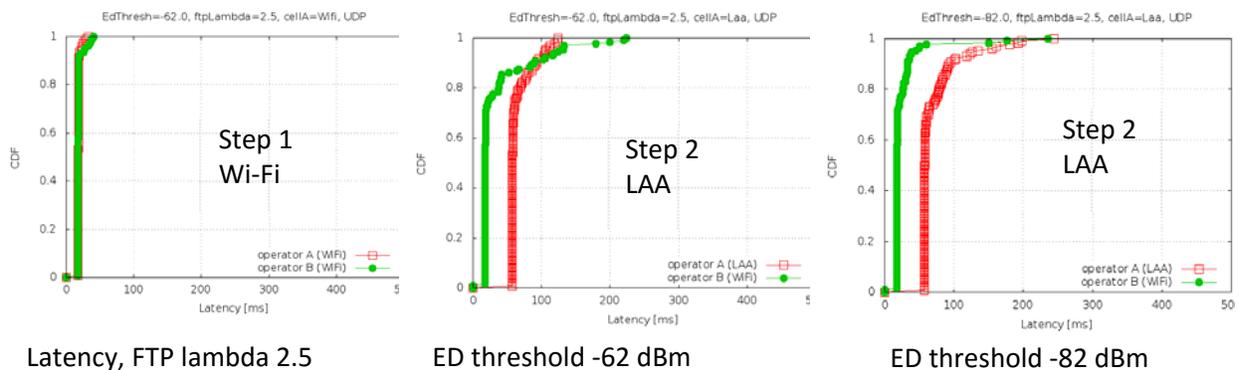


Figure 2-2 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over UDP. (Figure 3-2 of R1-156621)

## 2.2.2 Current results

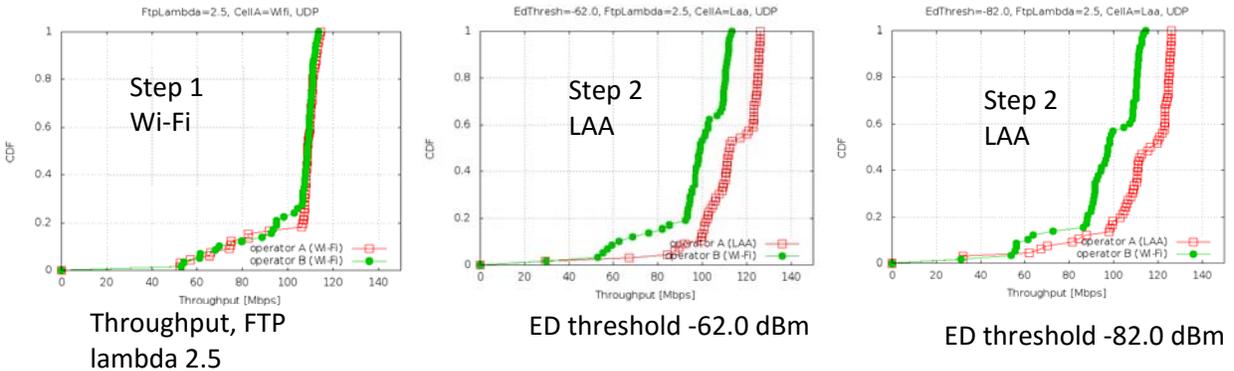


Figure 2-3 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over UDP (revised)

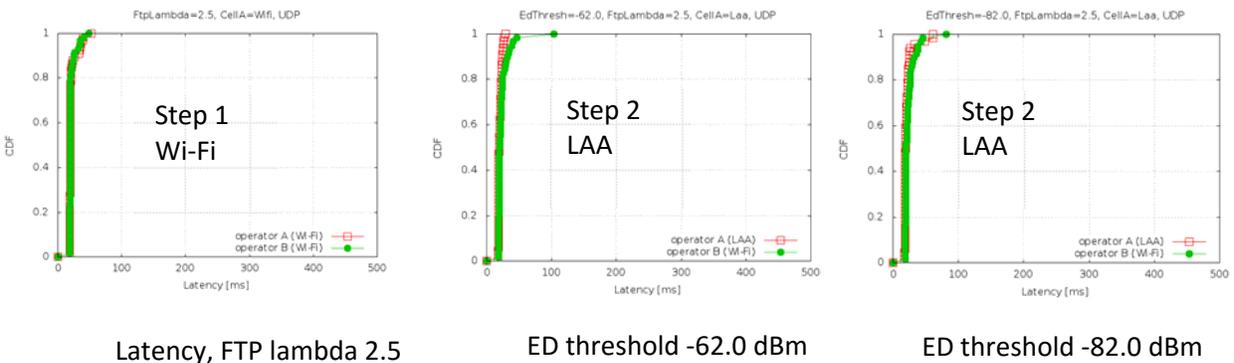
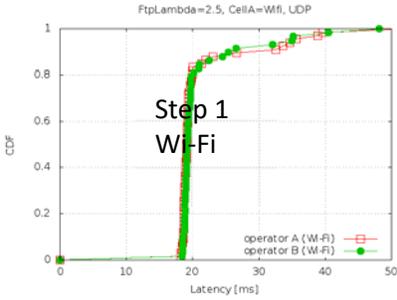


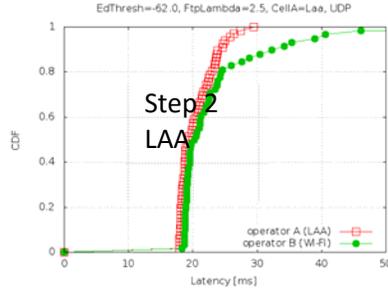
Figure 2-4 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over UDP (revised).

## 2.2.3 Discussion

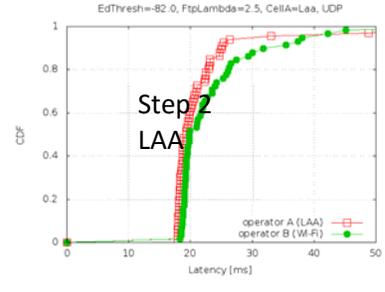
The performance for FTP file transfers is improved due to the series of changes outlined in Section 2.1 above. In particular, Figure 2-1 and 2-3 may be compared, and Figure 2-3 shows less throughput degradation for the non-replaced Wi-Fi network (the green curves). Also, Figure 2-2 shows degradation in step 2 Wi-Fi network latency (particularly at -62 dBm energy detection threshold) when the step 1 Wi-Fi network is replaced by LAA, while Figure 2-4 shows little if any degradation in latency observed by the step 2 Wi-Fi network. We believe that the primary reason for the improvement is due to more efficient channel usage due to LAA.



Latency, FTP lambda  
2.5



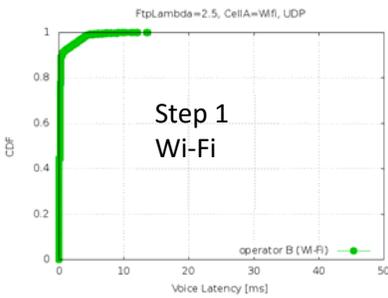
ED threshold -62.0 dBm



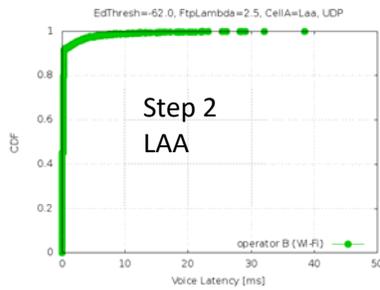
ED threshold -82.0 dBm

Figure 2-5 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over UDP (revised).

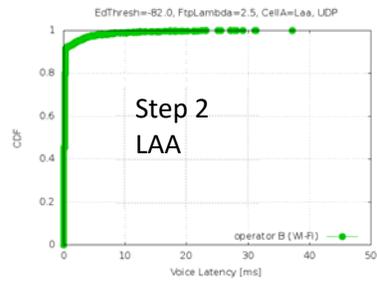
Figure 2-5 replots Figure 2-4 with increased resolution. The figures show only a small amount of degradation in the latency values for the Step 2 network variants.



Voice latency, FTP  
lambda 2.5



ED threshold -62.0 dBm



ED threshold -82.0 dBm

Figure 2-6 CDF of per-packet voice flow latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when two FTP flows in the operator B network are replaced by voice flows.

Figure 2-6 provides CDF plots of the observed per-packet latency for the voice application mentioned in response to question 5 of the liaison statement. It was mentioned earlier that the 98%ile latency for the two voice flows in the Step 1 Wi-Fi network is 3.3 msec, while for LAA it ranges from 4.7 to 5.5 msec depending on the energy detection threshold used. Figure 2-6 shows the corresponding CDF, showing that although the CDFs for per-packet latency exhibit slightly more latency in the LAA case, observed values are still short of the 50 msec outage threshold.

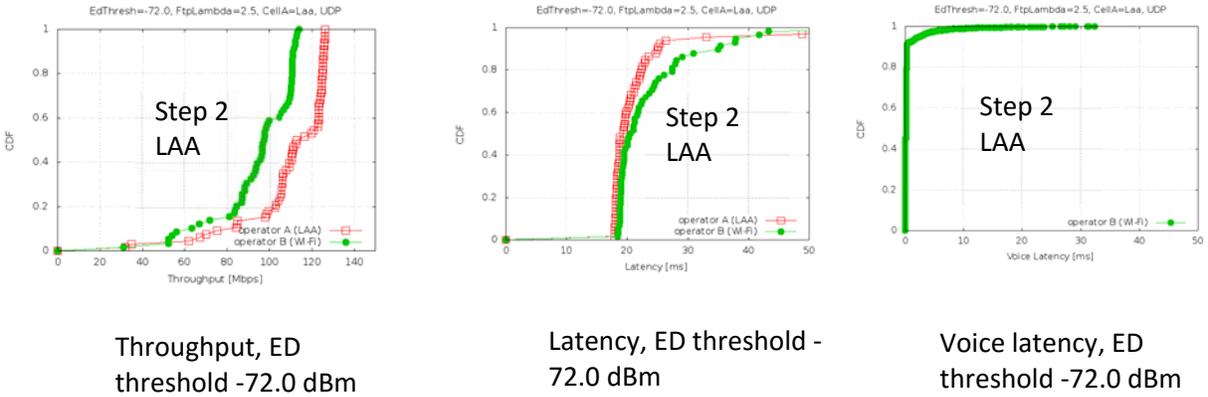


Figure 2-7 CDFs of throughput, latency, and per-packet voice flow latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi FTP transfers for LAA energy detection threshold of -72.0 dBm.

Figure 2-7 provides throughput, latency, and voice latency results for the LAA -72.0 dBm energy detection threshold (the Energy Detection Threshold Adaptation Procedure is not implemented). These figures can be compared with similar ones at -62 dBm and -82 dBm found in Figures 2-3, 2-5, and 2-6.

### 2.3 TCP results

We evaluate performances of FTP (lambda=2.5), run over a TCP protocol. The link layer of LAA is RLC-AM.

This use case was not studied in 3GPP but we decided to include it in our study since FTP is typically operated over TCP in practice, and since ns-3 has full-stack simulation capabilities permitting the insertion of TCP.

#### 2.3.1 R1-156621 results

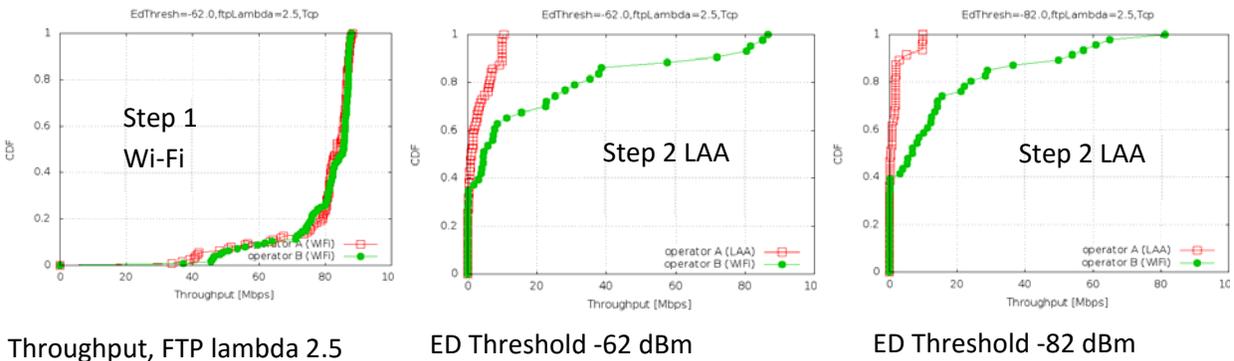


Figure 2-8 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over TCP (from Figure 3-3 of R1-156621).

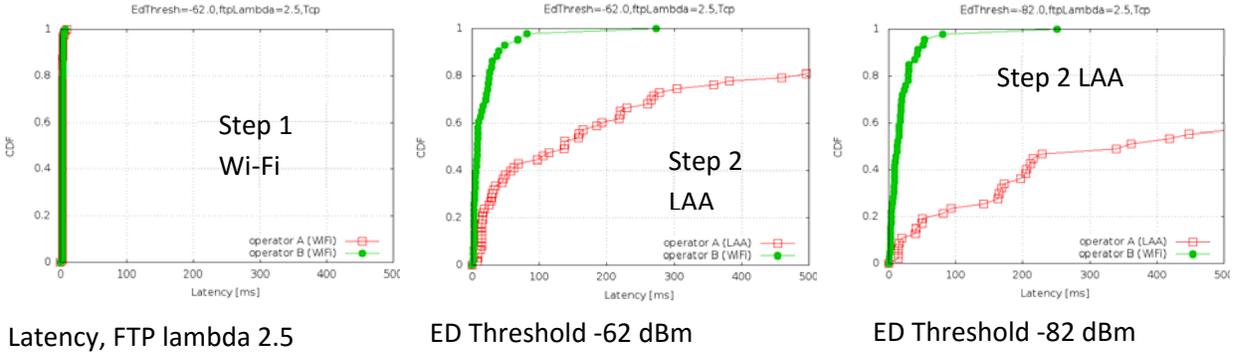


Figure 2-9 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over TCP (from Figure 3-4 of R1-156621).

In figures 2-8 and 2-9, the overall performance for step 1 was similar to that of the UDP case, but the performance for the step 2 LAA scenarios was much different. The LAA channel occupancy dramatically increased (reaching values in the range of 60-83%, depending on the simulation configuration) and the Wi-Fi Step 2 network performance was seriously impacted by the presence of the step 2 LAA network. The channel occupancy is so high that it dominates the improvements due to energy detection threshold, and even when increasing the LAA sensitivity, the Wi-Fi performance cannot be improved much.

### 2.3.2 Current results

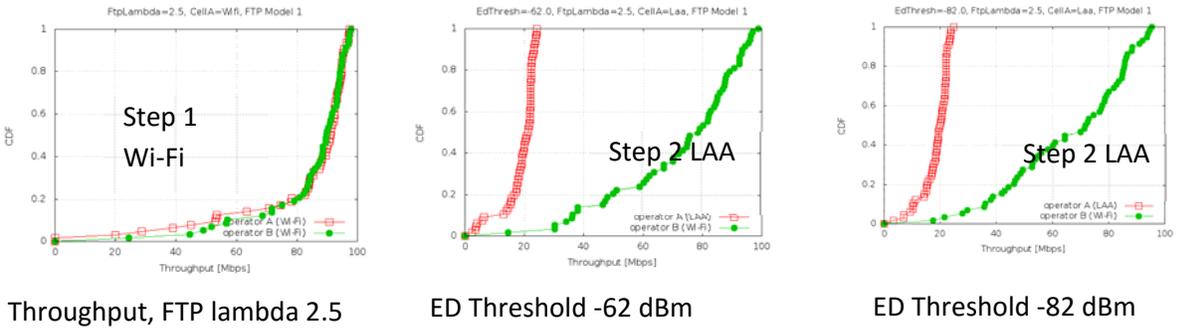


Figure 2-10 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over TCP (revised).

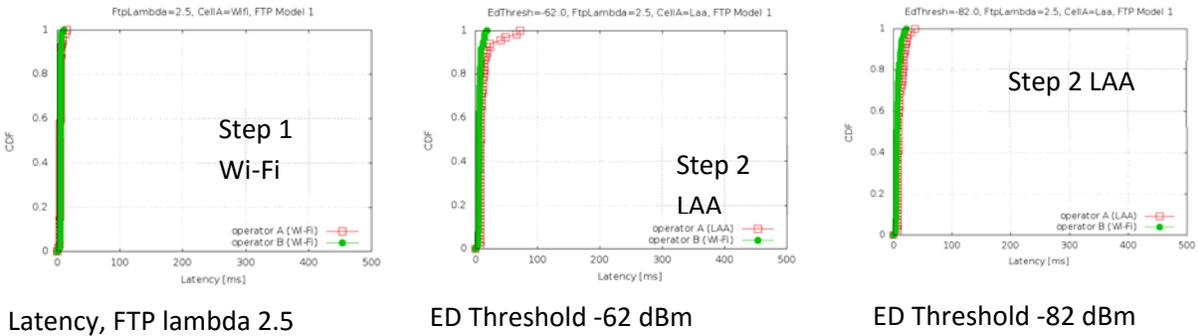


Figure 2-11 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over TCP (revised).

### 2.3.3 Discussion

The performance for TCP file transfers is significantly improved due to the series of changes outlined in Section 2.1 above. In particular, Figure 2-8 and 2-10 may be compared; the throughput impact was substantial due in large part to the inefficient implementation 1 reservation signal causing small amounts of TCP data to occupy a substantial fraction of the channel airtime. The LAA performance is also significantly improved, although the results show throughput limitations due to inherent latencies in LTE and LAA (larger than its Wi-Fi counterpart), and LAA throughput is limited to less than 40 Mb/s despite MIMO. The primary reason, we believe, for the improvement in performance since R1-156621 is due to more efficient channel usage with our updated LAA channel access manager.

Notice that the obtained LAA throughput is the expected one, considering the LAA Round Trip Time (RTT) with TCP, and the FTP files that are being transmitted. In particular, to transmit files of 512 Mbytes with TCP segment size of 1440 bytes, and using a somewhat aggressive initial congestion window of 10 segments, we found by examining traces that we need multiple RTTs of at least 15 msec (sometimes more, depending on buffer occupancy and timings involved). This RTT is higher in LAA than in Wi-Fi (in the step 2 scenario, the median RTT observed for Wi-Fi is approximately 8 msec, versus a median of 19 msec for LAA), and this results in Wi-Fi's higher throughput.

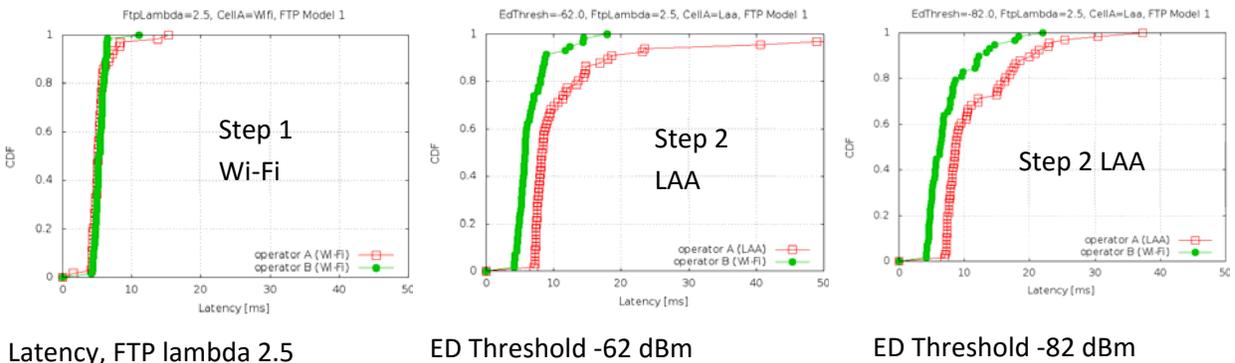


Figure 2-12 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, when FTP model 1 is run over TCP (revised)

Figure 2-12 replots Figure 2-11 with increased resolution. The figures show only a small amount of degradation in the latency values for the Step 2 network variants (compared with Step 1), while showing also the increased LAA latency with respect to Wi-Fi. The latency plotted here is the average downlink data transfer latency for the file transfer and not the round trip latency.

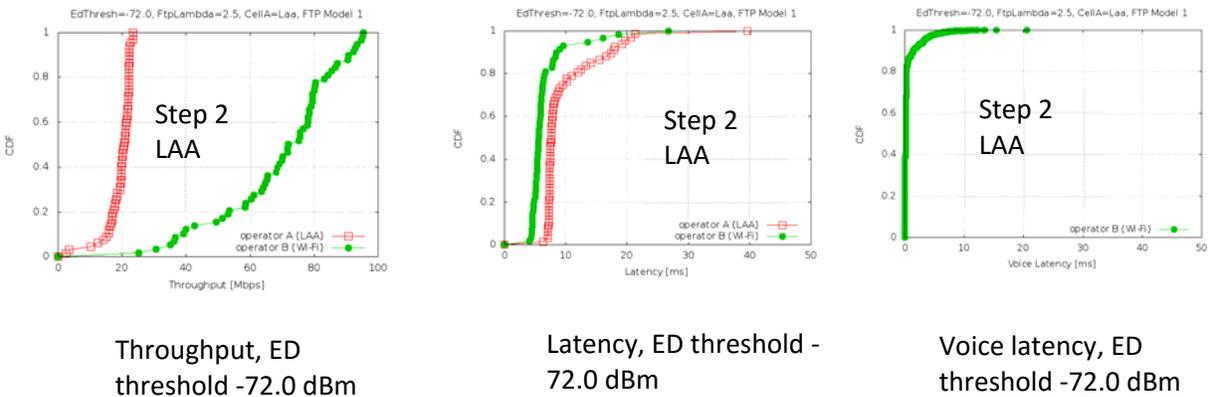


Figure 2-13 CDFs of throughput, latency, and per-packet voice flow latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi FTP over TCP transfers for LAA energy detection threshold of -72.0 dBm.

Figure 2-13 provides throughput, latency, and voice latency results for the LAA -72.0 dBm energy detection threshold (the Energy Detection Threshold Adaptation Procedure is not implemented). These figures can be compared with similar ones at -62 dBm and -82 dBm found in Figures 2-10 and 2-12.

## 2.4 UDP constant bit rate results

We also experimented with a non-FTP model, in which UDP packets are generated at a constant rate; this is sometimes referred to as the "full buffer" model. Similar to TCP results, when the transmitted rate is reduced (e.g. 75 Kbps per flow) and the channel occupancy is not that high (in general not higher than roughly 60%), Wi-Fi performance is not affected by LAA. On the other hand, when the transmitted rate is higher (e.g. 200 Kbps per node) and therefore the channel occupancy, Wi-Fi performance was highly affected by LAA, as shown in Figure 2-14 and Figure 2-15 (from R1-156621 results).

### 2.4.1 R1-156621 results

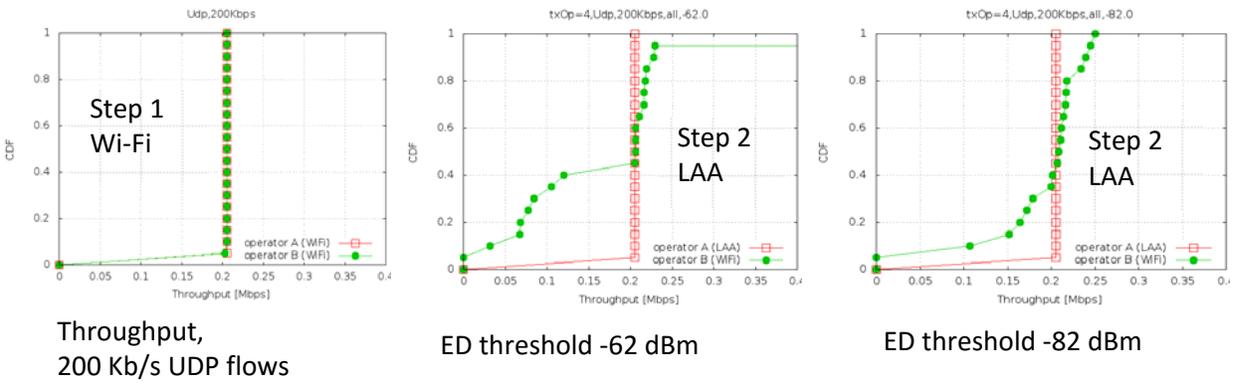


Figure 2-14 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, with UDP 200 Kbps flows (Figure 3-7 from R1-156621).

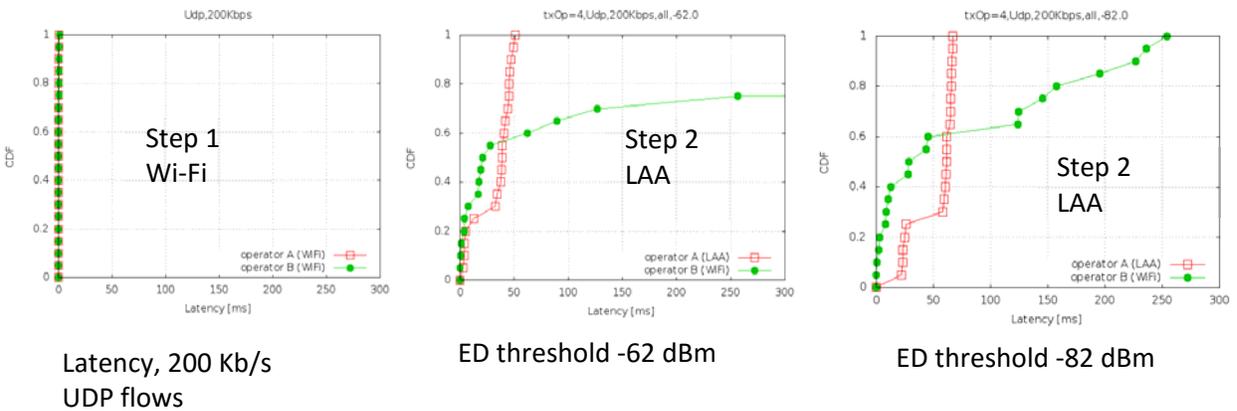


Figure 2-15 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, with UDP 200 Kbps flows (Figure 3-8 from R1-156621).

The above plots in Figures 2-14 and 2-15 are taken from R1-156621 and illustrate performance degradation when LAA replaces Wi-Fi in the step 2 network. The main reason for this is the inefficient usage of the channel due to the channel access method implemented for R1-156621.

## 2.4.2 Current results

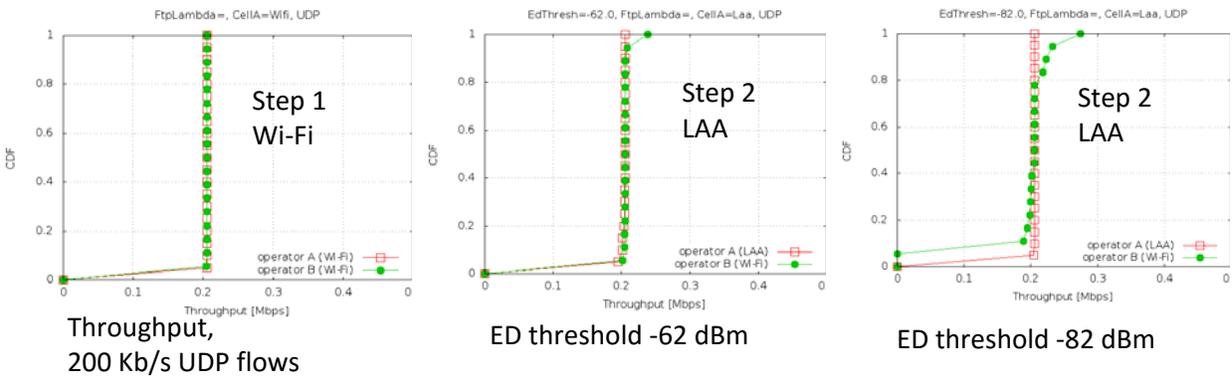


Figure 2-16 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, with UDP 200 Kbps flows (revised).

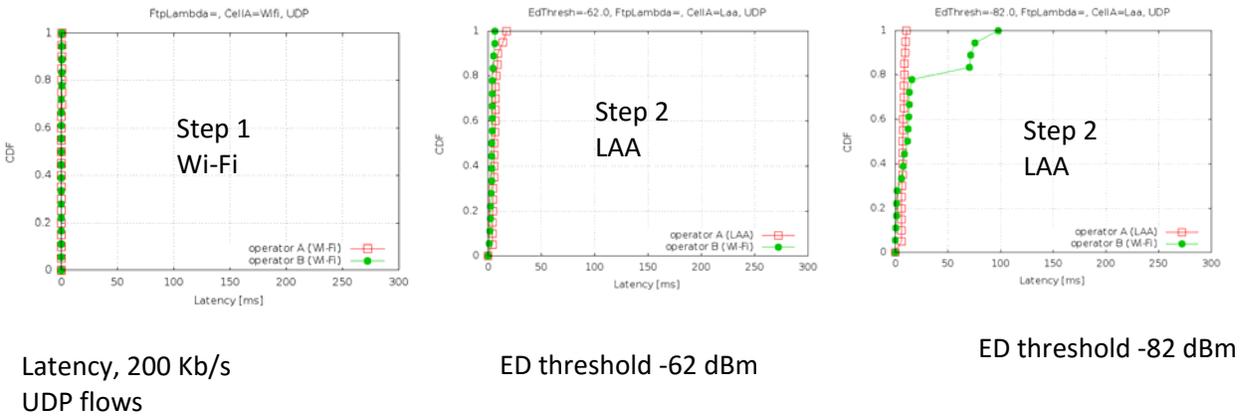
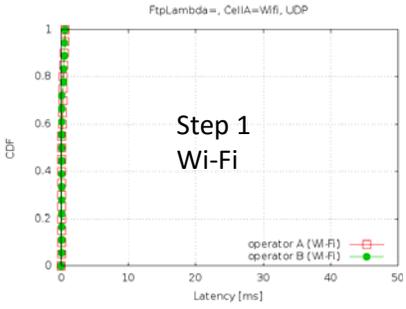


Figure 2-17 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, with UDP 200 Kbps flows (revised).

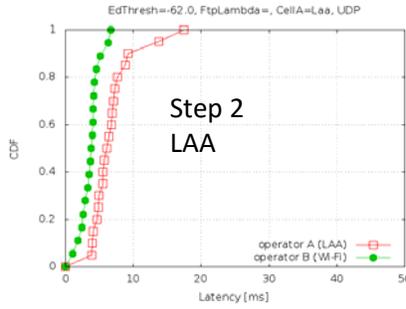
Figures 2-16 and 2-17 repeat the scenario shown in Figures 2-14 and 2-15 (from R1-156621) but with the current simulation models.

## 2.4.3 Discussion

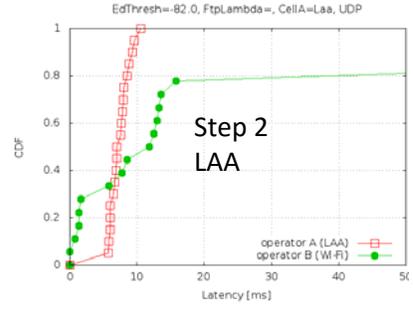
R1-156621 showed the impact of different rates of UDP constant bit rate traffic on the performance of the step 2 Wi-Fi network. In that document, it was shown that a rate of 75 Kb/s did not impact the non-replaced step 2 Wi-Fi network, but that a rate of 200 Kb/s significantly impacted the performance of the non-replaced network. The revised results in Section 2.4.2 illustrate that the performance impact is significantly reduced at 200 Kb/s, due to the improved efficiency in LAA channel access. Due to implementation efficiency improvements discussed above in Section 2.1 item 1), the UDP rate at which differences between Wi-Fi and LAA performance begin to show with the current implementation is higher, such as 400 Kb/s.



Latency, 200 Kb/s  
UDP flows



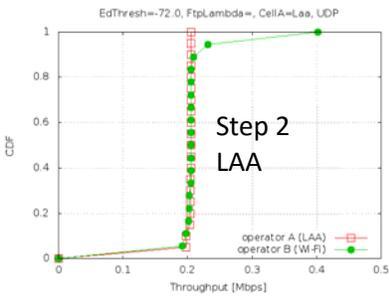
ED threshold -62 dBm



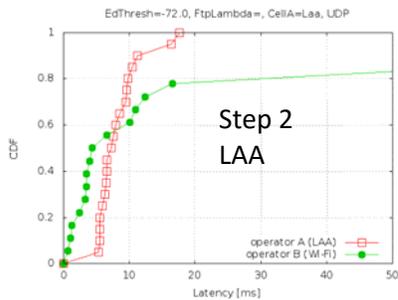
ED threshold -82 dBm

Figure 2-18 Latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, with UDP 200 Kbps flows (revised).

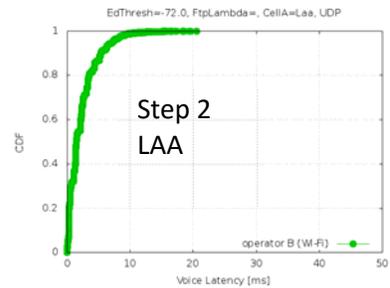
Figure 2-18 replots Figure 2-17 with increased resolution. Unlike Figures 2-5 (FTP/UDP) and 2-12 (FTP/TCP), these figures show that despite the throughput improvements (Figure 2-16), some latency impact due to LAA is still present for Step 2 networks.



Throughput, ED  
threshold -72.0 dBm



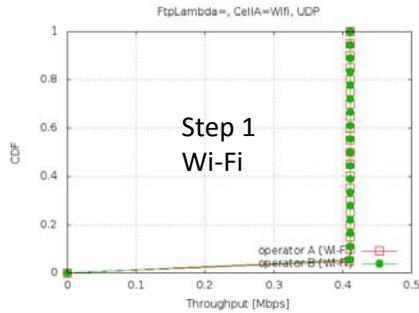
Latency, ED threshold -  
72.0 dBm



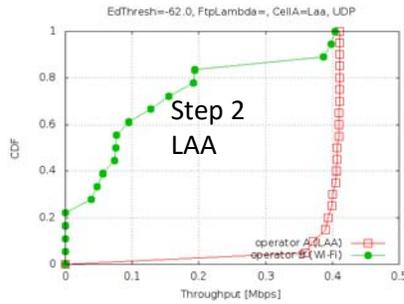
Voice latency, ED  
threshold -72.0 dBm

Figure 2-19 CDFs of throughput, latency, and per-packet voice flow latency performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi FTP over TCP transfers for LAA energy detection threshold of -72.0 dBm.

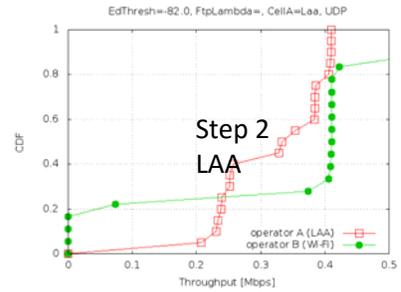
Figure 2-19 provides throughput, latency, and voice latency results for the LAA -72.0 dBm energy detection threshold (the Energy Detection Threshold Adaptation Procedure is not implemented). These figures can be compared with similar ones at -62 dBm and -82 dBm found in Figures 2-16 and 2-18.



Throughput, 400 Kb/s  
UDP flows



ED threshold -62 dBm



ED threshold -82 dBm

Figure 2-20 Throughput performance of Wi-Fi-Wi-Fi and LAA-Wi-Fi, with UDP 400 Kbps flows (revised).

Finally, Figure 2-20 shows results for UDP rates of 400 Kbps, illustrating that effects that were previously shown in R1-156621 at a rate of 200 Kbps are visible at higher data rates, and that the step 2 networks significantly impact the non-replaced Wi-Fi network under such a traffic load.