Google

An Experimental Evaluation of LTE-U/Wi-Fi Coexistence

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LTE in Unlicensed

- Use LTE carrier aggregation to simultaneously operate in licensed and unlicensed spectrum
  - Primary carrier always in a licensed band, secondary carrier(s) in unlicensed 5 GHz bands
  - Not standalone LTE in unlicensed spectrum (e.g., Multefire)
- Two variants:
  - LTE-U: proprietary technology developed by the LTE-U Forum (founding members: ALU, Ericsson, Qcom, Verizon, Samsung) that builds on earlier LTE releases, developed outside of 3GPP
  - LAA: LTE in unlicensed operation being standardized in 3GPP into LTE r13
- Why?
  - Some countries require use of listen-before-talk (LBT) in unlicensed, and 3GPP process can be slow -> LTE-U designed for non-LBT countries (e.g., US), and for faster time to market
  - LAA standardization completing this summer, with products expected ~ 2017

Overview of Wi-Fi MAC

- Uses CSMA/LBT to attempt to prevent multiple simultaneous transmissions
- Wi-Fi device (AP or client) listens to the medium, and waits until the air is clear
  - Air is not clear if:
    - Energy detected at a power level of -62 dBm or higher (ED: energy detection)
    - Wi-Fi preamble detected at a power level of -82 dBm or higher (preamble detect)
      - Many (most?) devices actually detect Wi-Fi preambles to lower levels, e.g., -92 dBm
- Once air is clear, wait a random amount of time (random backoff) - if air still clear, then transmit

LTE-U

- Standard LTE carrier aggregation, except that secondary carrier (in unlicensed) is duty cycled, e.g., 20 msec on/20 msec off
  - One or two 20 MHz carriers in unlicensed 5 GHz (not DFS bands)
  - Duty cycle can be varied in a semi-static fashion
- Coexistence with Wi-Fi and other unlicensed technologies:
  - Channel selection: LTE-U eNB attempts to select 20 MHz channel(s) in 5 GHz where there is no or limited co-channel interference
  - If co-channel interference, then duty-cycle to coexist
- No carrier-sense (i.e. listen and wait before beginning transmission) performed before LTE-U begins transmissions
- In contrast, LAA does perform LBT
  - Specifics being set by 3GPP, with ETSI also playing a role

Overview of Our Work

- Evaluated performance of retail Wi-Fi equipment operating in the presence of emulated LTE-U transmissions
  - LTE-U emulated via a signal generator, using the description of LTE-U coexistence in LTE-U Forum documentation
  - Over-the-air testing, in an RF isolation chamber
- Key Findings:
  - LTE-U duty-cycling can disproportionately reduce Wi-Fi throughput
    - Lack of carrier-sense leads to LTE-U interrupting Wi-Fi mid-frame
  - Moderate power interference from LTE-U can be even more detrimental to Wi-Fi than high-power interference

Wi-Fi/LTE-U Coexistence Testing

- Wi-Fi AP-client pair running TCP/UDP over a 20 MHz channel in U-NII-3, with a single emulated LTE-U eNB operating in the same 20 MHz
- Focus on LTE-U's co-channel sharing mechanism: duty-cycling
  - In dense settings, expect all Wi-Fi channels in U-NII-1 and U-NII-3 to be used
    - LTE-U defined for U-NII-1 and U-NII-3
  - Despite LTE-U channel selection, co-channel sharing by LTE-U and Wi-Fi is very likely
  - Considered different LTE-U duty-cycles and periods
- Wi-Fi energy detect (ED) threshold: A Wi-Fi device does not transmit if it receives energy exceeding the -62 dBm energy-detect threshold
- Measured the effect of LTE-U on Wi-Fi in 2 regimes
  - High-power interference (above ED)
  - Moderate-power interference (below ED)

LTE-U Duty-Cycling Can Disproportionately Affect Wi-Fi

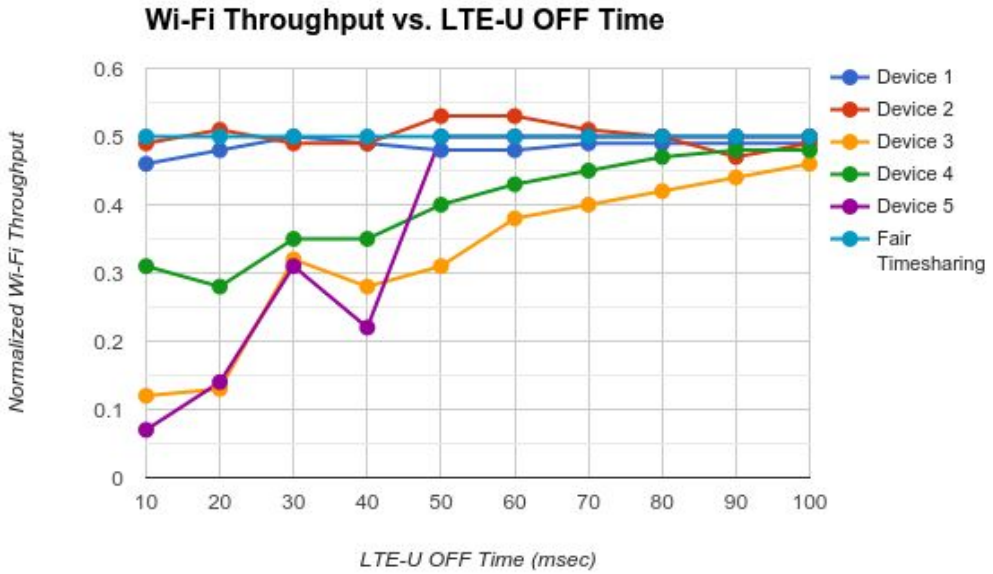
- Above ED: Wi-Fi AP, Wi-Fi client, and LTE-U eNB all hear each other well above ED (-62 dBm)
- If LTE-U uses an X% duty-cycle, is Wi-Fi throughput reduced (relative to its LTE-U-free throughput) by X%?

- Our finding: Sometimes yes, but often times Wi-Fi throughput is reduced by much more than X%

Short LTE-U OFF Times Severely Degrade Wi-Fi

- LTE-U duty cycle fixed at 50% and LTE-U OFF time varied (x-axis)
- Y-axis: Wi-Fi throughput / Wi-Fi throughput without LTE-U (normalized Wi-Fi throughput)
  - 0.5 corresponds to effective time-sharing
- Results shown for different AP/client pairs

- Findings:
  - Short LTE-U OFF times can lead to severe reduction in Wi-Fi throughput
  - Considerable variation across devices and run-to-run

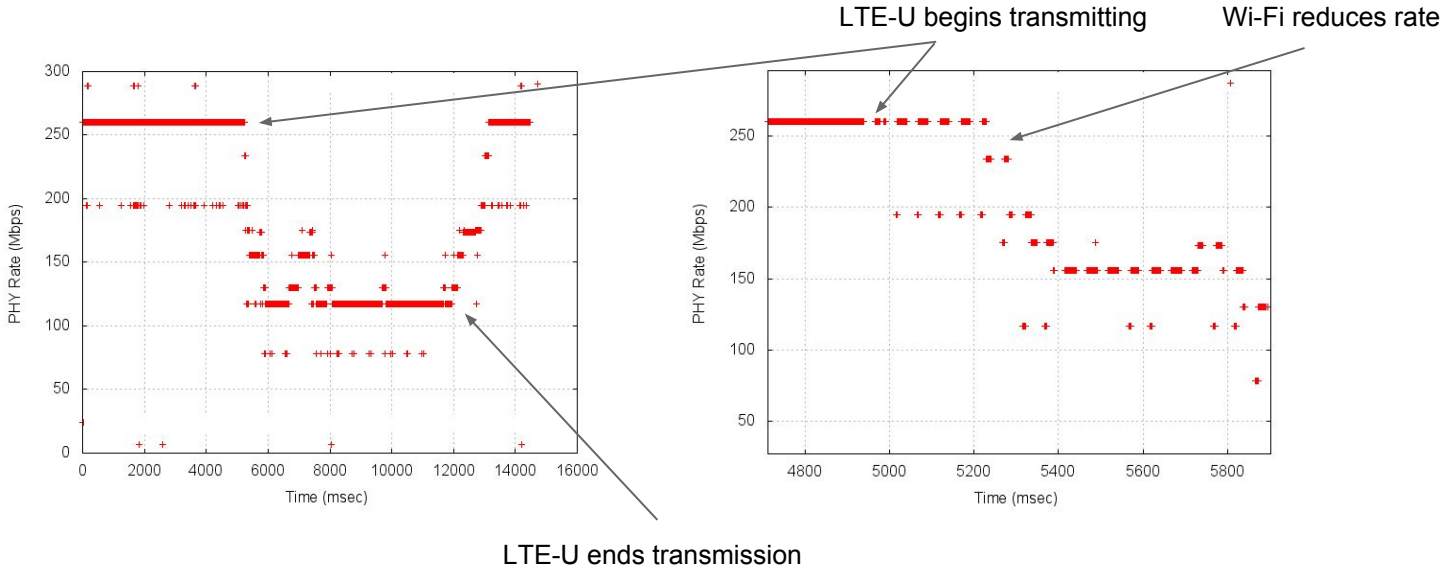


Why Does LTE-U Disproportionately Impact Wi-Fi?

- Each LTE-U transmission start interrupts an ongoing Wi-Fi frame and leads to a Wi-Fi frame error
  - Periodic frame errors can cause Wi-Fi rate control to reduce the transmitted rate
  - Increasing LTE-U off time decreases the severity and occurrence of this problem
    - Lower percentage of Wi-Fi frames affected by the start of LTE-U transmission
- Additional testing showed that the key dependence is on the absolute LTE-U OFF time, regardless of the duty-cycle percentage

Wi-Fi Rate Control Reacting to Duty-Cycled LTE-U

- Plot: Wi-Fi transmitted rate vs. time (right plot is a zoomed in version of left)
- LTE-U begins duty-cycled transmission (30 msec on, 30 msec off) at time 4900, and Wi-Fi decreases rate at time 5250



Long LTE-U ON Times Can Also Degrade Wi-Fi

- Wi-Fi stays off the air while LTE-U transmitting, so long LTE-U ON times can cause issues with:
  - Delay-sensitive traffic
  - Beacons and power-save
- Puncturing (~ 1 msec gaps in the LTE-U ON cycle) introduces an additional LTE-U transmission start, and thus can exacerbate the rate-control issue highlighted earlier
  - Intention is to allow Wi-Fi to transmit high QoS frames, eg., VoIP, but Wi-Fi is unaware that the medium is clear only for a short period of time

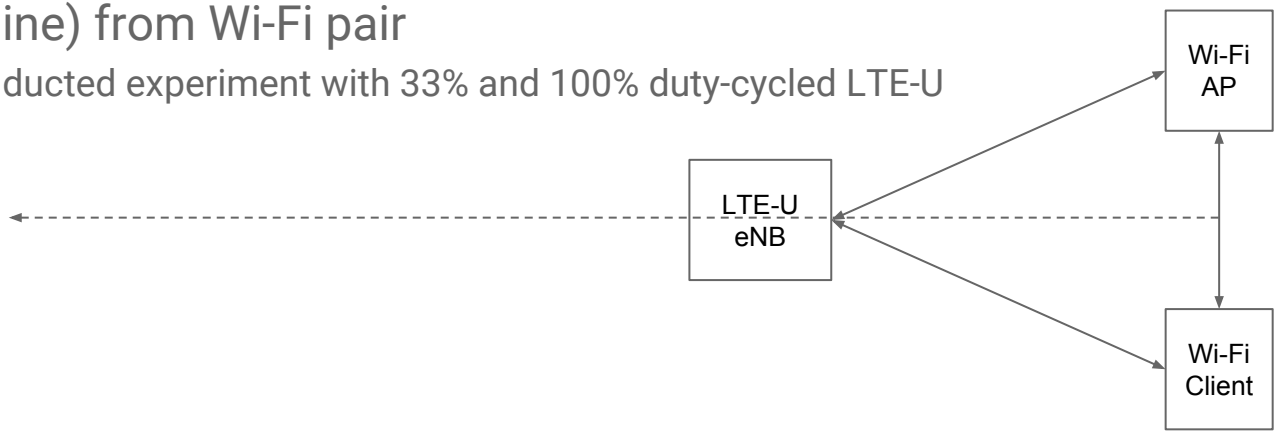
Effect of Moderate Power LTE-U on Wi-Fi

- Two additional issues when Wi-Fi and LTE-U hear each other below ED:
  - Not clear if LTE-U eNB will perform duty-cycling when Wi-Fi AP is heard below -62
    - LTE-U Forum coexistence tests only defined for above ED scenarios, and design documentation does not specify below ED behavior
  - Wi-Fi devices will attempt to transmit even when LTE-U is transmitting

- Finding: Wi-Fi throughput can be degraded by an even larger fraction when LTE-U (with or without duty-cycling) is received below rather than above ED

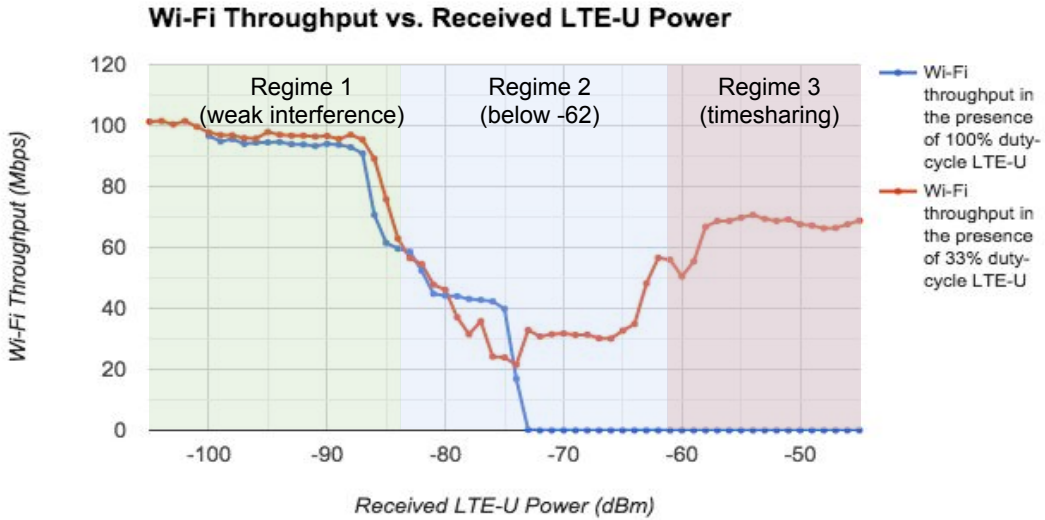
Moderate Power LTE-U Test Setup

- Wi-Fi AP and client placed at fixed positions
- LTE-U eNB emulator positioned to be received at same power level by Wi-Fi AP and client
- Measured Wi-Fi throughput as LTE-U eNB was moved farther away (along dotted line) from Wi-Fi pair
  - Conducted experiment with 33% and 100% duty-cycled LTE-U



Moderate Power LTE-U Severely Degrades Wi-Fi

- Client receives AP at -57 dBm, client and AP receive LTE-U eNB at power shown on x-axis
- 33% duty-cycled LTE-U: Steep drop in Wi-Fi throughput when LTE-U falls below ED
- 100% duty-cycled LTE-U: Wi-Fi achieves no throughput when LTE-U received above -72 dBm
- Regime 3: corresponds to earlier material on above ED, although effective time-sharing seen here



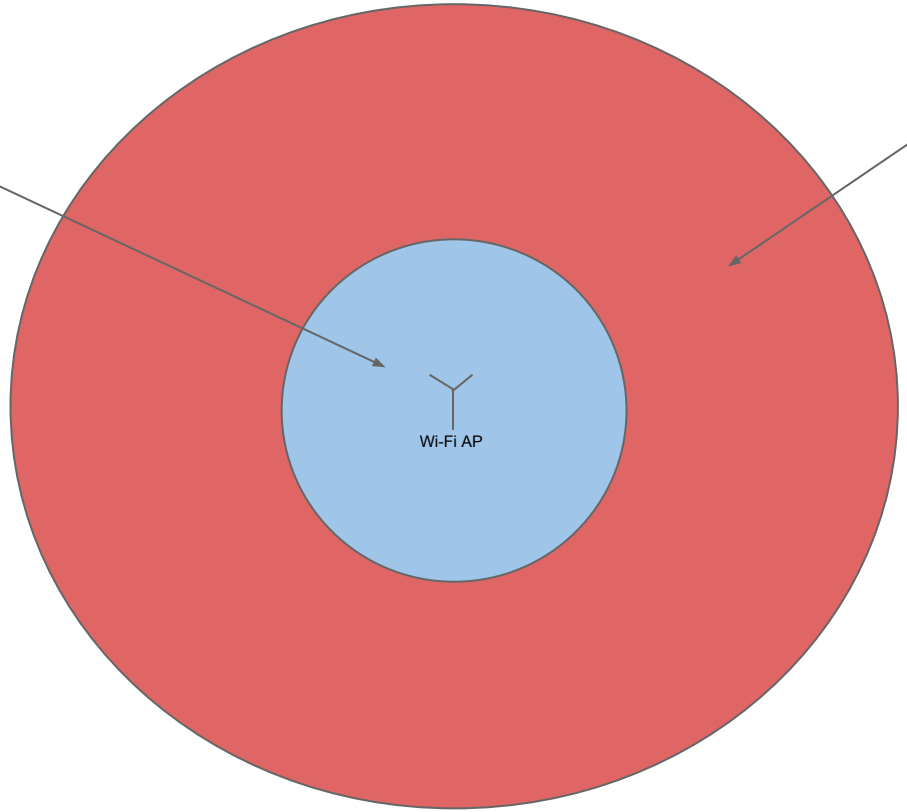
Why is Moderate Power LTE-U So Detrimental?

- Because LTE-U received below ED, Wi-Fi always attempts to transmit
- Vastly different Wi-Fi SINR during LTE-U OFF period vs. ON period
  - Interference-free SNR when LTE-U is off
  - SINR when LTE-U is on depends on relative powers of Wi-Fi and LTE-U signals
    - May or may not be able to support lowest Wi-Fi rate while LTE-U is transmitting
- A few possibilities for Wi-Fi rate control:
  - Highest rate achievable during the LTE-U off time (very high frame error rate)
  - Highest rate achievable during the LTE-U on time
- If RTS/CTS used can see continual RTS/CTS failures while LTE-U is on
  - This can limit data frames to LTE-U OFF periods, but repeated RTS/CTS failures can also lead to reducing Wi-Fi transmission rate

Moderate Power LTE-U is More Detrimental and More Likely

High Power LTE-U (> ED)

- LTE-U duty cycles
- Wi-Fi can see throughput degradation due to LTE-U interruptions



Moderate Power LTE-U(< ED)

- LTE-U may perform duty-cycle
- Wi-Fi throughput can degrade severely, especially if Wi-Fi link is not very strong
- Considerably larger area than above ED (blue)

Conclusions

- Evaluation of technology coexistence can be very challenging
  - Often see unexpected and complex interactions between technologies
- Simulations and experimental evaluation are both necessary
  - But “black-box” results -- results provided without any attempt to explain the underlying causes -- are of limited use, especially due to the heated nature of coexistence
  - Every technology will have critical proprietary features (e.g., rate control) that require experimentation to evaluate
- Wi-Fi Alliance has been tasked with developing a Wi-Fi/LTE-U test plan, which is nearing completion