OPTIWI-FI REPORT
2.3 & 2.4 GHZ COEXISTENCE

Version 1.0

Testing the impact of TDD Base Station and TDD User Equipment on Wi-Fi Access Points and Wi-Fi Clients

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1. About OptiWi-fi

OptiWi-fi is a Wi-Fi networks performance management solutions company. The patented technology at the core of our solutions comes from over 12 years of research led by Co-founder Dr. Mark Davis, a Wi-Fi expert at Ireland's award winning "Communications Network Research Institute" (CNRI), based at Dublin Institute of Technology. The CNRI conducts research into chronic issues affecting the provision of quality of service (QoS) on wireless networks.

**"MAKING WI-FI BETTER!
DYNAMICALLY, AUTONOMOUSLY, REAL-TIME"**

Our advanced Wi-Fi S.O.N. solution (Self-Optimising Network) enables Wi-Fi operators to Plan, Configure, Diagnose, Manage, Optimise bandwidth capacity and user experience in a way usually only found on Cellular Networks.

Due to the nature of Wi-Fi being unlicensed/ unmanaged spectrum, operators find it very difficult to see the causes of poor QoS at hotspot locations. They are unable to see what the true Wi-Fi quality is for a user and, are thus not in a position to manage or improve the service for them. What follows is a summary of what our solutions provide:

- We heal networks automatically, dynamically and autonomously in response to real-time changing network loads:
  - Wi-Fi is a shared medium and, as such, performance is inherently unpredictable
  - Managing services over unpredictable networks is extremely difficult
  - OptiWi-fi is the first company globally to make the performance of Wi-Fi networks predictable
- OptiWi-fi delivers critical network intelligence enabling true user experience management, identifying poor Wi-Fi quality in real-time:
  - We can identify network saturation before it occurs in real-time and take corrective action to delay or eliminate the onset of saturation in congested environments
- Our Network Alarms warn operators when service is poor or not functioning for users

2. Award Band

Ofcom is considering the award of a block of spectrum in the 2.3 GHz band for 4G mobile services. This spectrum is adjacent to the 2.4 GHz unlicensed band that is primarily used for Wi-Fi. Concern has been raised about the potential impact new users of the 2.3 GHz frequencies would have for existing users in the 2.4 GHz band.

- Award Band
  - 40 MHz of licensed spectrum within the 2.3 GHz band (2350 - 2390 MHz)
  - The spectrum is unpaired and may be used for Long-Term Evolution (LTE) using Time Division Duplexing (TDD)

- Guard Band
  - 10 MHz guard band (2390 – 2400 MHz)

- Unlicensed Band
  - 83.5 MHz of unlicensed spectrum within the 2.4 GHz band (2400 to 2483.5 MHz)
  - Used primarily for Wi-Fi and shared with a number of other unlicensed wireless technologies

3. Test Strategy and Limitations

OptiWi-fi was tasked with determining the impact of TDD LTE on Wi-Fi using scenarios that represent real world conditions. At a high level we focused on two key aspects:

1) Impact of TDD Base Station on Wi-Fi Access Points and Wi-Fi Clients

2) Impact of TDD User Equipment on Wi-Fi Access Points and Wi-Fi Clients

Wi-Fi operates in an unlicensed environment. Already Wi-Fi devices must compete with non-Wi-Fi devices, such as microwave ovens, security cameras, bluetooth devices and cordless phones, as well as with all other Wi-Fi devices. The 2.3GHz band would be an additional factor to consider on top of the significant range of interference sources already present, particularly in crowded urban areas.

Taking this into account, the decision was made to conduct testing in a live office building while office staff were attending normal business. This strategy was used for all tests related to the impact of TDD Base Station signal on Wi-Fi. For the impact of TDD User Equipment (UE) on Wi-Fi, the tests were conducted in a Faraday Cage, ensuring the TDD UE remained connected to the TDD Base Station and not other cellular sources.

The benefit is that the results of the tests should be closer to what users would experience in the real world once TDD LTE and Wi-Fi coexist. However, the approach implies a number of limitations which should be clearly communicated:

- The test environment was not controlled. There were, at times, over 150 Wi-Fi clients on the Wi-Fi channel tested, each competing for access and generating unpredictable network traffic. This ensured that the Wi-Fi environment was representative of real world conditions.

- Given the environment, tests were conducted on a dedicated Wi-Fi Access Point that was carrying no other traffic aside from the Wi-Fi Client device being used in the test. This ensured that the key findings identified were directly relevant to the impact of TDD signal on Wi-Fi.

- The study was more concerned with examining a wide variety of different test scenarios rather than carrying out an in-depth experimentation on a small set of scenarios. 236 results were obtained, with scenarios incorporating a range of APs, mobile devices and network configurations.

- The trade-off with having a large variety of tests, was that the sample size was small with most tests having only two result sets. Given the small sample size used in the tests, there is likely to be a margin of error associated with the results. However, overall, the trends are correct and it is possible to provide key findings from this analysis.

- Finally, testing was done using file uploads and downloads over TCP to reflect typical user behaviour.

4. Key Findings

4.1 Impact of TDD Base Station

- At a distance of 5 meters from the LTE antenna, there was only a minimal performance impact on the Wi-Fi AP. On average the throughput was reduced by 10%.

- When the Wi-Fi AP was placed at less than 0.5 meters from the LTE antenna, the throughput was reduced by 50% on average. However, the Wi-Fi connection was still useable.

- All Wi-Fi channels were impacted by the TDD signal in a similar fashion. The tests completed did not highlight a significant performance difference between Wi-Fi channels.

- The Consumer APs behaved similarly to the Enterprise APs with only a minimal performance impact on the Wi-Fi at 5 meters from the LTE antenna. On average the throughput was reduced by 10% under TDD power level of -42dBm.

- The TDD Base Station signal had no material impact on the Wi-Fi connection maintained between a Wi-Fi AP and a Wi-Fi client over long range (over 50m through several internal walls resulting in an RSSI of -80dBm).

4.2 Impact of TDD User Equipment (UE)

- For the Wi-Fi Clients tested, there was minimal impact on performance when positioned further than 0.5 meters away from the TDD UE transmitting at full power. On average the throughput was reduced by less than 10%.

- Even at distances under 0.5 meters, there was no major impact unless the TDD UE, transmitting at full power, was positioned directly against the Wi-Fi Client antenna, physically blocking it. With the TDD UE placed directly onto the keyboard of the laptop being tested, the reduction in throughput was less than 20% on average.

- For the Wi-Fi APs tested, the impact of the TDD UE varied depending on the device. One of the devices tested experienced less than 15% degradation in throughput with the TDD UE adjacent and at full signal strength. Other devices experienced a greater impact but on average the throughput degradation was less than 50% when the TDD UE was placed at more than 1 meter from the Wi-Fi device.

- TDD UE impact was apparent only while actively transmitting. On average, the impact was more pronounced when the TDD UE was uploading to the network than when it was downloading. With the TDD UE passively connected to the network there was no substantial impact.

5. TDD Base Station with Enterprise Wi-Fi

5.1 Objectives

The purpose of this set of tests was to validate the operation of an Enterprise AP under potential interference from a TDD base station. The following Wi-Fi AP was used:

Device under Test	Type	Device Name	Vendor
DuT #1	Enterprise AP	Enterprise AP 1	Vendor 1

- Tests were focused on measuring the impact of TDD transmissions on the receiver of the AP
- Wi-Fi measurements were made on the uplink from the Client to the AP

5.2 Test Configuration

Two scenarios were tested using the configuration shown in Figure 1:

a) Wi-Fi AP is located adjacent to the LTE antenna (less than 0.5 meters from the LTE antenna)
b) Wi-Fi AP is 5 meters from the LTE antenna

The Wi-Fi Client Device (CD) and OptiCube [see Appendix A, Section 4] were placed in a shielded position from the LTE antenna, with no direct line of sight. The OptiCube is passive, monitoring the quality of the Wi-Fi connection between the AP and the CD.

This represents a scenario where the Wi-Fi Client is further away from the LTE source while the Wi-Fi AP is directly subjected to potential interference from TDD transmissions.

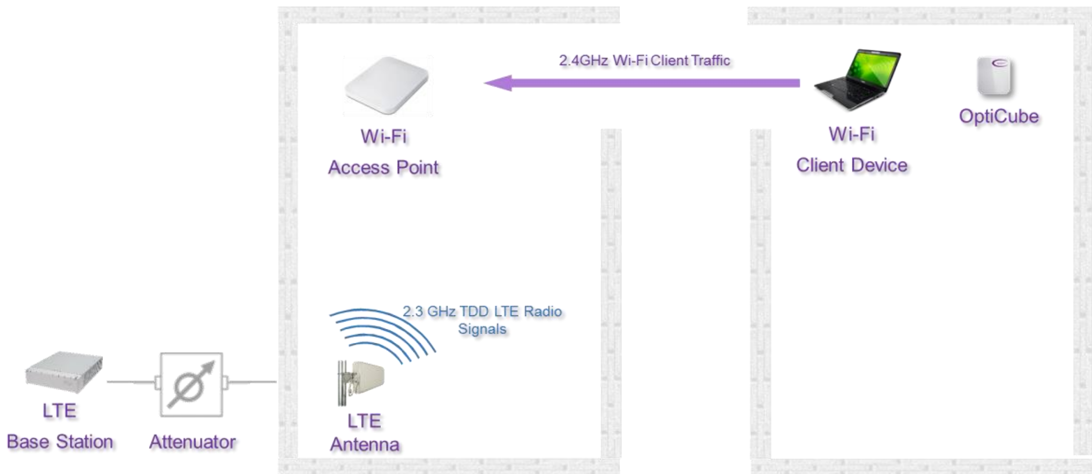

Figure 1. Test Configuration: TDD Base Station with Enterprise Wi-Fi

The TDD base station was configured in Test Mode 1 Full Power All Timeslots. This is a worst case scenario, corresponding to a reasonable approximation of a fully loaded base station. See Appendix B for more details on the TDD signal used.

No TDD UE was used for the test.

Power levels were measured using a spectrum analyser:

- The TDD power level next to the LTE antenna was -30dBm
- The TDD power level at 5 meter from the LTE antenna was -42dBm
- The TDD power lever at the Wi-Fi client was -60dBm

5.3 Test Results

At 5 meters from the LTE antenna, there was only a minimal performance impact on the Wi-Fi. On average the throughput was reduced by less than 10%.

When the Wi-Fi AP was placed at less than 0.5 meters from the LTE antenna, the throughput was reduced by 50% on average. However, the Wi-Fi connection was still useable.

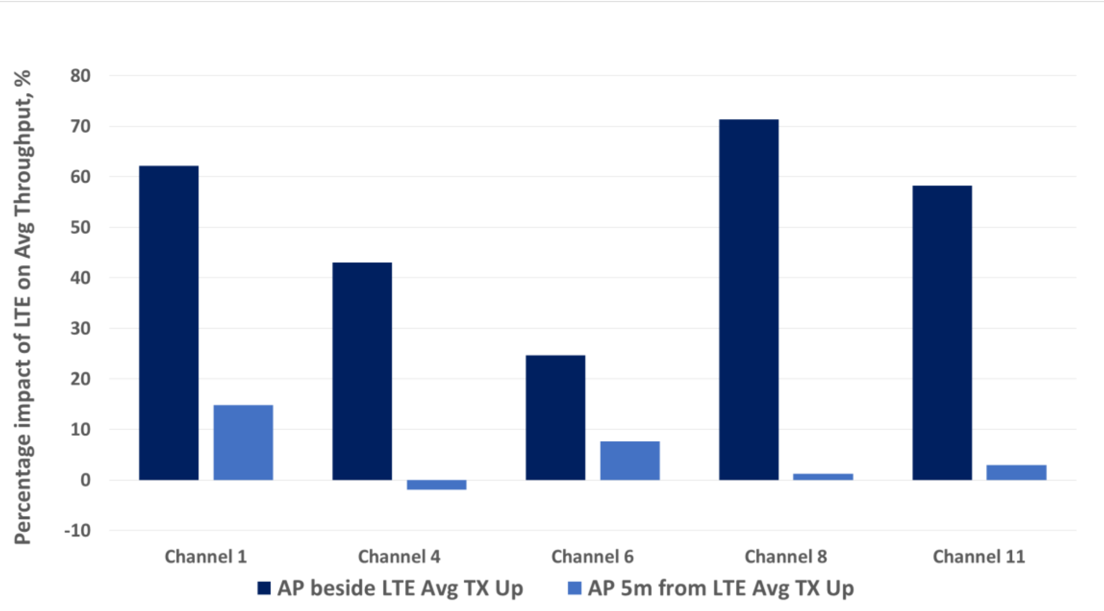

Figure 2. Percentage Impact of LTE on Average Throughput as a function of distance between Enterprise AP 1 and LTE Antenna

5.4 AP and LTE adjacent

This is the scenario in which the TDD Base Station signal had the strongest impact on the Wi-Fi. The Wi-Fi AP was placed at less than 0.5 meters from the LTE antenna. The measured TDD power level at the AP location was -30dBm.

The degradation of the throughput was substantial with reductions between 30% and 70%. However, the Wi-Fi link remained usable. The presence of the TDD signal resulted in a degradation of performance rather than a degradation of the provision of service.

The impact on the different Wi-Fi channels was also assessed. The key finding is that the degradation applied across each channels examined and was not limited to Channel 1. [Channel 1, centred on 2412 MHz, is the closest Wi-Fi channel to the TDD signal centred on 2380Mhz.]

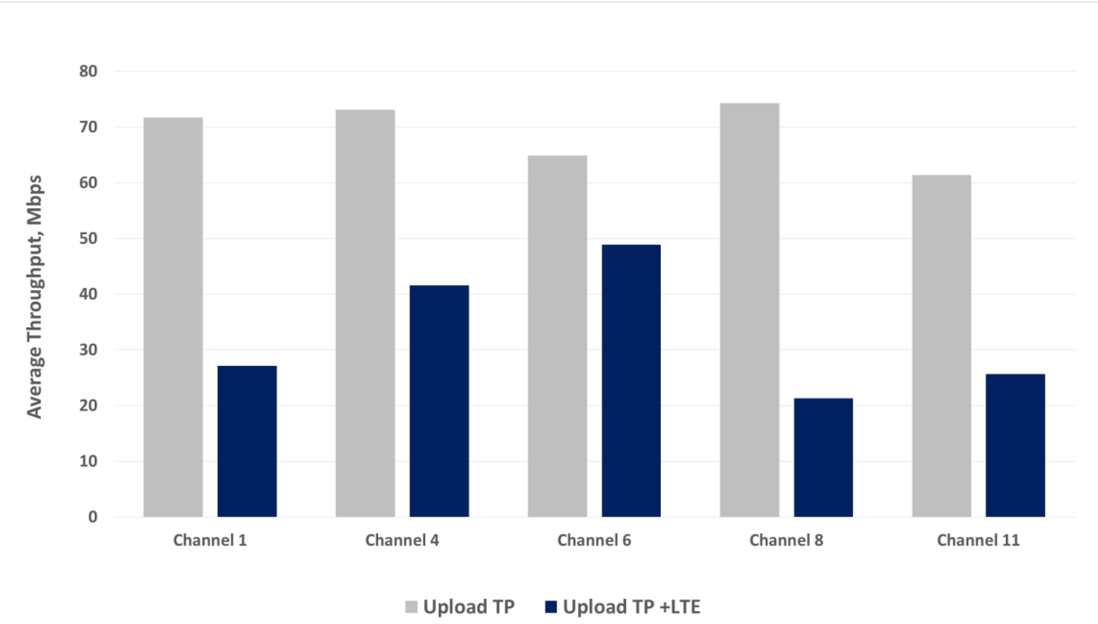

Figure 3. Impact of LTE on Average Throughput for Enterprise AP 1, with AP and LTE Antenna adjacent

The data in Figure 3 should not be used to conclude that one channel is better or worse than another. The tests were made in a live environment which had a large number of Wi-Fi devices operating on each channel generating unpredictable network traffic. The duration of the tests and the number of samples captured was not sufficient for the variations in each channel to be statistically significant. We can simply say that the observed impact applied to all channels.

5.5 AP and LTE 5 meters apart

At 5 meters from the LTE antenna we had a TDD power level of -42dBm. With this signal strength there was only a minimal impact on the Wi-Fi performance with the throughput reduced by less than 10% on average.

As with the results captured when the AP and LTE were adjacent, the impact of the TDD signal was observed across all Wi-Fi channels. It was not limited to the Wi-Fi channels closest to the TDD frequencies.

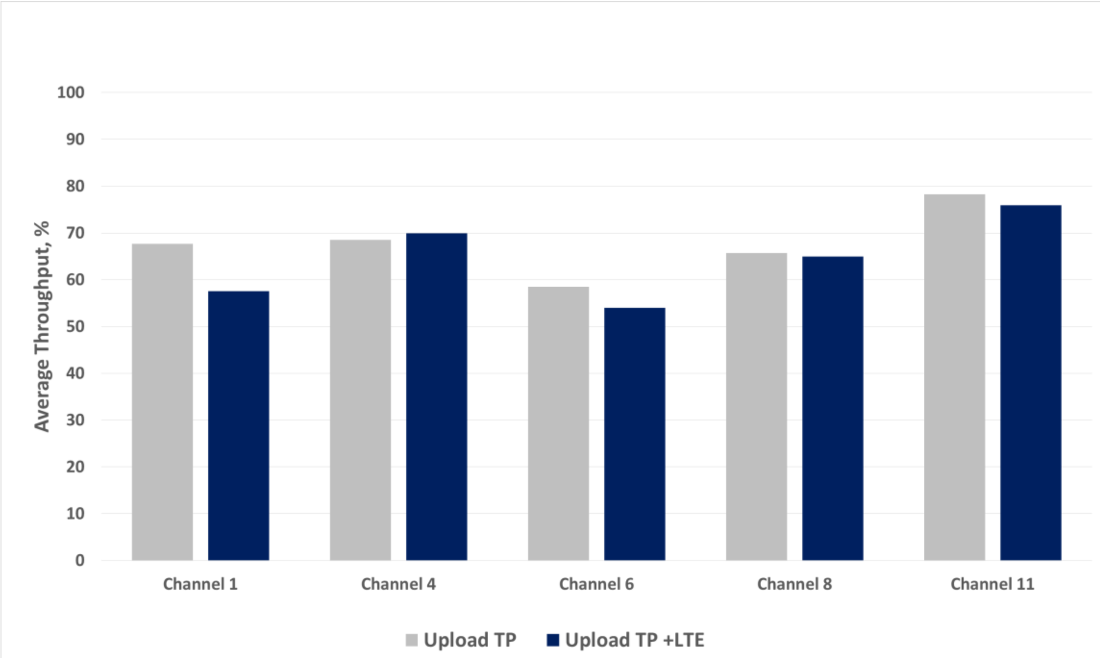

Figure 4. Impact of LTE on Average Throughput for Enterprise AP 1, with AP and LTE Antenna 5 meters apart

The data captured on Figure 4 should not be used to conclude that one channel is better or worse than another. The tests were made in a live environment which had a large number of Wi-Fi devices operating on each channel generating unpredictable network traffic. The duration of the tests and the number of samples captured was not sufficient for the variations in each channel to be statistically significant. We can simply say that the impact observed applied to all channels.

6. TDD Base Station with Consumer Wi-Fi

6.1 Objectives

The purpose of this set of tests was to validate the behaviour of Consumer APs experiencing potential interference from a TDD base station transmissions. The following Wi-Fi APs were used:

Device under Test	Type	Device Name	Vendor
DuT #2	Consumer AP	Consumer AP 1	Vendor 2
DuT #3	Consumer AP	Consumer AP 2	Vendor 3

- Tests were focused on measuring the impact of the TDD transmissions on the receiver of the AP
- Wi-Fi measurements were made on the uplink from the Client to the AP

6.2 Test Configuration

For this scenario the Wi-Fi AP was located 5 meters from the LTE antenna.

As per Figure 5, the Wi-Fi Client Device and OptiCube were placed in a shielded position from the LTE antenna. The OptiCube passively monitors the quality of the Wi-Fi connection between the AP and the CD.

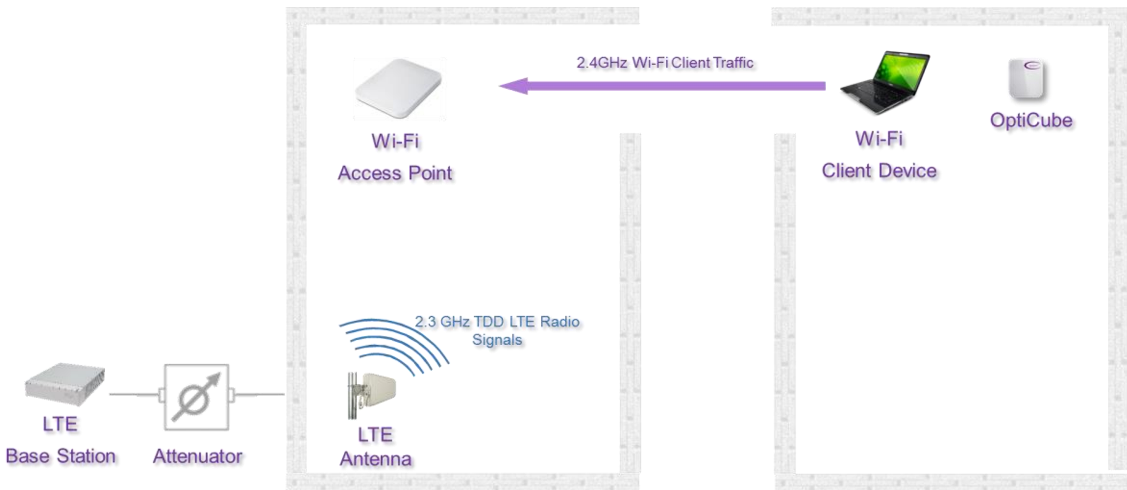

Figure 5. Test Configuration: TDD Base Station with Consumer Wi-Fi

The TDD base station was configured in Test Mode 1 Full Power All Timeslots.
See Appendix B for details on the TDD signal used.

No TDD UE was used for the test

Power levels were measured with a spectrum analyser:

- The TDD power level at the Wi-Fi AP was -42dBm
- The TDD power level at the Wi-Fi client was -60dBm

6.3 Test Results

The Consumer APs behaved similarly to the Enterprise APs with only a minimal performance impact on the Wi-Fi at 5 meters from the LTE antenna. On average the throughput was reduced by 10% while receiving TDD power level of -42dBm.

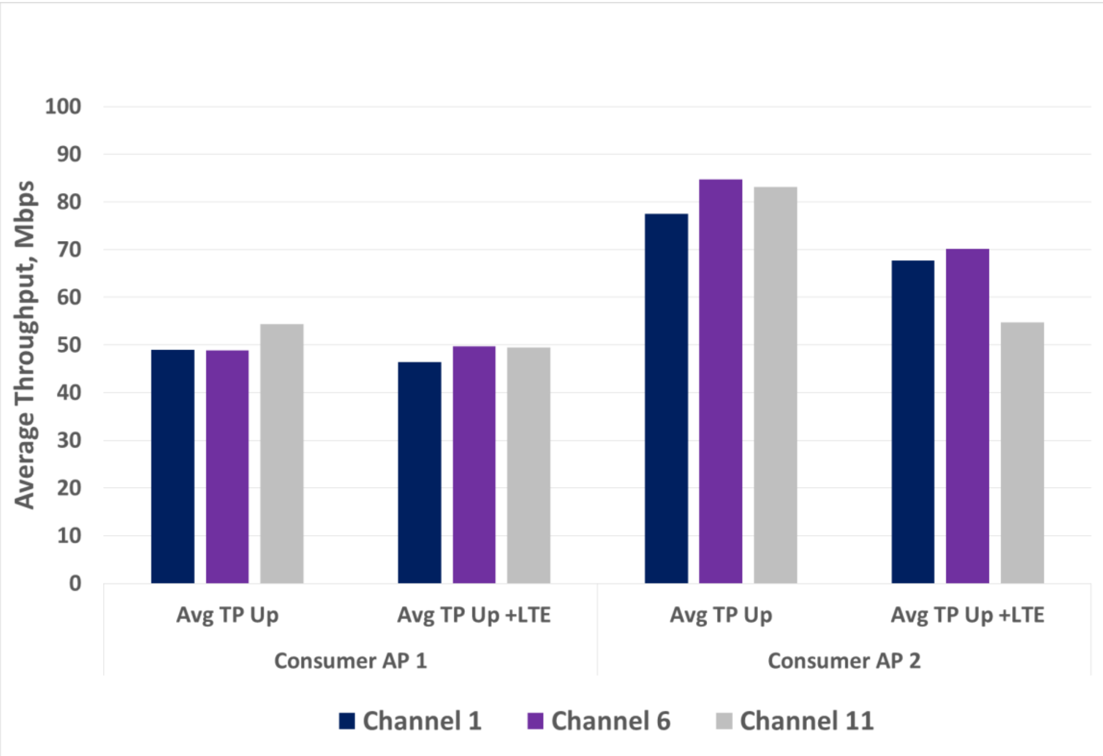

Figure 6. Impact of LTE on Average Throughput for Uploads on Consumer APs

6.4 Differences in AP behaviour

It was observed that Consumer AP 2 had a better throughput performance than Consumer AP 1, with the throughput, on average, being 60% higher (30Mbps).

However, Consumer AP 2 was impacted more heavily by the presence of the TDD signal. On average, the reduction in throughput was 20% for Consumer AP 2 while it was less than 5% for Consumer AP 1.

The 5% throughput difference measured for Consumer AP 1 under TDD Base Station signal indicates the TDD signal had only a minor impact on Consumer AP 1. This is similar to the results for Consumer AP 1 obtained during the TDD UE tests presented in Section 8.

In relation to the different Wi-Fi channels tested, the impact of the TDD signal appeared more consequent on Channel 11 and less on Channel 6. However, given the nature of the live environment used with an unequal distribution of Wi-Fi devices across channels and the low number of samples used we cannot conclude one channel is superior to another. All we can say is that the impact is visible across the different Wi-Fi channels.

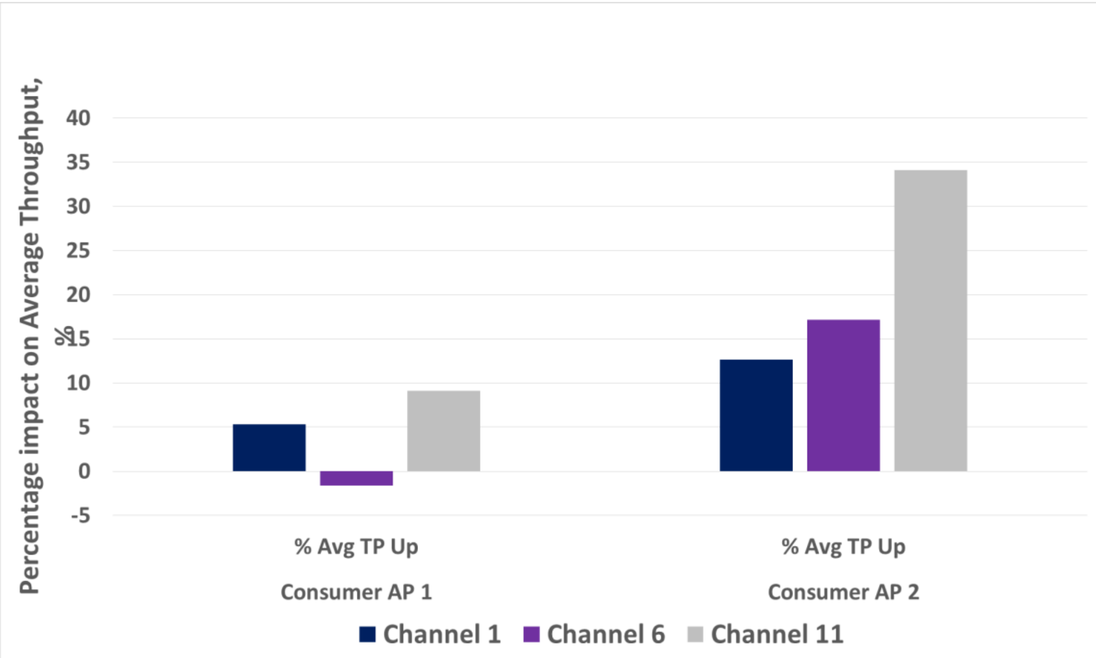

Figure 7. Percentage Impact of LTE on Average Throughput for Uploads on Consumer APs

7. TDD Base Station at limit of Wi-Fi range

7.1 Objectives

The purpose of this series of tests was to assess the TDD Base Station signal impact on a Wi-Fi AP trying to maintain connection with a Wi-Fi client placed at the limit of the Wi-Fi coverage range. The following Wi-Fi devices were used for the test.

Device under Test	Type	Device Name	Vendor
DuT #1	Enterprise AP	Enterprise AP 1	Vendor 1
DuT #8	Laptop	Laptop 1	Vendor 6

- Tests were focused on measuring the impact of the TDD transmissions on the receiver of the AP Wi-Fi
- Wi-Fi measurements were made on the uplink from the Client to the AP

7.2 Test Configuration

Three scenarios were tested using the configuration shown in Figure 8:

a) Wi-Fi Client at -80dBm from the Wi-Fi AP signal
b) Wi-Fi Client at -60dBm from the Wi-Fi AP signal
c) Wi-Fi Client at -50dBm from the Wi-Fi AP signal

Figure 8. Test Configuration: TDD Base Station at limit of Wi-Fi range

The TDD base station was configured in Test Mode 1 Full Power All Timeslots. See Appendix B for details on the TDD signal used.

- The Wi-Fi AP was located 1 meter from the LTE Antenna. The TDD power level at the AP was -64dBm.

- In the first scenario the Wi-Fi Client was placed at 54 meters from the Wi-Fi AP without direct line of sight. The TDD power level at the Client was below floor noise level. The AP signal strength was reduced to achieve a Wi-Fi RSSI of -80dBm at the Wi-Fi Client location.

- In the second scenario the Wi-Fi Client was placed at 16 meters from the Wi-Fi AP without direct line of sight. The TDD power level at the Client was -80dBm. The AP signal strength was reduced to achieve a Wi-Fi RSSI of -60dBm at the Wi-Fi Client location.

- In the third scenario the Wi-Fi Client was placed at 11 meters from the Wi-Fi AP with direct line of sight. The TDD power level at the Client was -60dBm. The AP signal strength at the Wi-Fi Client location was -50dBm.

7.3 Test Results

The TDD Base Station signal had no material impact on the Wi-Fi connection maintained by a Wi-Fi AP with a Wi-Fi client at long range (over 50m through several internal walls resulting in an RSSI of -80dBm).

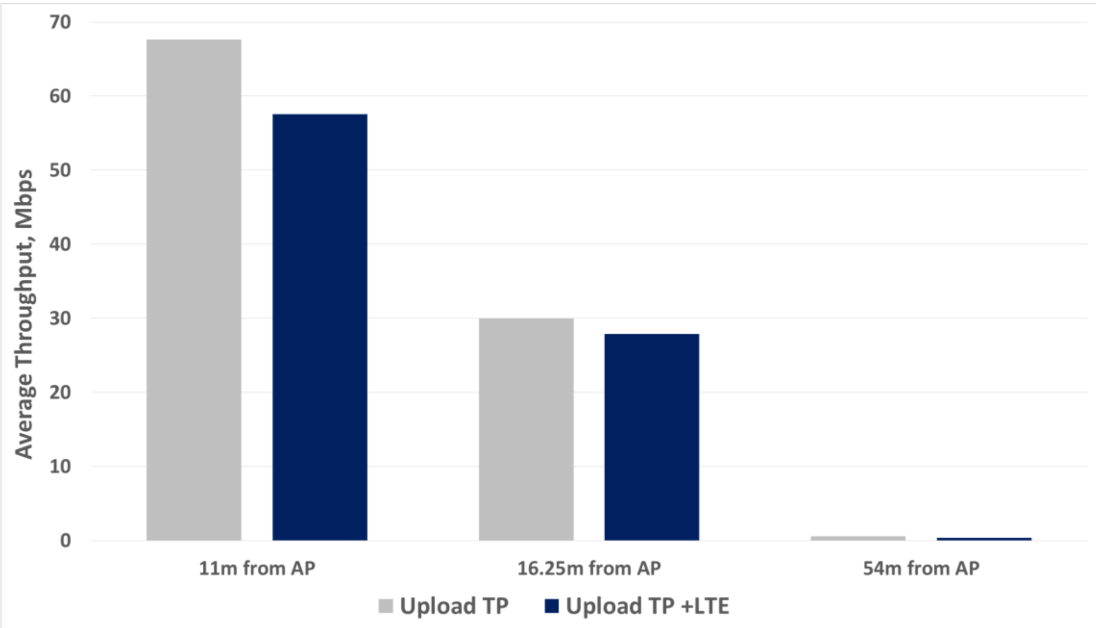

Figure 9. Impact of LTE on Average Throughput for Channel 1 with Laptop 1 at different distances from Enterprise AP 1

At a distance of 54 meters from the AP, through several internal walls, with a RSSI of -80dBm the Wi-Fi client was at the limit of being able to maintain the Wi-Fi connection. The measured throughput was a few 100 Kb/s with unpredictable variations due to the poor quality of the Wi-Fi connection. The difference measured with and without TDD signal was not significant.

At a distance of 16 meters from the AP, through one internal wall, with a RSSI of -60dBm the Wi-Fi connection was stable and the throughput more predictable. There was no substantial difference recorded with or without TDD signal.

At a distance of 11 meters from AP, with a RSSI of -50dBm, the Wi-Fi connection was excellent. There was a 20% reduction of throughput recorded with TDD signal. However even with the throughput degradation the Wi-Fi connection continued to perform satisfactorily.

8. TDD User Equipment with Wi-Fi APs

8.1 Objectives

The purpose of this set of tests was to assess the impact of TDD User Equipment (UE) on Wi-Fi Access Points. The following Wi-Fi Access Points were tested:

Device under Test	Type	Device Name	Vendor
DuT #1	Enterprise AP	Enterprise AP 1	Vendor 1
DuT #2	Consumer AP	Consumer AP 1	Vendor 2
DuT #3	Consumer AP	Consumer AP 2	Vendor 3
DuT #4	Consumer AP	Consumer AP 3	Vendor 3

- Tests were focused on measuring the impact of the TDD transmissions on the receiver of the AP
- The measurements were made on the uplink from the Client to the AP

8.2 Test Configuration

The tests focused on the TDD and Wi-Fi transmitting simultaneously. This is essentially a worst case scenario for UE interference and is likely to only occur rarely in typical use.

As per the configuration shown in Figure 10, testing took place in a Faraday cage to ensure the TDD UE remained connected to the TDD Base Station:

- The signal from the TDD Base Station was attenuated so that the TDD UE would be transmitting at full power. This was confirmed using device diagnostic tools.
- The TDD Base Station was configured for the test with a 3:2 downlink/uplink ratio. See Appendix B for more details on the TDD signal used.
- The TDD UE was a Mobile Phone:

Equipment	Type	Device	Vendor
Eq #2	TDD User Equipment	Mobile Phone 4	Vendor 5

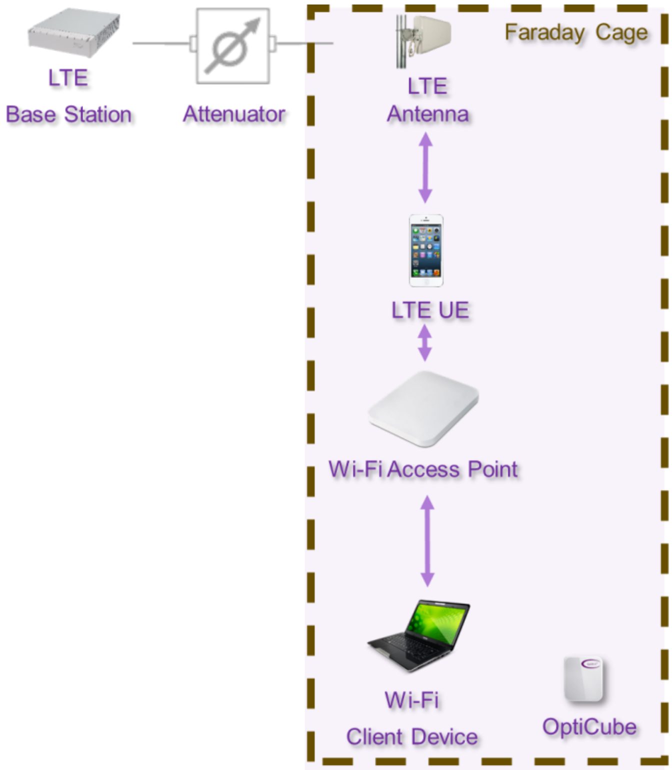

Figure 10. Test Configuration: TDD User Equipment with Wi-Fi APs

- The TDD power level at 1 meter from the LTE UE (with phone actively transmitting) was -25dBm
- The Wi-Fi RSSI at the Wi-Fi Client Device was -50dBm
- All tests from this series were conducted on Wi-Fi Channel 1

8.3 Test Results

- For the Wi-Fi APs tested, the impact of the TDD UE varied depending on the device. One of the devices tested experienced less than 15% degradation in throughput with the TDD UE adjacent and at full signal strength. Other devices experienced a greater impact but on average the throughput degradation was less than 50% when the TDD UE was placed at more than 1 meter from the Wi-Fi device.

- TDD UE impact was apparent only while actively transmitting. On average, the impact was more pronounced when the TDD UE was uploading to the network than when it was downloading. With the TDD UE passively connected to the network there was no substantial impact.

- Although this was not the focus of the study we also noted a degradation of the speed of the TDD LTE at close proximity to a transmitting Wi-Fi device. In certain conditions the TDD Base Station signal strength had to be increased to maintain the connection to the TDD UE.

8.4 Enterprise AP 1

Enterprise AP 1 was tested in two different positions adjacent to the TDD UE:

1) "LTE beside AP" - The TDD UE was placed on the side of the AP with its back casing towards the antenna array.
2) "LTE on AP" - The TDD UE was placed on top of the AP with its back casing towards the antenna array.

With the TDD UE in either of these positions, the throughput was severely impacted, up to 70% lower than if the TDD signal was turned off.

However, once the distance from the TDD UE increased the impact reduced quickly. At more than 0.2 meters the impact on throughput was already less than 50%.

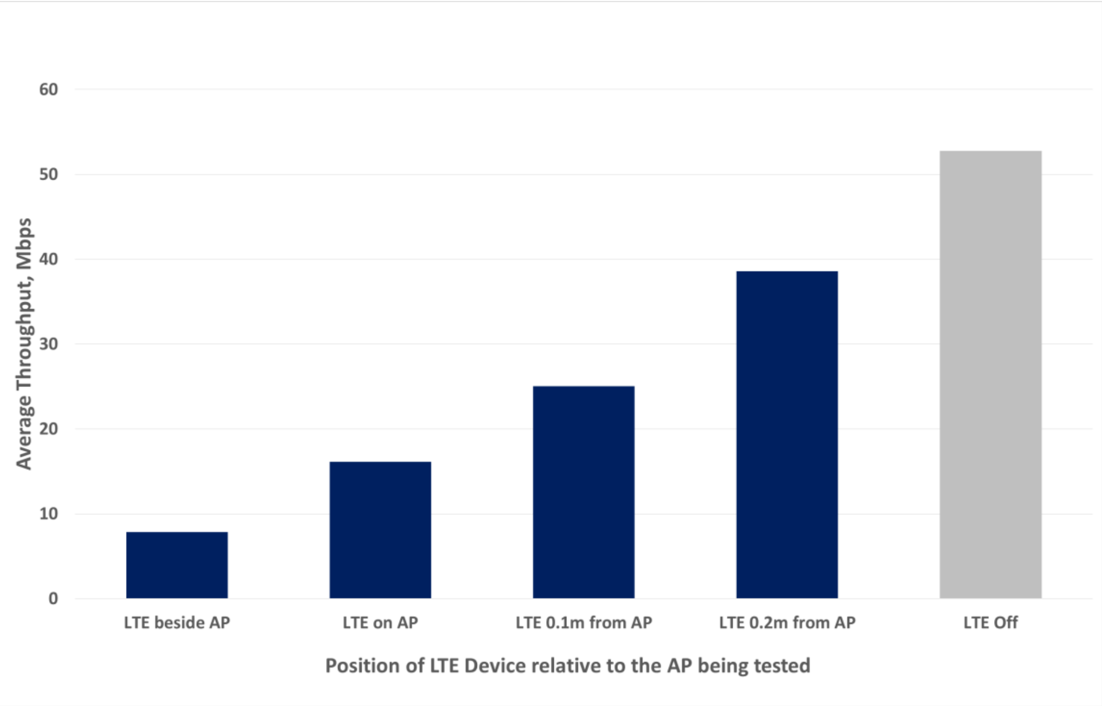

Figure 11. Impact on Average Throughput of moving the TDD UE relative to Enterprise AP 1

- Measures taken with the TDD UE actively uploading from the network
- "LTE Off" is the reference measure with both TDD Base Station and TDD UE turned off

8.5 Consumer AP 1

Of all the APs tested, Consumer AP 1 was identified as the AP the least impacted by the presence of the TDD UE, even with the TDD UE adjacent to the AP.

The data presented in Figure 12 was captured with the TDD UE adjacent to Consumer AP 1, with the back casing of the TDD UE facing upwards. There was virtually no difference with LTE off or while the TDD UE was downloading. With the TDD UE uploading and adjacent to the AP, there was only a 15% throughput reduction.

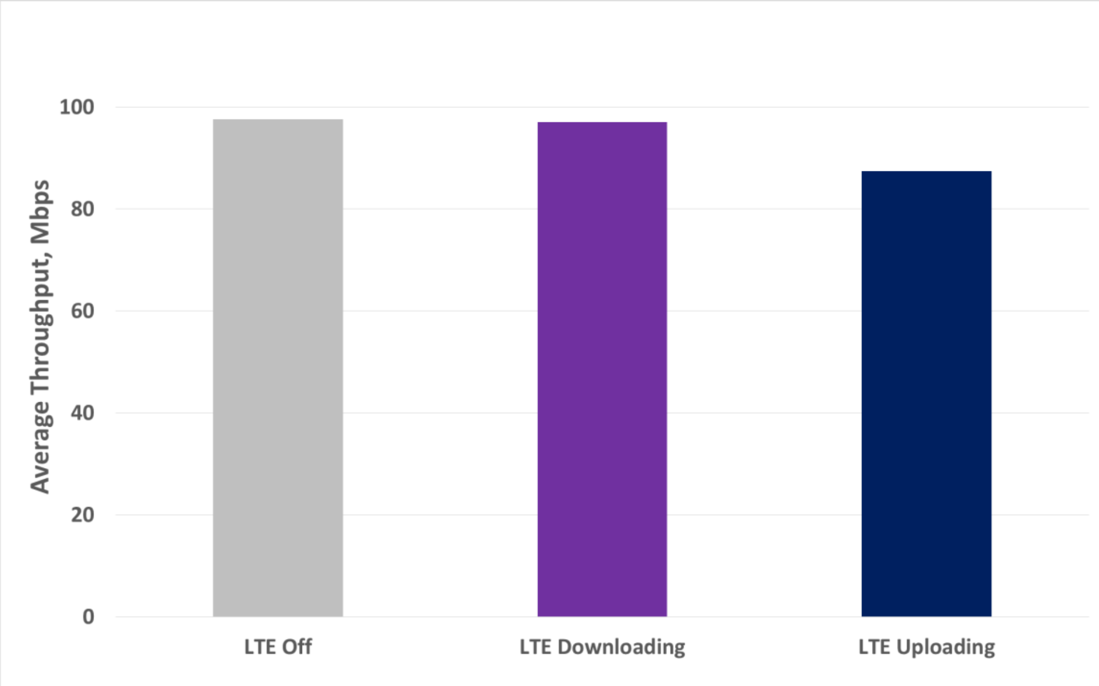

Figure 12. Impact of LTE on the Average Throughput on Consumer AP 1

- "LTE Off" is the reference measure with both TDD Base Station and TDD UE turned off
- "LTE Downloading" is taken with the TDD UE actively downloading from the network
- "LTE Uploading" is taken with the TDD UE actively uploading from the network

8.6 Consumer AP 2 and Consumer AP 3

Two versions of the same AP from the same vendor were tested. Consumer AP 2 was an older version while Consumer AP 3 was the most recent version.

Both versions performed similarly. The TDD UE impact on the throughput was substantial at distances of less than 1 meter. At distances greater than 1 meter from the TDD UE the impact on throughput was less than 50%.

The data shown in Figure 13 was gathered on the Consumer AP 2 while the TDD UE was uploading to the network.

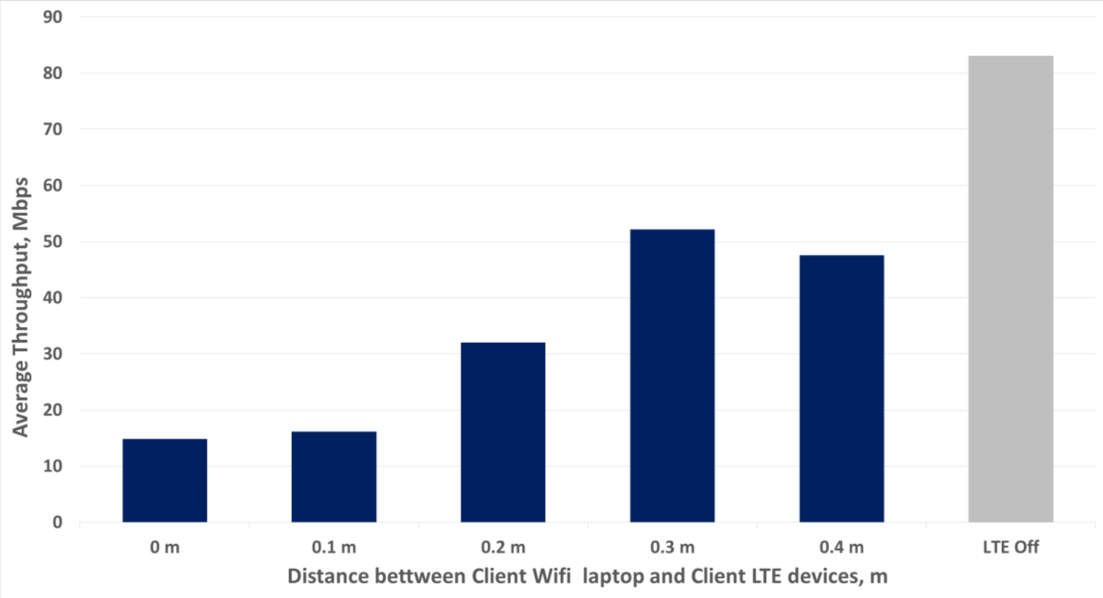

Figure 13. Relationship between Average Throughput and Distance from Consumer AP 2 to TDD UE

The data shown in Figure 14 was gathered on the Consumer AP 3 while the TDD UE was uploading to the network.

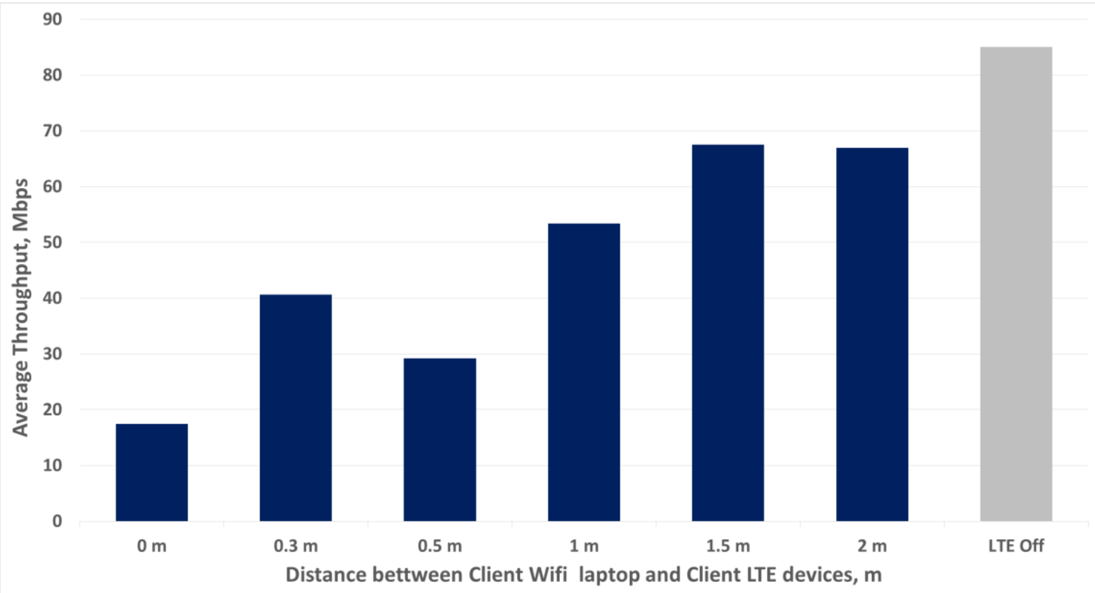

Figure 14. Relationship between Average Throughput and Distance from Consumer AP 3 to TDD UE

9. TDD User Equipment with Wi-Fi Clients

9.1 Objectives

The purpose of this set of tests was to assess the impact of TDD UE on Wi-Fi Clients. The following Wi-Fi Clients were tested:

Device under Test	Type	Device Name	Vendor
DuT #5	Mobile Phone	Mobile Phone 1	Vendor 4
DuT #6	Mobile Phone	Mobile Phone 2	Vendor 4
DuT #7	Mobile Phone	Mobile Phone 3	Vendor 5
DuT #8	Laptop	Laptop 1	Vendor 6
DuT #9	Laptop	Laptop 2	Vendor 7

- Tests were focused on measuring the impact of the TDD transmissions on the receiver of the Wi-Fi Client
- The measurements were made on the downlink from the AP to the Client

9.2 Test Configuration

The configuration in Figure 15 is similar to the one used in Section 8, with the difference being that the Wi-Fi Client is now in the centre next to the LTE UE.

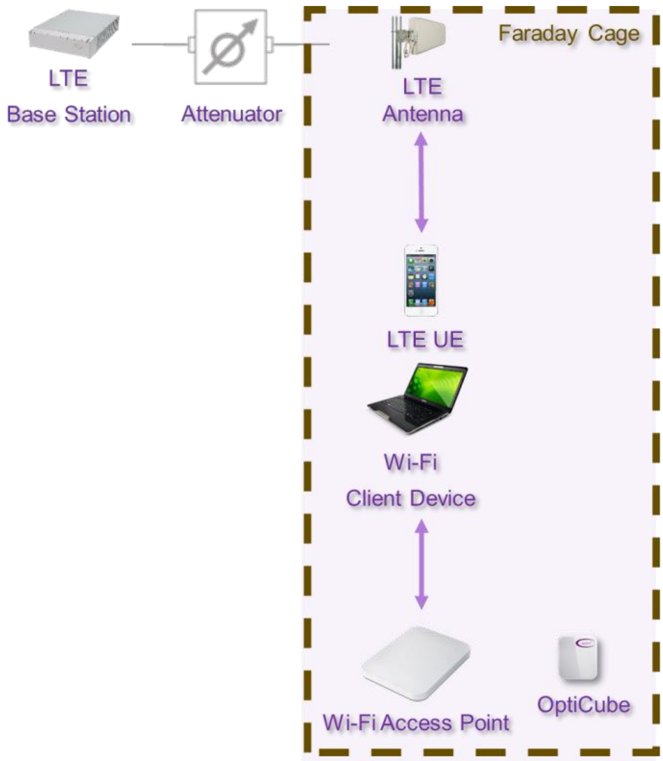

Figure 15. Test Configuration: TDD User Equipment with Wi-Fi Clients

- The TDD Base Station was configured for the test with a 3:2 downlink/uplink ratio. See Appendix B for more details on the TDD signal used.
- The TDD UE was a Mobile Phone:

Equipment	Type	Device	Vendor
Eq #2	TDD User Equipment	Mobile Phone 4	Vendor 5

The signal from the TDD Base Station was attenuated so that the TDD UE would be transmitting at full power:

- The TDD power level at 1 meter from the LTE UE (with phone actively transmitting) was -25dBm
- The Wi-Fi RSSI at the Wi-Fi Client Device was -50dBm
- All tests from this series were conducted on Wi-Fi Channel 1

9.3 Test Results

- For the Wi-Fi Clients tested, there was minimal impact on performance when positioned further than 0.5 meters away from the TDD UE transmitting at full power. On average the throughput was reduced by less than 10%.

- Even at distances under 0.5 meters, there was no major impact unless the TDD UE, transmitting at full power, was positioned directly against the Wi-Fi Client antenna, physically blocking it. With the TDD UE placed directly onto the keyboard of the laptop being tested, the reduction in throughput was less than 20% on average.

- TDD UE impact was apparent only while actively transmitting. On average, the impact was more pronounced when the TDD UE was uploading to the network than when it was downloading. With the TDD UE passively connected to the network there was no substantial impact.

9.4 Mobile Phone 1

Mobile Phone 1 was tested in two different positions adjacent to the TDD UE, representing the worst case situation:

1) "Devices back to back" – Mobile Phone 1 and TDD UE were placed on the side with their back casing against each other.

This was intended to maximize the potential interference due to the positions of the antennas on the two phones. Indeed some impact was recorded but only substantial when the TDD UE was performing uploads to the network. When downloading there was no substantial difference recorded.

2) "LTE on top" - Mobile Phone 1 was placed flat with its screen facing up. The TDD UE was placed on top of Mobile Phone 1 with the TDD UE back casing against the Mobile Phone 1 screen.

   There was a 15% impact recorded when the TDD UE was uploading at full signal strength. There was no substantial difference recorded when the TDD UE was downloading.

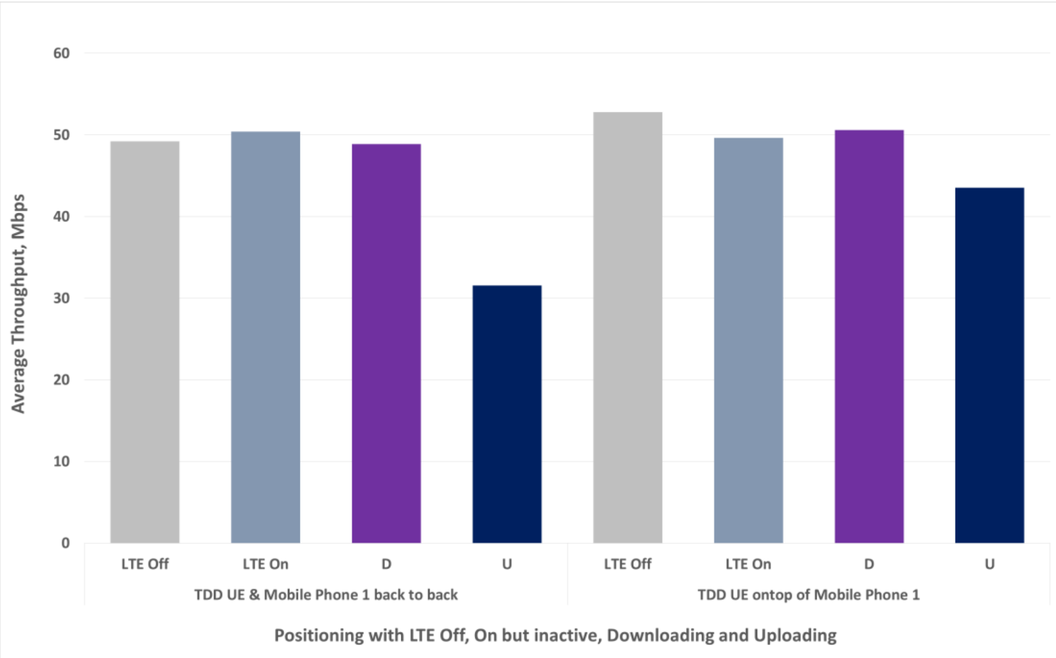

Figure 16. Impact of positioning Mobile Phone 1 relative to TDD UE for different LTE operation states

- "LTE Off" is the reference measure with both TDD Base Station and TDD UE turned off
- "LTE On" is the measure with the TDD Base Station and the TDD UE turned on but with no active upload or download taking place
- "D" is the measure with the TDD UE actively downloading from the network
- "U" is the measure with the TDD UE actively uploading from the network

9.5 Mobile Phone 2

Mobile Phone 2 was tested in two different positions adjacent to the TDD UE:

1) “Face to face” – Mobile Phone 2 and the TDD UE were placed on the side with their screen against each other.

   This configuration was chosen to maximize the possible interference due to the positions of the antennas on the two phones. In this configuration there was a substantial degradation of the Wi-Fi throughput while the TDD UE was uploading. The throughput reached only 20% of what it was while the TDD UE was downloading.

2) “Adjacent and upright” – Mobile Phone 2 and the TDD UE were placed next to each other with their screens facing up.

   The degradation was minimal in this configuration even though the two phones were next to each other. On average there was a 15% difference in the Wi-Fi throughput between when the TDD UE was uploading and when the TDD UE was downloading.

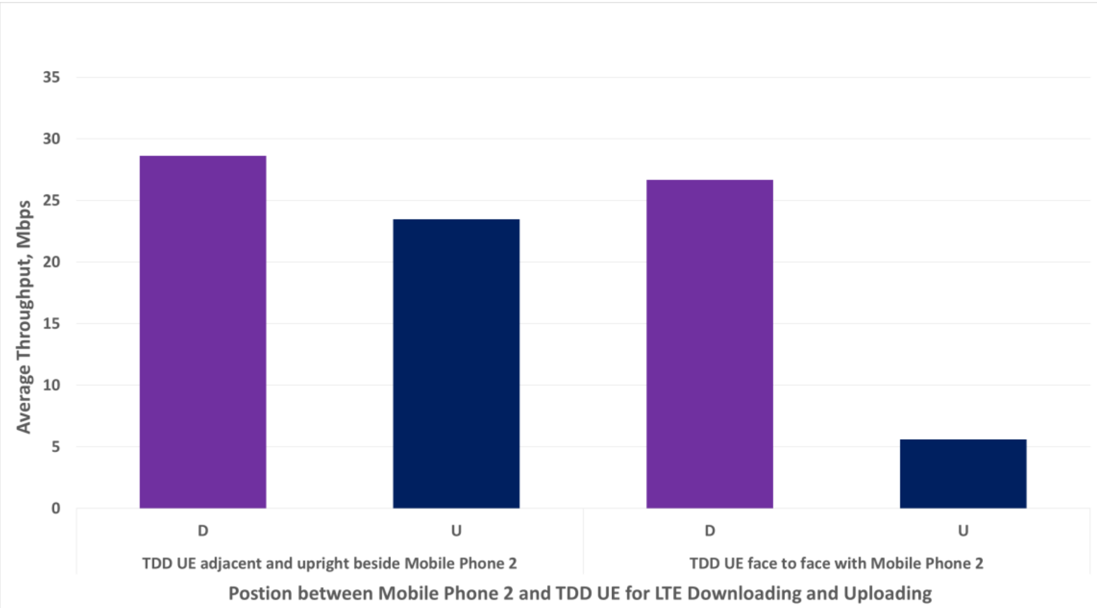

Figure 17. Impact of position between Mobile Phone 2 and TDD UE on Consumer AP 3 for LTE Downloading and Uploading

- “D” is the measure with the TDD UE actively downloading from the network
- “U” is the measure with the TDD UE actively uploading from the network

9.6 Mobile Phone 3

Mobile Phone 3 was tested side by side with the TDD UE with both devices placed flat next to each other with their screens facing up.

The validation showed a substantial throughput degradation when the distance between the two phones was 0.1 meters or less. With a 0.5 meters distance between the phones the throughput degradation was minimal.

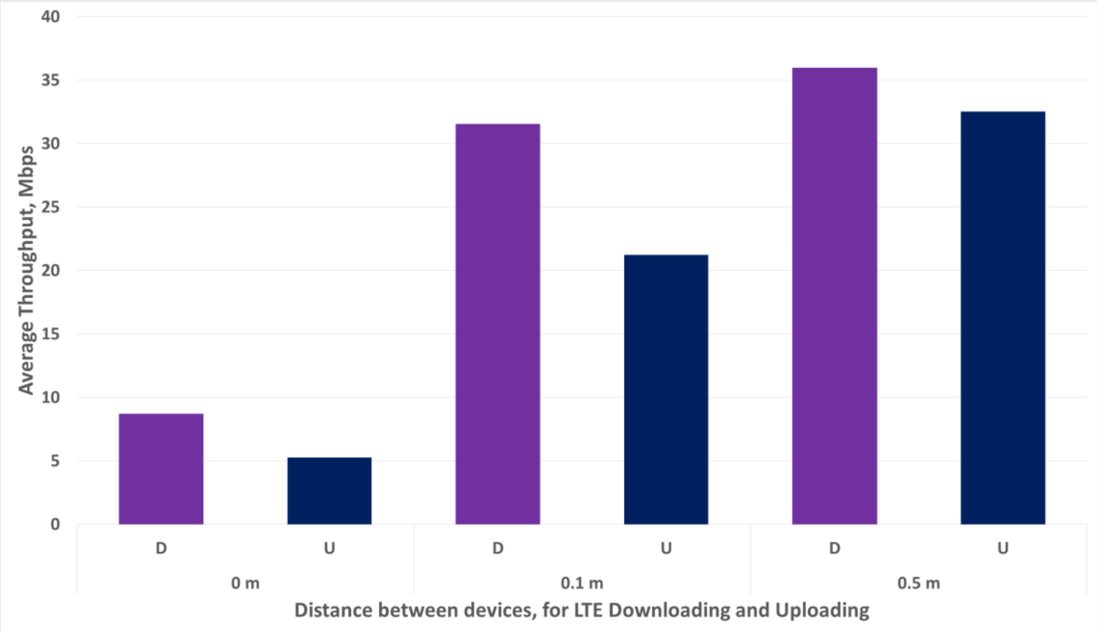

Figure 18. Impact on Average Throughput of varying distance between Mobile Phone 3 and TDD UE, for LTE Downloading and Uploading

- "D" is the measure with the TDD UE actively downloading from the network
- "U" is the measure with the TDD UE actively uploading from the network

9.7 Laptop 1

Laptop1 was tested in two different positions adjacent to the TDD UE:

1) "Back facing back" – The back casing of the TDD UE was against the back casing of the laptop screen.

   This was chosen to be the worst case scenario due to the position of the Wi-Fi antennas in the phone and in the laptop. The Wi-Fi throughput achieved when the TDD UE was uploading was reduced by 50% on average.

2) "Adjacent and upright" – The TDD UE was placed flat on the side of the laptop with its screen facing upwards.

   The Wi-Fi throughput degradation under TDD UE upload was similar to what was experienced in the "Back facing back" configuration. The degradation under TDD UE download was also substantial but this may not be representative due to the low number of samples used.

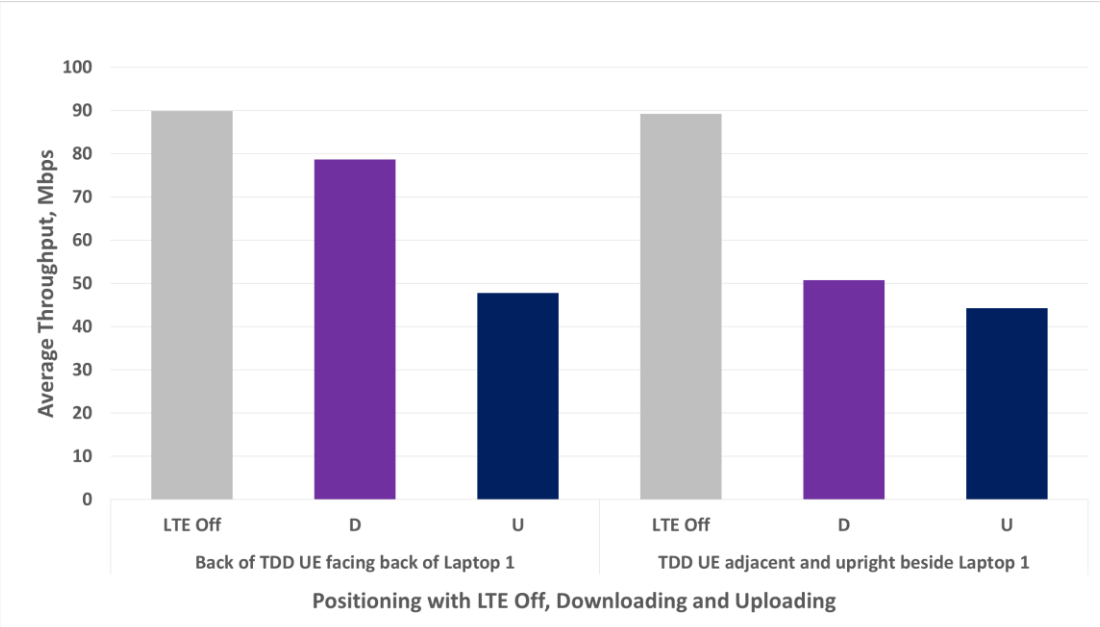

Figure 19. Impact of positioning TDD UE relative to Laptop 1

- "LTE Off" is the reference measure with both TDD Base Station and TDD UE turned off
- "D" is the measure with the TDD UE actively downloading from the network
- "U" is the measure with the TDD UE actively uploading from the network

9.8 Laptop 2

For the purpose of this test the TDD UE was placed on top of the keyboard of the Laptop 2, with the TDD UE screen facing up. The Wi-Fi antenna in most laptops is located at the top of the screen. The Laptop 2 test showed a 20% degradation of the Wi-Fi throughput with the TDD UE device actively uploading to the network at full signal strength.

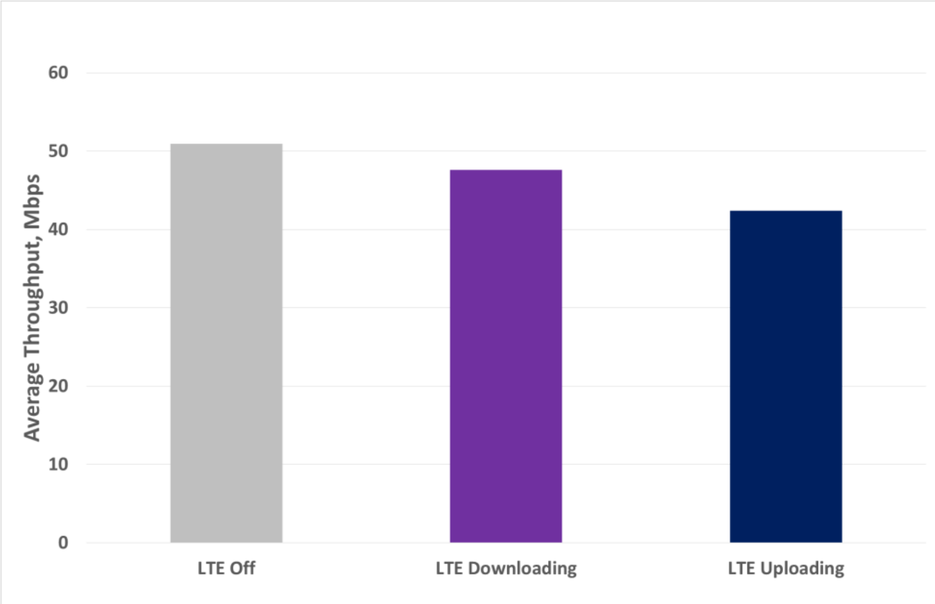

Figure 20. Impact of LTE on the Average Throughput on Laptop 2

- “LTE Off” is the reference measure with both TDD Base Station and TDD UE turned off
- “LTE Downloading” is taken with the TDD UE actively downloading from the network
- “LTE Uploading” is taken with the TDD UE actively uploading from the network

APPENDICES

APPENDIX A - Test Environment and Equipment

1. Test Environment

The tests were performed in October 2014 at the following Telefonica location:

354 Buckingham Avenue
Slough
Berkshire
SL1 4HR

Most of the tests were conducted in regular office space while office staff were attending normal business. A number of Wi-Fi devices were operating on the channel while tests were being done, reflecting the condition of a live enterprise deployment.

Figure 21 shows the number of Wi-Fi devices detected on Channel 1 during a Tuesday in October 2014.

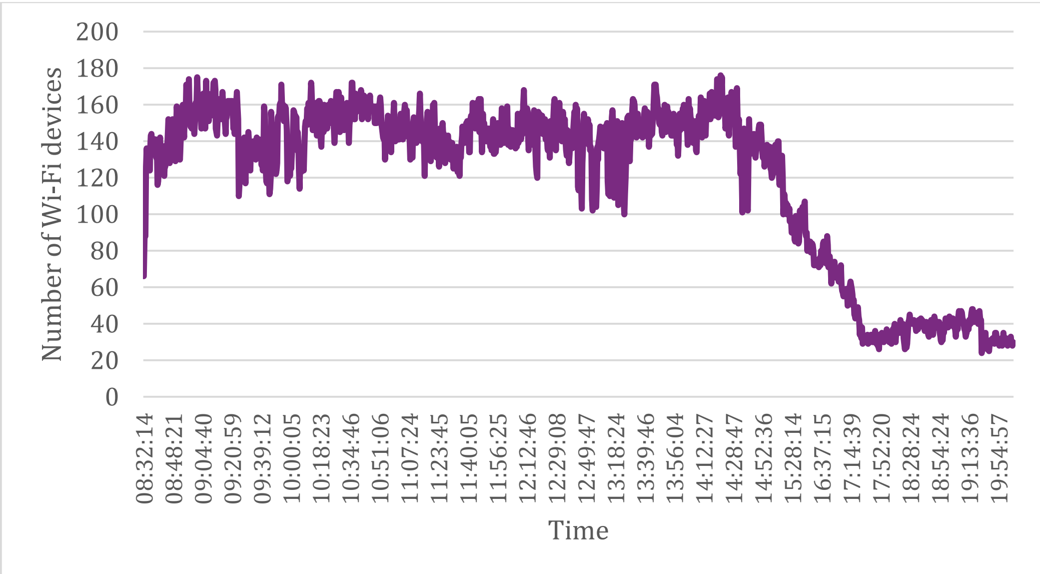

Figure 21. Number of Wi-Fi devices on Channel 1

The exception are the TDD UE tests which were conducted in a Faraday cage to ensure the TDD UE was connected to the TDD Base Station. For the TDD UE tests there was no active Wi-Fi device on the channel aside from the devices being tested.

2. Wi-Fi Equipment

The following Wi-Fi devices were used for testing.

Device under Test	Type	Device Name	Vendor
DuT #1	Enterprise AP	Enterprise AP 1	Vendor 1
DuT #2	Consumer AP	Consumer AP 1	Vendor 2
DuT #3	Consumer AP	Consumer AP 2	Vendor 3
DuT #4	Consumer AP	Consumer AP 3	Vendor 3
DuT #5	Mobile Phone	Mobile Phone 1	Vendor 4
DuT #6	Mobile Phone	Mobile Phone 2	Vendor 4
DuT #7	Mobile Phone	Mobile Phone 3	Vendor 5
DuT #8	Laptop	Laptop 1	Vendor 6
DuT #9	Laptop	Laptop 2	Vendor 7

3. TDD LTE Equipment

The following TDD LTE equipment was used for the tests.

Equipment	Type	Device Name	Vendor
Eq #1	TDD Base Station	Base Station	Vendor 8
Eq #2	TDD User Equipment	Mobile Phone 4	Vendor 5
Eq #3	TDD Antenna	Beam Antenna	Vendor 9

In addition attenuators were used between the LTE base station and the antenna. Depending on the test we used attenuations between 16 dB and 30 dB.

4. OptiCubes

An OptiCube is a Wireless Network Probe Hardware device used by OptiWi-fi Ltd. to analyse Wi-Fi performance with our patented diagnostics software. This device is a passive mini-Wi-Fi AP set to monitor mode only. It uses an Ethernet connection to send diagnostic results back to OptiWi-fi Cloud Servers, it does not emit any Wi-Fi signal and as such has no impact on the results of the tests.

OptiCubes were used to provide an accurate picture of the performance of the Wi-Fi connection between the Access Point (AP) and the Client Device (CD).

The impact of interference needs to be assessed from the perspective of the Receiver in the AP and CD rather than from a pure signal perspective. An RF analyser provides an insight into the signal interference at the RF level but it will not give any information as to how the signal is effectively processed by the AP and CD. OptiCubes bridge this gap by providing direct visibility on how the quality of the Wi-Fi connection is impacted by potential interference from TDD transmissions in the 2.3 GHz band.

To avoid potential LTE interferences, the OptiCubes were placed in a shielded position from the LTE antenna.

5. RF Analyser

Two RF analysers were used to measure the effective TDD signal strength received on the devices being tested. This was used to calibrate the TDD signal.

APPENDIX B – LTE Configuration

The LTE Base Station was configured to operate in the frequency range 2370-2390 MHz. This is the closest range to the Wi-Fi band therefore likely to be the worst case scenario.

Two TDD modes were validated.

1. Full Power All Timeslots

Tests without TDD UE were conducted using the test mode E-TM1.1

This mode is a worst case scenario, corresponding to a reasonable approximation of a fully loaded base station.

E-TM	Notes	Test case
E-TM1.1	Maximum power tests	Output power, occupied bandwidth, ACLR, operating band unwanted emissions, transmitter spurious emissions, transmitter intermodulation, reference signal absolute accuracy

2. 3:2 downlink/uplink

Tests with TDD UE were conducted with the base station using TDD frame configuration 1 with special subframe configuration 7.

This corresponds to a downlink/uplink ratio of 3:2 which was chosen to maximize potential interferences generated by the TDD UE transmissions.