Authors: Leigh Chinitz, CTO, octoScope
Amit Zeevi, Senior Member of Technical Staff, Intel
Doron Nevipur, Integration Team Leader, Intel

Triathlon: RF, MAC, PHY analyzer for Wi-Fi 6 (11ax) and legacy Wi-Fi

Overview

Triathlon is a combination of hardware and software that finally makes it possible to analyze wireless data across the RF, PHY and MAC layers, and provides the ability to correlate information among the layers and to drill down easily to any issue being explored. Packet sniffers make it possible to look at protocol elements across various layers of the OSI protocol stack. However, the realms of "RF analysis" and "protocol analysis" have long been completely separate, leading to wasted time and energy as teams with different tools attempt to jointly debug solutions Triathlon merges those two domains together, making it possible for teams with expertise in those various domains to analyze data together, and to solve problems faster.

Why do we need Triathlon?

The creation of wireless products is challenging, especially in the early stages of development. By definition, teams are working, at that time, with early versions of both hardware and software, and none of the elements have been optimized. Firmware, drivers, and application software are largely untested. And, to add to the challenges, the environment in which the devices are tested is highly dynamic, since that is the nature of RF. On top of all of this, early-stage products may have different interpretations of standards, leading to interoperability challenges that can add to, or mask, the other problems discussed above.

The challenges of new wireless product development are nowhere more obvious than in the development of the latest version of the Wi-Fi set of products, Wi-Fi 6, based on the 802.11ax amendment to the standard. Details of Wi-Fi 6 can be found elsewhere, but the highlights are listed here:

- Higher throughput through the use of higher order modulations, lower per-symbol overhead, and a higher number of MIMO streams,
- More efficient handling of airlink resources by using OFDMA (orthogonal frequency division multiple access) to permit simultaneous communication between an access point (AP) and multiple client (or "station" or "STA") devices.

It is this second item that creates some very challenging requirements for Wi-Fi 6. Since Wi-Fi 6 is designed to allow an AP to communicate, simultaneously, with multiple devices, there are very tight time, frequency, and power synchronization requirements that are part of Wi-Fi 6 that are different from what has been the case in Wi-Fi up until now. Multiple station activity is coordinated relative to what is known as a "trigger frame" in Wi-Fi 6, and some requirements surrounding that trigger frame are:

- Absolute and relative transmit power accuracy on the order of a few dB for various device classes
- Packet arrival time within a ±400 nanosecond window
- Carrier frequency offset compensation such that the residual offset is no more than 350 Hz. This is on the order of 0.07 ppm at 5 GHz.

These are the types of challenges that engineers need to address when developing, integrating the elements of, and deploying the latest wireless technologies.

A classic, initial test of a wireless system would be to look at the throughput the system is able to obtain under nearly optimal wireless conditions. But even under those conditions, the system may not perform as expected. There can be many ways in which this can be the case. In one of the simplest, the throughput might be much lower than anticipated. More complicated problems may relate to the kinds of requirements discussed above (timing or frequency correction may be out of specification, OFDMA resource assignments may be wrong, etc.) To understand the root cause, developers need to look everywhere.

- Is it the problem at the MAC layer? (Congestion, Fragmentation, Aggregation, Scheduling, etc?)
- Is the problem at the PHY layer? (Low data rates, wrong channel widths, suboptimal MIMO, bad power, time, or frequency offset alignment, etc?)
- Or is the problem at the RF layer? (I/Q constellation not clean, EVM too high, phase noise, problem with pilots tracking frequency/phase/amplitude, noisy RF environment affecting the SNR, etc?)

The current state of the art is to use (at least) two separate types of tools to look at the system, and to try to understand where there might be problems by analyzing the data independently.

One tool is a packet sniffer. This tool speaks the same language as the technology being developed and is able to capture data packets sent and received by the system. Those packets can then be broken into their component pieces and analyzed for problems. A well-known tool for analyzing packet captures is the Wireshark analysis tool.

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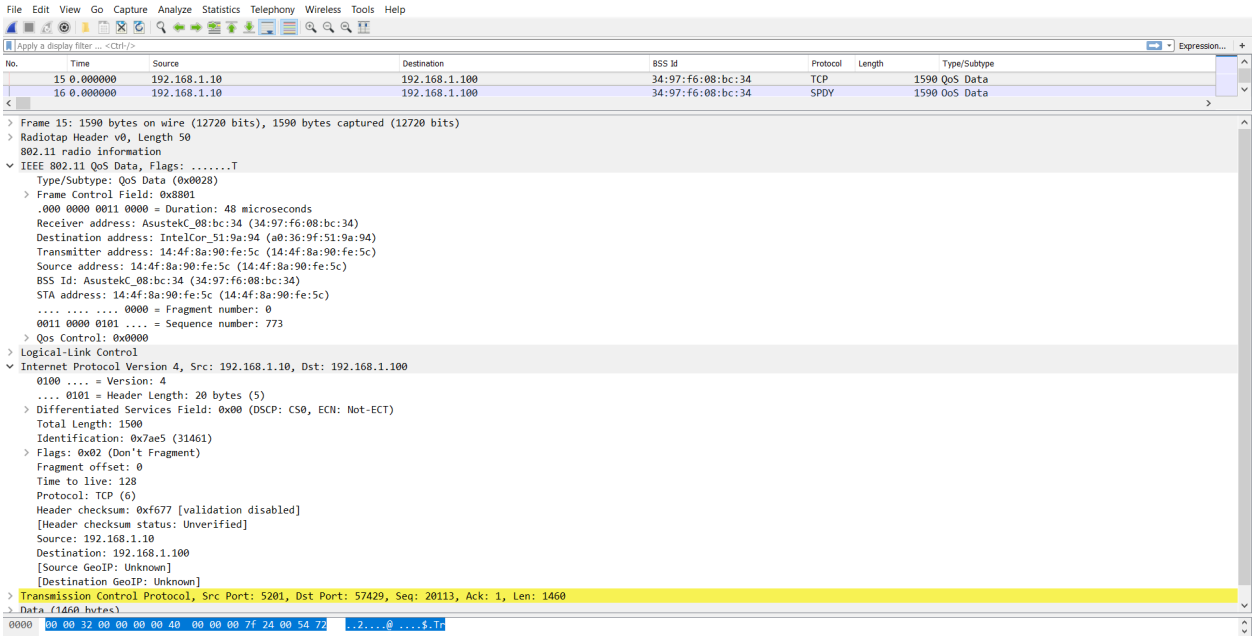

Figure 1: Example Wireshark packet analysis

While Wireshark is an excellent tool for analyzing individual packets, the answer to questions about under-performing systems still requires an engineer to make sense of what may be tens of thousands (or more) of packets. Is the system seeing too many retries? Is the expected number of MIMO streams being achieved? Is the PHY data rate too low? If so, why? All of this requires the ability to analyze a large number of packets, and it may even require the ability to get beyond the protocol level, all the way to the basic RF level.

Another tool that is commonly used is a vector signal analyzer. This type of tool can measure the known signals, analyze them in terms of magnitude and phase, and then report such quantities as error vector magnitude (EVM), spectral flatness, etc.

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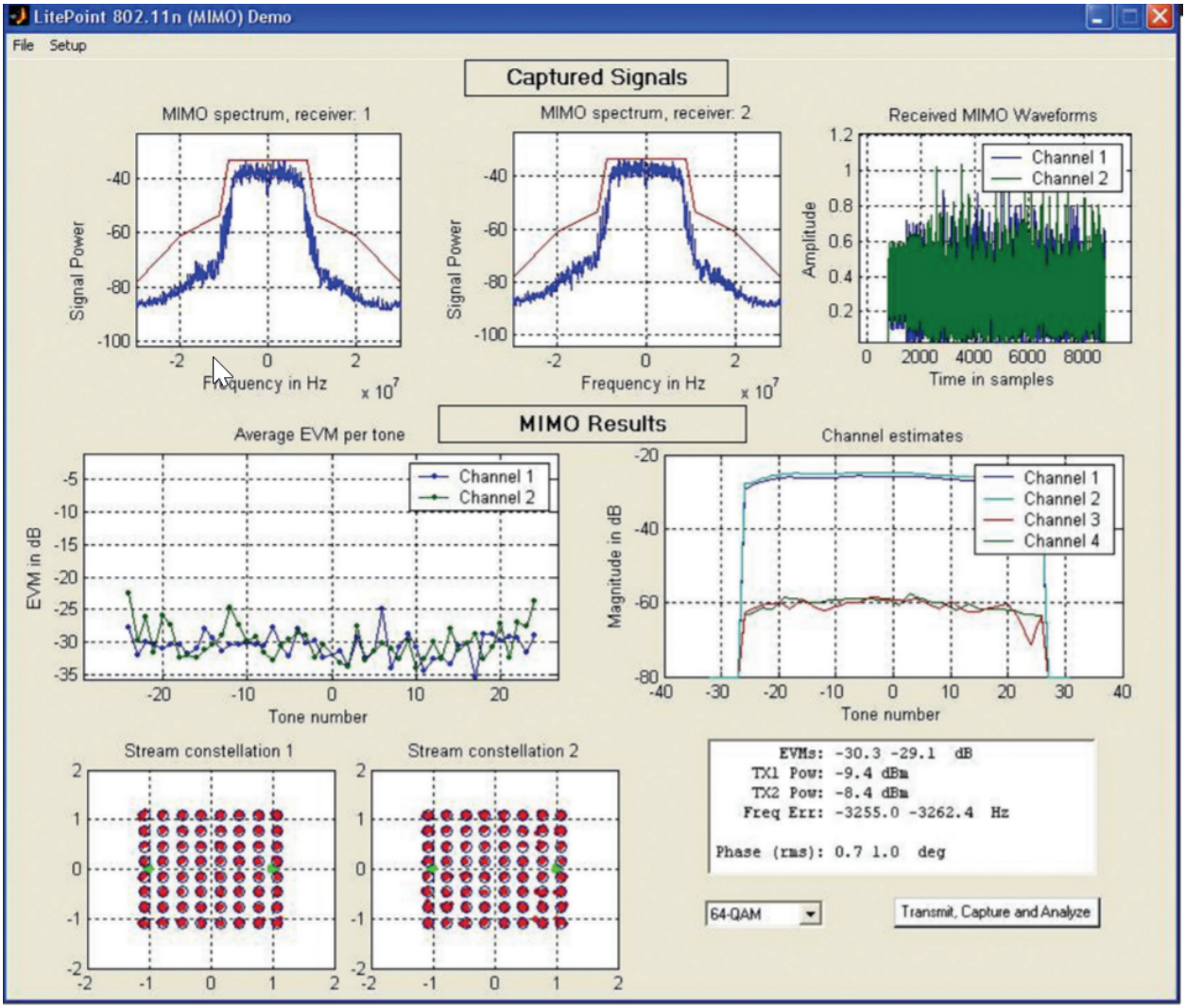

Figure 2: Output from a typical vector signal analyzer, showing a constellation diagram, demodulation error data, signal spectrum, and the real-time measured signal

The difficulty, to date, has been in unifying the views that come from these different types of tools. For example, imagine that a developer using a packet sniffer identifies "low PHY data rates" as a possible cause for the low throughput issue he is debugging. Is that related to a rate adaptation scheme (a protocol problem), or is it due to a more basic problem of high EVM at the RF layer? How would this developer go about answering this question?

How does Triathlon make these tests easier to do?

It is precisely to answer the question asked at the end of the last section that Triathlon has been developed. The concept is to be able to make simultaneous, synchronized measurements using both a sniffer (protocol analyzer) *and* a vector signal analyzer (RF analysis tool). In that way, the answer to the

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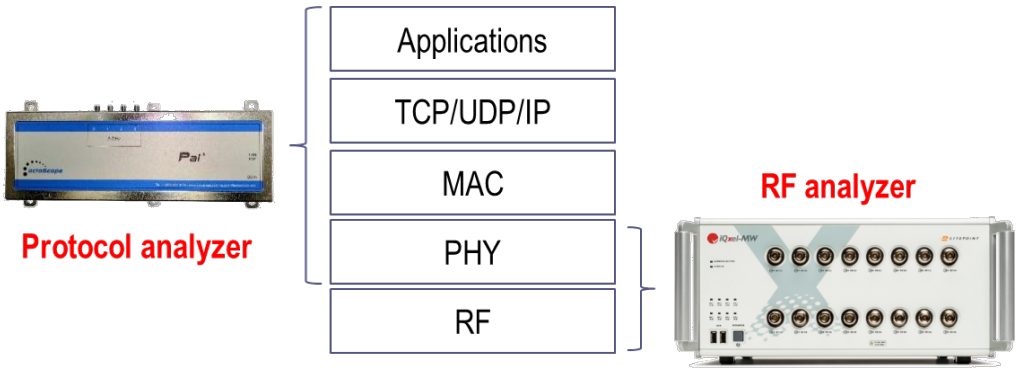
question posed above ("Is this a protocol problem or an RF problem?") can be answered immediately. With Triathlon it is possible to:

(1) Use event triggering to capture precisely the packets of interest, and then to
(2) Go directly from viewing a packet in a protocol analyzer to the corresponding I/Q samples, and vice versa.

With Triathlon, the historical separation between these two analysis domains has been removed.



For a more concrete example, imagine that a team of engineers are trying to understand why they measure lower throughput in one test compared to another, as in Figure 3.

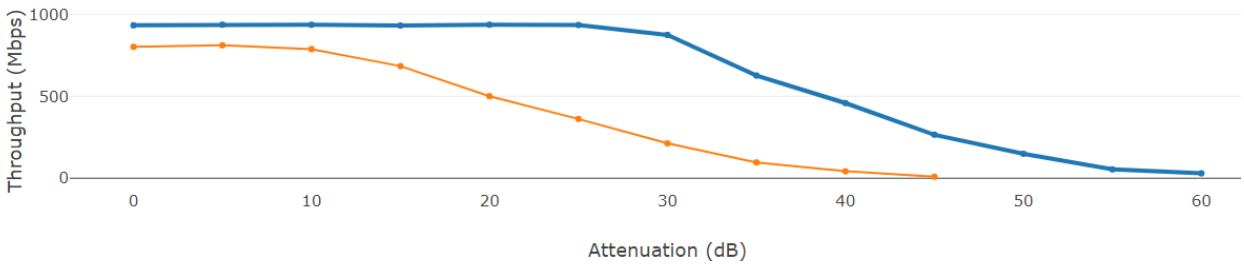


Figure 3: Throughput vs. Attenuation plot, comparing two tests. Notice that one of the tests shows lower throughput at all attenuation values

There are many reasons this could be the case, as discussed in previous sections. The engineers may be able to determine, for example, that the lower throughput is in fact due to lower PHY data rates, as in Figure 4.

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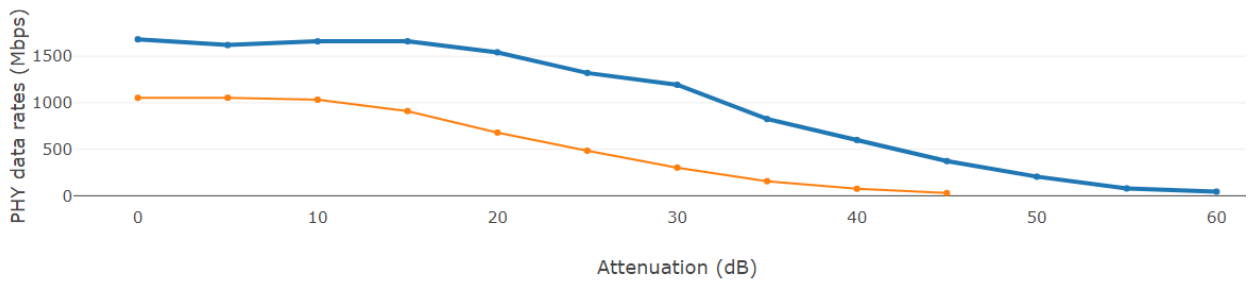

Figure 4: Data rates vs. Attenuation plot, comparing two tests.

The next question in the root-cause-analysis will be "why are the data rates lower in one test compared to the other?" It may be that the rates are lower because of some protocol issue that can be debugged using the available information, but it may also be the case that the problem is at a lower level – at the RF layer. For example, if the receiver can create a "clean" constellation (see the right side of Figure 5), there will be fewer bit errors, and the corresponding throughput will be high. However, if the constellation is poor (see the left side of Figure 5), the bit error rate will be higher, and the throughput will be correspondingly lower.

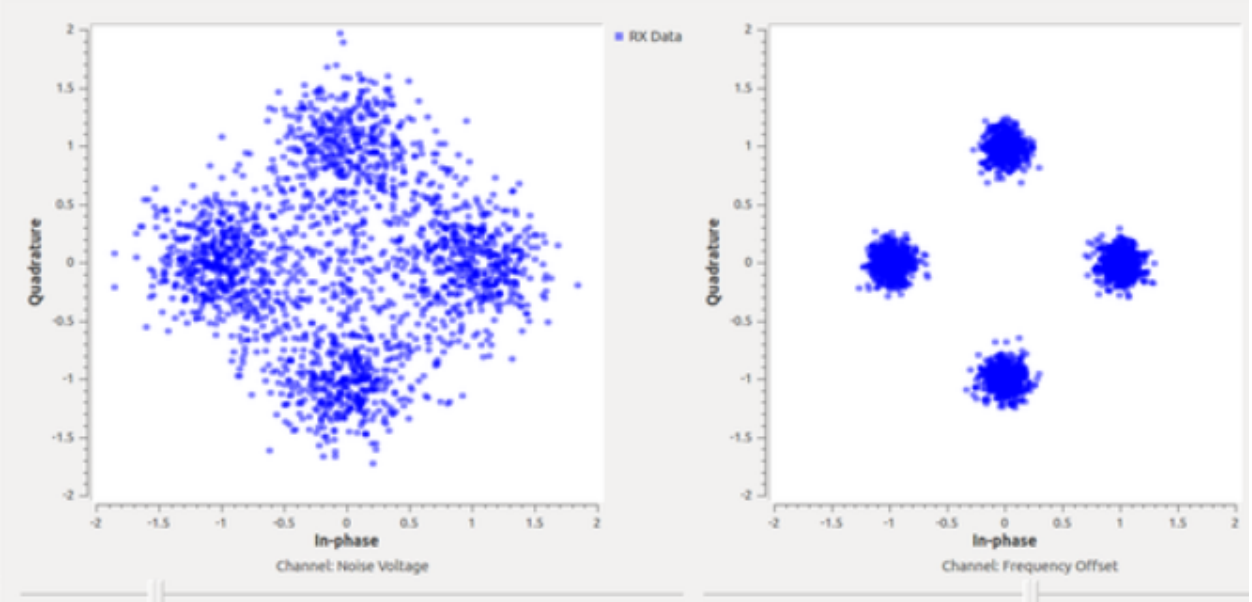

Figure 5: Example of a constellation diagram for a noisy signal (left) vs. a clean signal (right)

Therefore, it can be extremely useful for the engineers to be able to dive down all the way to the RF layer. This is what Triathlon allows.

With Triathlon, while the throughput data is being accumulated, packet sniffers are capturing the actual packets. Packet information is gathered both for decoded packets (at the protocol level), as well as at

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the RF layer (raw I/Q information.) Since the packets captured at the protocol level can be analyzed in real-time, Triathlon allows the user to create event-based triggers using the protocol-level captures (see "4.1.3 Event-based triggering", below) which cause the RF layer packet capture to begin. When we have both protocol level and RF-level packet captures, this data is combined into a single sniffer trace, with packets from both types of sniffers, as shown in Figure 6.

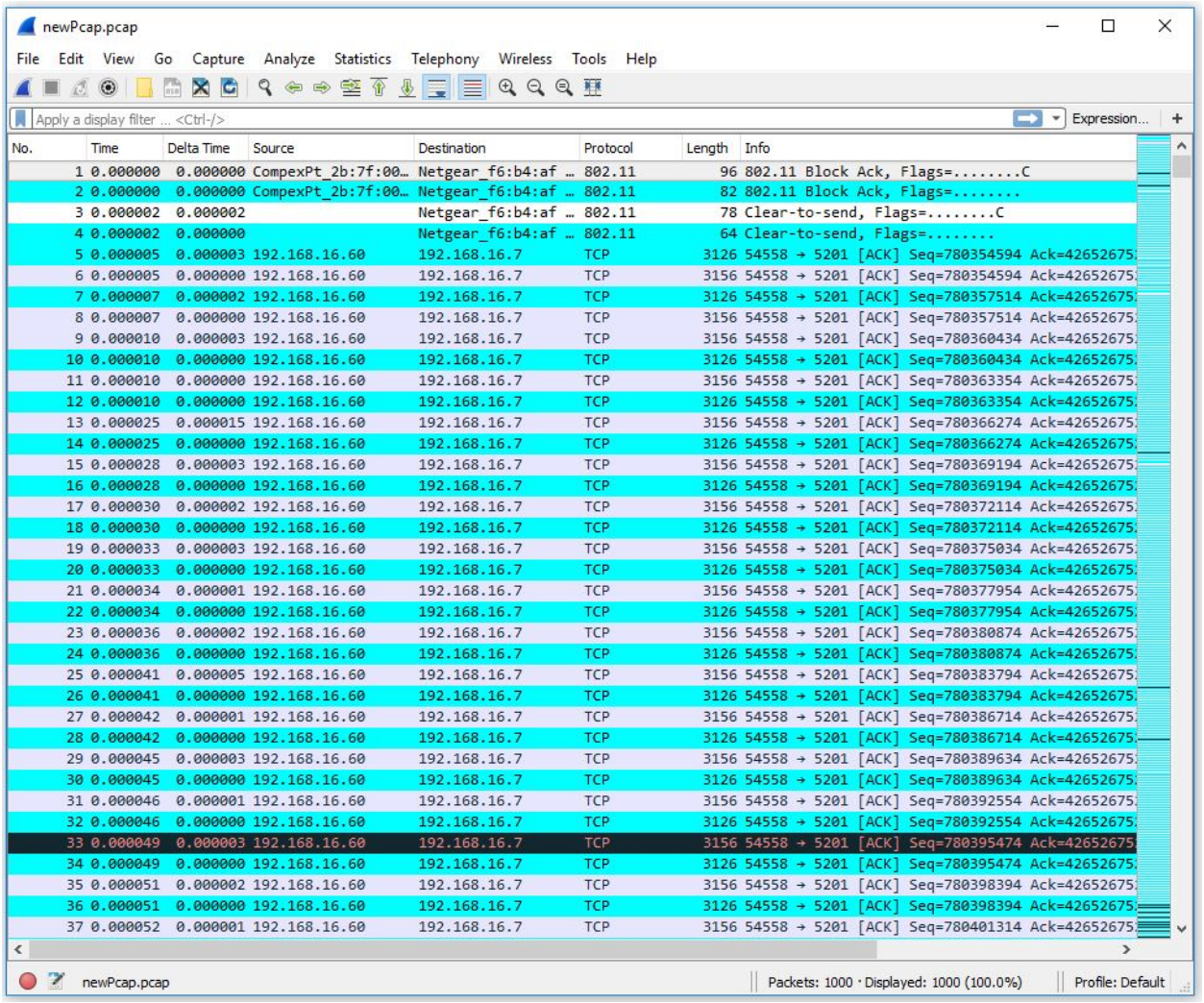

Figure 6: A combined Triathlon sniffer file. Highlighted packets contain links to raw RF information

The file typically contains duplicates of all the packets – one version of the packet as captured by a protocol analyzer, and one version as captured by an RF capture tool. The packets captured by the RF capture tool contain a link to the raw RF level information, and the engineers can access that

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information directly simply by clicking on the packet in the display. The RF level information is displayed by the LitePoint IQxel-MW as shown in Figure 7.

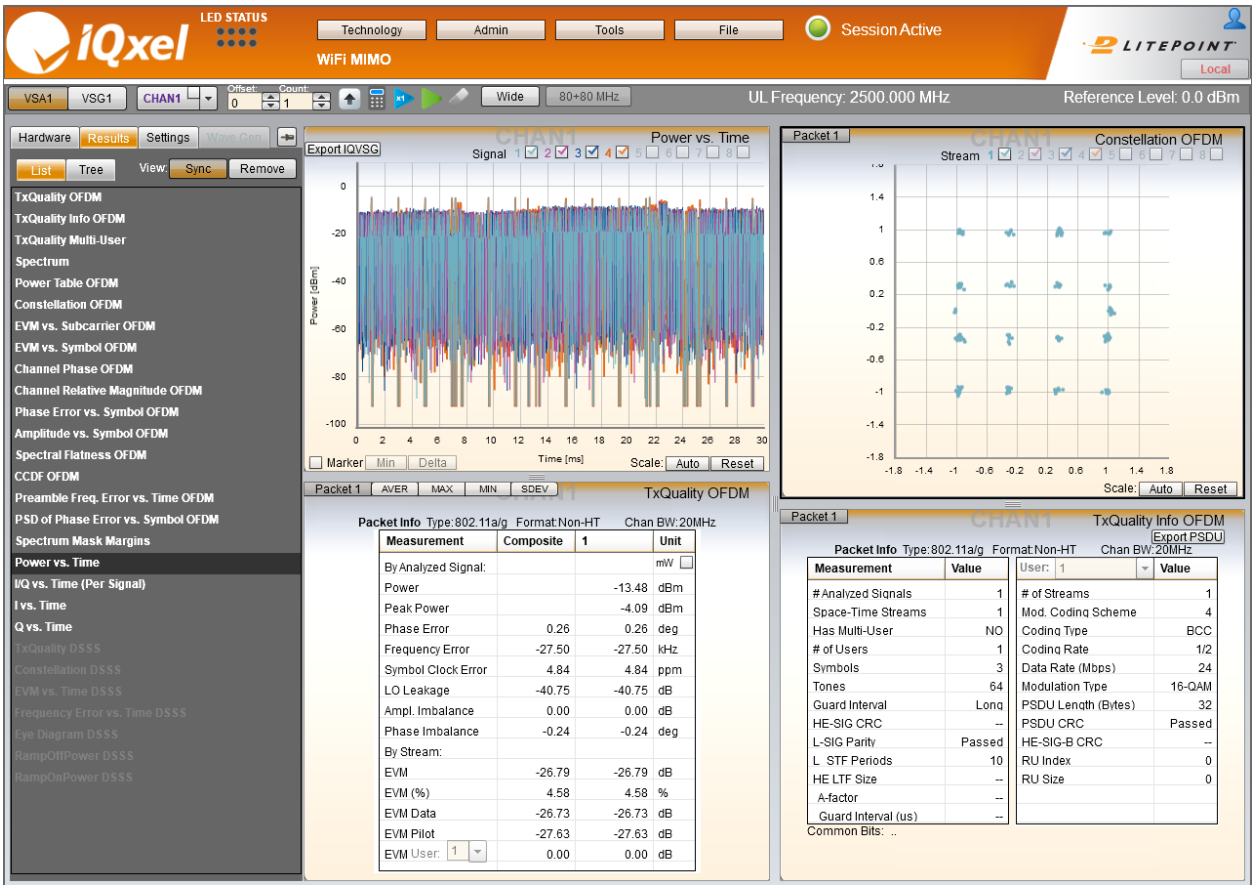

Figure 7: Raw RF information from LitePoint's IQxel-MW available by clicking on a highlighted packet in the combined capture file

The process of aligning the packets between the two views (RF and protocol) can be challenging, and octoScope has developed some unique tools to make this possible. Packets are not always uniquely distinguishable, and effort needs to be made to make it possible to tell the difference between the packets. This often involves deep packet inspection, going through the header and LAN information into the IP and TCP level.

What benefit do companies get from being able to do these tests more easily?

Combining the protocol-level and RF-level capture information, with the ability to transition easily between those two domains, provides immediate benefits to the engineering team. Since the root cause of an identified problem (e.g. low throughput) can be anywhere (RF, PHY, MAC, etc. including

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combinations), such analysis generally involves multiple teams. And it is time consuming and inefficient to debug these problems across multiple teams using different analysis tools.

Triathlon is the first tool designed to integrate signaling, RF measurements, PHY measurements, and decoding of bits on Rx and Tx into one single HW/SW platform. This allows multiple teams to work together using a single tool, reducing inefficiencies, and speeding root-cause-analysis and development times.

Brief introduction to the octoBox testbed

What are the main elements, and what do they do?

In order to understand the Triathlon system, it is necessary to understand the various components, including the octoBox® personal wireless testbed. That testbed is described in more detail elsewhere[1], so this document will provide only a high-level description, sufficient to understand how Triathlon works.

The octoBox is a wireless personal testbed ("octoBox"), which means that it is a testbed for testing wireless devices and having a form factor that is much smaller than what has been used for wireless testing traditionally. An octoBox can be configured to sit on the desk of an individual engineer, and in such a configuration can still contain everything necessary to run a wide variety of wireless tests.

An octoBox is typically made up of some set of the following elements

- Small MIMO OTA chambers. These are used to provide isolation from the surrounding environment, as well as to isolate various pieces of the test from other pieces. In addition, they create the environment in which MIMO testing can be done. These chambers are much smaller than traditional shield rooms and can be, as mentioned, placed on an engineer's desk.
- Pals®. These are octoScope instruments used during test as "testbed APs", "testbed clients", packet sniffers, and more. They are

[1] https://youtu.be/gu0LlUYo3Ek

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traditionally Wi-Fi devices, but newer generations are gaining additional functionality (e.g. Bluetooth.)

- Programmable attenuators. These are used to create RF separation, and emulate motion, between the devices under test.
- Antennas. These are used to distribute signals between various elements of the test setup.
- Traffic generator. This is used to create traffic streams between various endpoints in the test.
- Interference generators. These can be used to create controlled interference during the test.
- Multipath emulators. These can be used to emulate the effect of a particular multipath environment within which the devices under test can be located.

There are other elements that may be used as well, but the above list covers the majority of the typical octoBox use cases.

A very basic octoBox configuration can look like the one shown in 8.

An AP and a client (or "STA" in Wi-Fi terminology) are each placed in separate RF chambers. This shields them from the external environment, but also from each other. They are connected to each other using antennas inside each chamber to allow the devices to communicate over-the-air ("OTA"), and those signals are transmitted from box to box using RF cabling that passes through a programmable attenuator. Depending on the setting of that attenuator, the devices can either be "close to" each other (low attenuation) or "far from" each other (higher attenuation), yet the devices never have to be physically moved. This allows engineers to do testing such as the very common "rate vs. range" testing without ever having to move the devices, physically separate them, or even leave their desk. This is not only very convenient, it also makes for much more repeatable testing than is typically possible in a wireless test environment.

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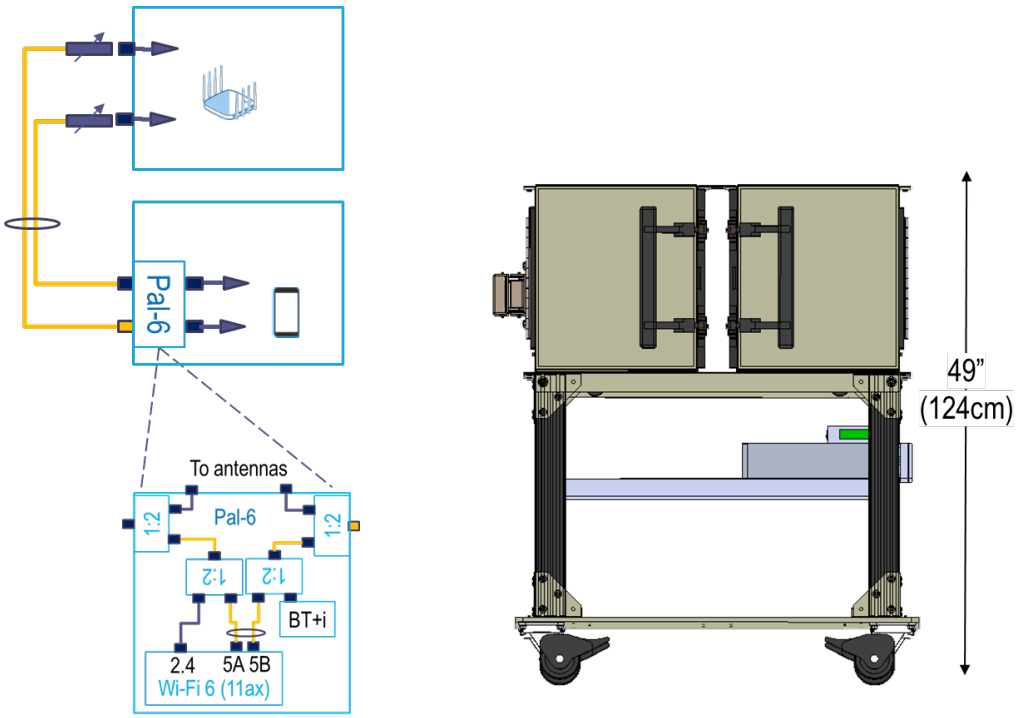

8: Simple octoBox configuration for testing an AP and client at different "distances"

Figure 9 shows an example of data collected from a rate-vs-range test in such an octoBox setup. While the data is collected as a function attenuation (the setting on the variable attenuator), this can easily be converted to path loss in the octoBox, and then to “range”, using an appropriate path loss model.

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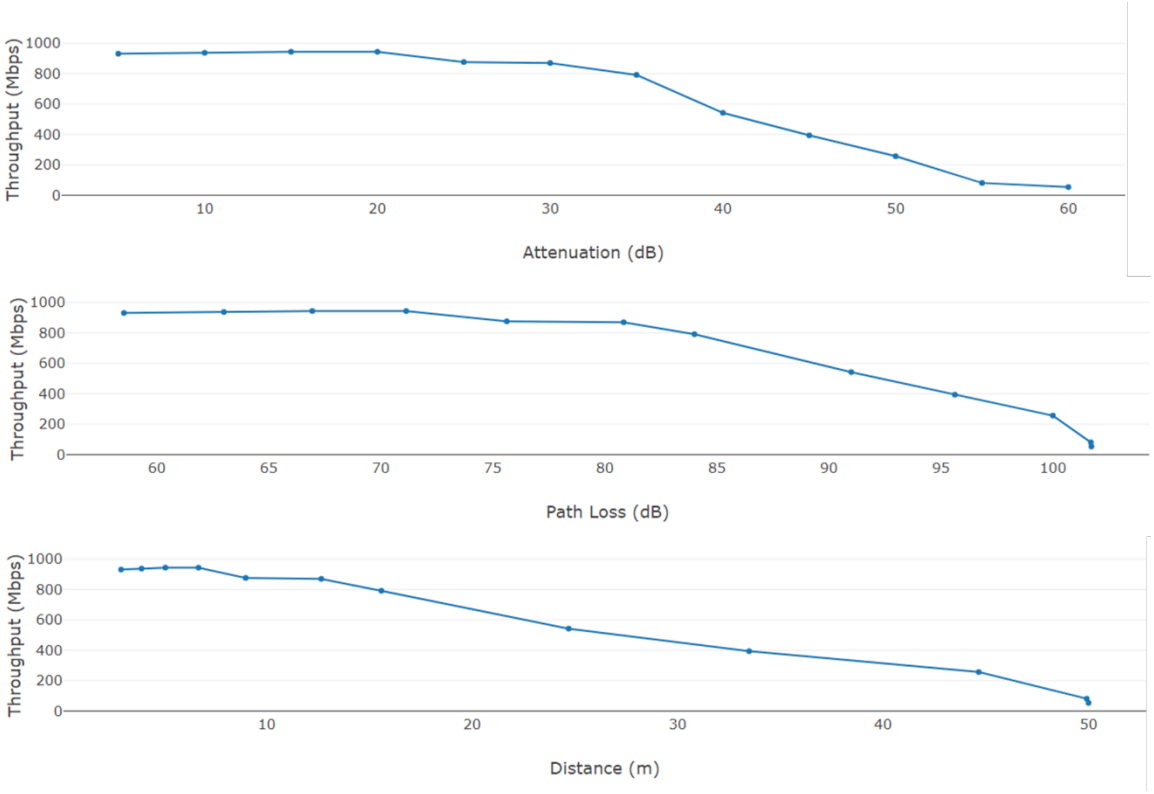

Figure 9: Example "Rate vs. Range" data as collected in the octoBox. Data collected as a function of attenuation can be converted to path loss which can be converted to distance using a desired path loss model

Triathlon technical detail

Elements of a Triathlon system

In a simple configuration, a Triathlon system can be configured as shown in Figure 10.

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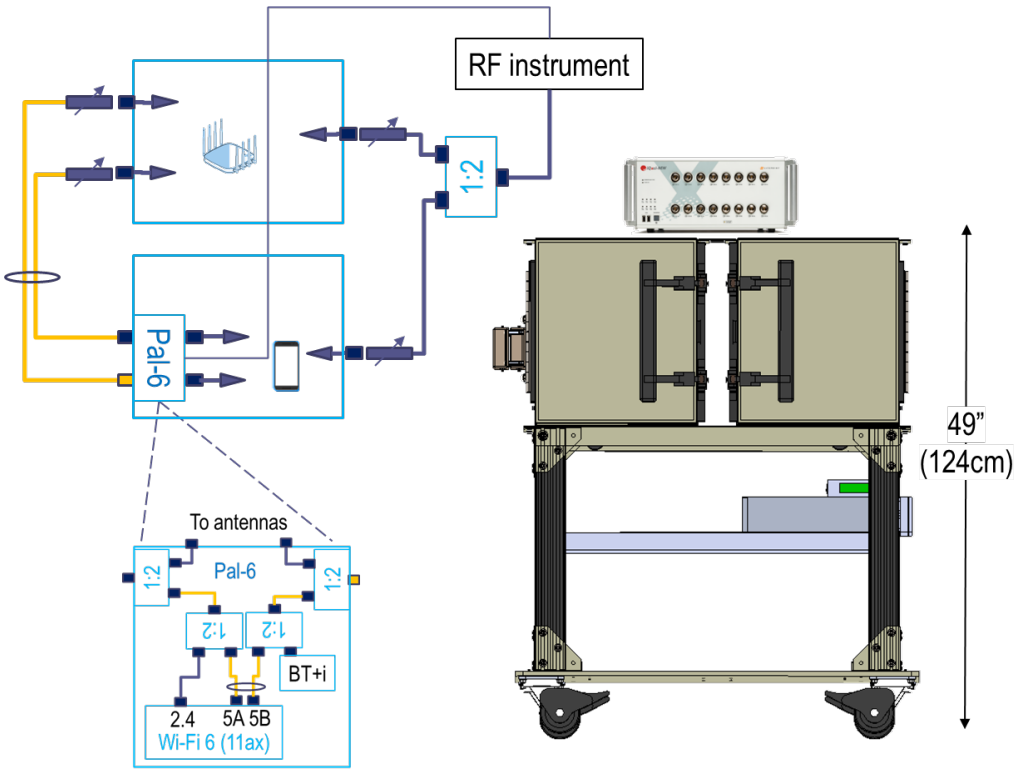

Figure 10: Simple Triathlon configuration

This configuration contains many of the elements discussed above, for a basic octoBox configuration, as well as an RF instrument to provide the RF level details. In this figure we show, specifically, the LitePoint IQxel-MW.

As above, the devices being tested are shown as an access point (in the upper RF chamber) and a client device (in the lower RF chamber.) The devices are coupled over the air, using test antennas in each box. These are connected to each other using RF cables.

The main difference from the configurations shown above is the presence of the octoScope "Pal-6", being used as a protocol sniffer, and the IQxel-MW, being used as the RF capture tool.

When traffic is generated between the AP and STA, that traffic can be captured by both the Pal and the IQxel-MW. Triathlon will then combine these captures, as shown in Figure 6, enabling engineers to move between protocol analysis and detailed RF analysis on a packet-by-packet basis, as shown in Figure 7

octoScope Pal

The Pal® is a versatile and highly controllable instrument that functions as a station (STA), virtual stations (vSTAs), access point (AP), traffic generator, load generator, sniffer and an expert monitor for

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tests such as throughput, forwarding rate, roaming, mesh/IoT, band steering and more. The Pal can be used in the controlled RF environment of the octoBox wireless testbed or as a stand-alone instrument.

In this Triathlon configuration, the Pal is being used as a packet protocol sniffer. From its location in the chamber containing the STA, it is able to see all of the data transferred between the AP and the STA. A future version of the Pal software will allow the Pal to act, simultaneously, as both AP and sniffer, so that testing can be done, using a single Pal to test a Wi-Fi STA, where that Pal is both the traffic endpoint (the AP), as well as the Triathlon protocol sniffer, as described in more detail below.

4.1.2 LitePoint IQxel-MW

The IQxel-MW Connectivity test system delivers high performance verification of a wide range of wireless technologies. This includes the latest generation of Wi-Fi 6 (802.11ax), as well as all IEEE 802.11 specifications including 802.11a/b/g/n/p/ac/ah/af/j and other popular wireless connectivity standards like Bluetooth, DECT and ZigBee. IQxel-MW delivers high-quality EVM performance, which ensures precise analysis of the device's modulation accuracy. The IQxel-MW additionally contains multiple vector signal generators (VSGs) and vector signal analyzers (VSAs) that can be internally synchronized for true MIMO test scenarios.

4.1.3 Event-based triggering

Those familiar with test tools like the Pal and IQxel will recognize that there are some potential complications with the Triathlon system as it has been described so far. A protocol-level packet capture tool like the Pal can decode packets in real-time. The Pal, in fact, can stream its decoded packets to external storage, making its ability to capture packets virtually unlimited.

RF analyzers, however, do not typically have this flexibility. RF tools, capturing raw I/Q samples, require much more memory for each packet than do protocol analyzers, which are storing only the decoded packet information. Therefore, while protocol analyzers may store packets from seconds or even minutes of traffic, RF tools can usually store data from much shorter capture periods.

This highlights another strength of the Triathlon system, as it is able to trigger the RF tool's capture function using the Pal, in order to capture data at the time of interest to the engineers.

Since the data is being analyzed by two tools at the same time (the Pal as a protocol analyzer, and the RF tool) it is possible to use the line-rate analysis capabilities of the Pal to indicate when the RF tool should be operating. We can imagine some simple scenarios.

- Triggering on packet types. Suppose that the engineers want to be able to examine specific types of packets, for example, beacons. Rather than trying to set up a case in which beacons will be sent and the RF instrument will, hopefully, capture them, we can use the fact that the Pal can recognize a beacon packet, and can trigger the RF tool to save the data from exactly the time that the beacon packet would have been detected.
- Triggering on error conditions. It may be useful to be able to see what is happening at the RF layer when specific errors occur, for example, CRC errors. Again, since the Pal can see this

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happening in real-time, the Pal is able to trigger the RF tool to save its data at the appropriate time.

- Etc. More complicated scenarios are easy to imagine. The Pal can process packets at line-rate, and complicated trigger logic can be implemented based on what the Pal has seen.

Since raw I/Q samples captured by the RF tool produce large amounts of data, it is able to keep a certain amount of information in the buffer and continue to overwrite this data as new information arrives. When the Pal logic detects a condition of interest, it can trigger the RF instrument to save the data in its buffer, and this saving process can be configurable. For example, the instrument may save everything that is already in its buffer, it may save everything that enters its buffer after the trigger arrives, or it may do something in between. This is shown in Figure 11, in which the information in the buffer in shown, changing over time. The Pal trigger occurs at a specific time, and the saved information may be what is already in the buffer, what is about to be in the buffer, or some combination, as represented by the two-sided (green) arrows.

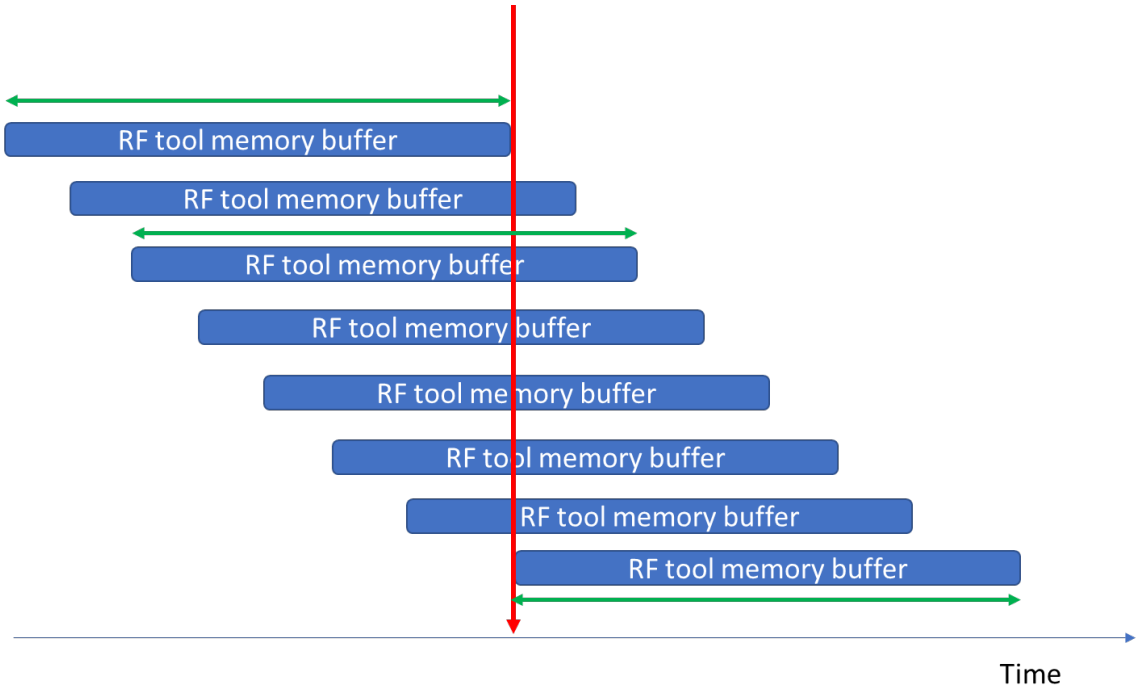

Figure 11: Pal trigger causes the RF tool to save the information in its memory, but exactly which information can be configurable

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How do these elements work together?

The Pal and the RF tool work together as shown in Figure 10, with the addition of trigger logic and the ability for the Pal to trigger the RF instrument, as shown in

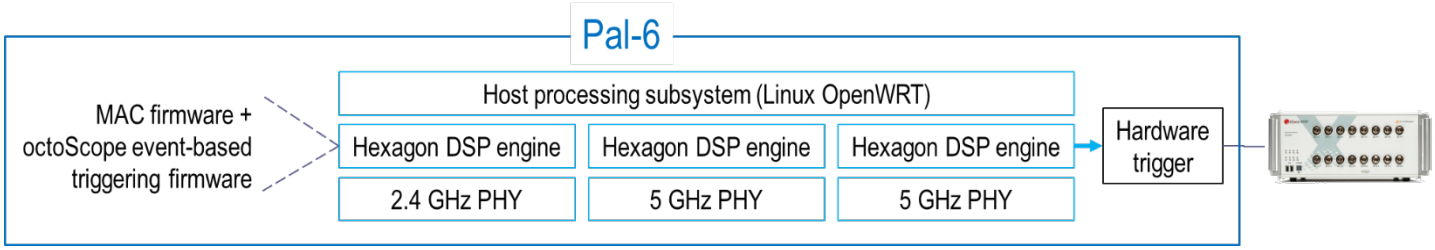

Figure 12.

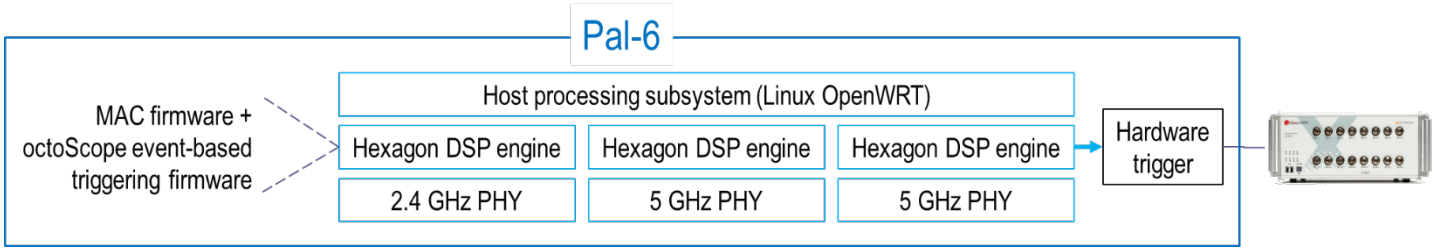

Figure 12: Triathlon configuration with trigger logic and trigger output from the Pal

What output does Triathlon produce?

As shown in Figure 6, Triathlon produces a file that combines that Pal capture (protocol level) and the RF tool capture into a single file. This file contains packets that give the engineers one-click access to the RF level information. Since the files, as discussed above, can be of vastly different sizes covering vastly different time spans, Triathlon outputs a combined file that covers only the general area of overlap, as illustrated in Figure 13.

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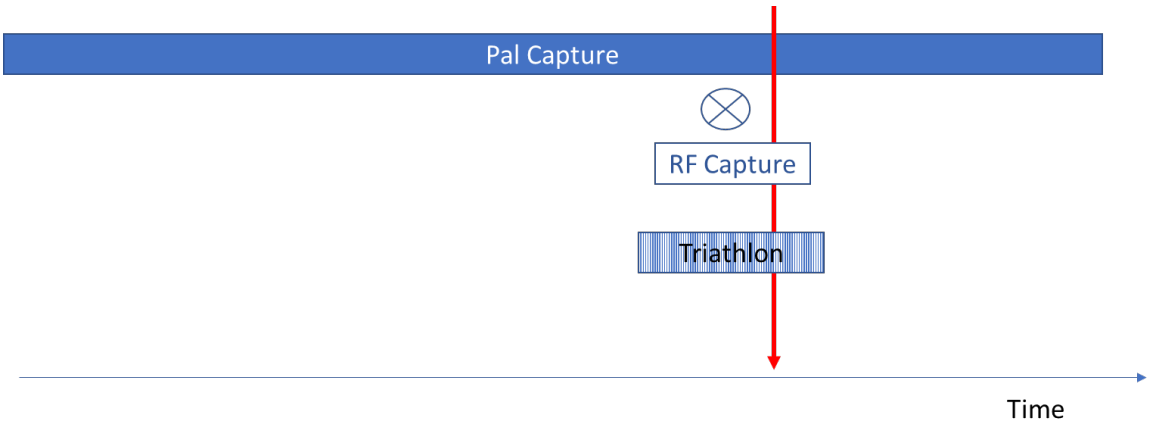

Figure 13: Merged triathlon packet capture is a combination of the Pal (protocol) capture and the RF tool capture

In fact, Triathlon itself produces all three (or more) capture files. That is, the Pal capture in its entirety is stored, as are the RF captures generated whenever the Pal triggers the RF tool. This may happen more than once. And for every trigger event, a Triathlon "merged" file is also created, for simple, multi-layer analysis.

How can that output be analyzed?

Triathlon greatly simplifies cross-layer, and cross-team, root cause analysis. Teams that are used to analyzing protocol captures (with tools such as Wireshark) can continue doing that using the extensive Pal captures of all of the traffic. Teams that are used to looking at RF information can do that, using the RF captures from the RF tool. But, what is possible, as never before, is the ability for both teams to talk about, and examine, exactly the same packets of interest. The merged data file contains packets of particular interest (based on the triggers) which can be examined not only at the protocol layers, but via a simple click, at the RF layer as well.

And because the data was captured in an isolated and highly controlled environment, it is straightforward to make changes to the devices, re-run the tests, and very quickly identify and solve problems that lead to performance issues. Triathlon leads to an entirely new way of identifying and solving problems, as illustrated in Figure 14.

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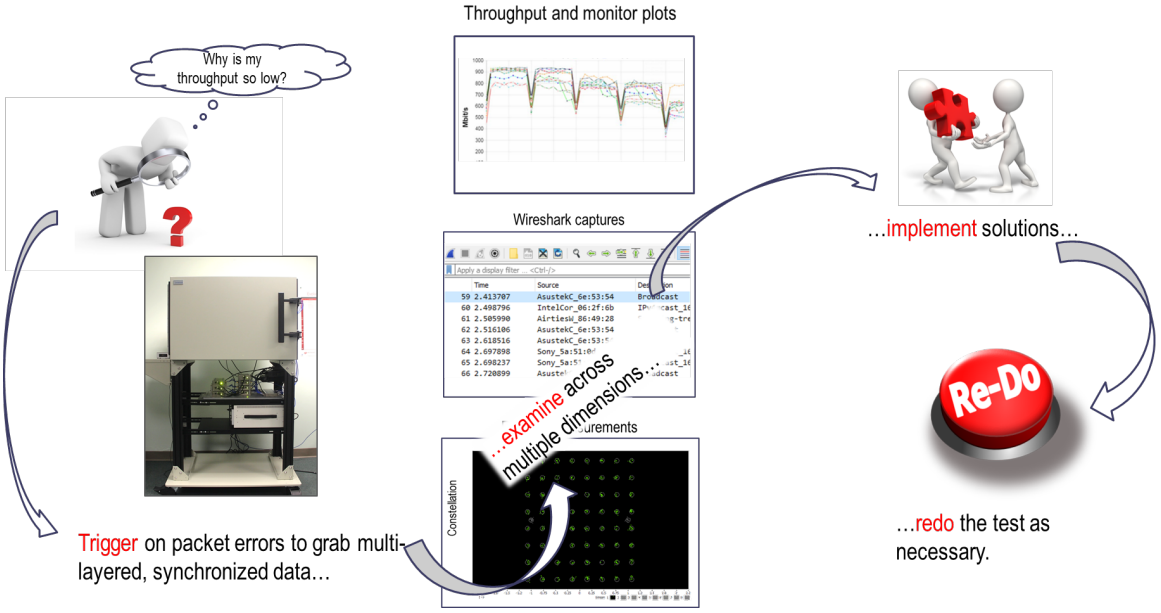

Figure 14: Triathlon opens up new ways of identifying and solving wireless performance problems

When a performance issue is identified, Triathlon can be used to:

- Create an event-based trigger condition,
- Simultaneously capture both protocol and RF data in the region of the desired event,
- Automatically match up those two sets of data,
- Move from the protocol layer to the RF layer via a single click,
- Implement solutions based on what is found, and
- Repeat the process until the problem is solved

Examples of Triathlon tests

As described above, Triathlon is broadly useful as an efficient tool for helping teams work on technologies across protocol layers. However, also as discussed, a strong driver for the creation of Triathlon is the need for such a tool by teams working specifically on the development of Wi-Fi 6, the latest update to the Wi-Fi family of standards.

5.1 Wi-Fi 6 (802.11ax) tests

Although Wi-Fi 6 has a number of updates compared to the legacy 802.11 standards, possibly the key one is the implementation of OFDMA for both uplink and downlink communications. In the downlink (AP-to-STA communication) this means that the AP can send data to multiple STAs, simultaneously, by using one group of OFDM subcarriers for one STA, and a different group for other STAs. As the name implies, it is a frequency division mechanism of communicating with multiple STAs, simultaneously. These groups of OFDM subcarriers are called “resource units”, or “RUs”.

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Where this gets really complex is in the uplink direction. The same basic thing happens, that is, different STAs communicate, simultaneously, with the AP by using different RUs. This is complex because in order for this to happen, those communications have very strict synchronization requirements across a number of dimensions. For example:

- Since the AP will be receiving transmissions from multiple STAs at the same time, and since some of the STAs may be closer to the AP than other STAs, it's necessary that the STAs be able to control their transmit powers so that transmissions from one STA do not overwhelm transmissions from another. Even though the STAs are using different RUs, the out-of-band emissions from a nearby STA can still overwhelm the signal from a far-away STA unless the received power at the AP from all the STAs is reasonably similar.
- Similarly, since the AP needs to receive these STA transmissions simultaneously, carrier frequencies across all of the STAs must be highly aligned. The requirement is that, after alignment, the error in the carrier frequency offset be no more than 350 Hz, which is less than 0.07 ppm at 5 GHz.
- Finally, the STAs that will be simultaneously sending information to the AP need to send that information at the "same time". And the definition of that is that the uplink transmissions need to arrive at the AP at ±400 nsec from some time offset from the frame that initiates these transmissions, known as the "trigger frame" in Wi-Fi 6.

This complexity lends itself immediately to the Triathlon analysis tool.

5.1.1 Trigger frame conformance

One set of measurements that Triathlon can enable is simple conformance to the trigger frame requirements, as set out above. Devices in a Wi-Fi 6 link can be communicating, and the Triathlon event-based triggering can be used to capture not only trigger frames, but the resulting uplink data frames from the associated STAs. The protocol-side capture can be used to verify the content of the trigger frame, and the RF-side capture can be used to validate the types of power, frequency, and time alignment (or "pre-correction") described above. An example of the timing conformance test is illustrated in Figure 15.

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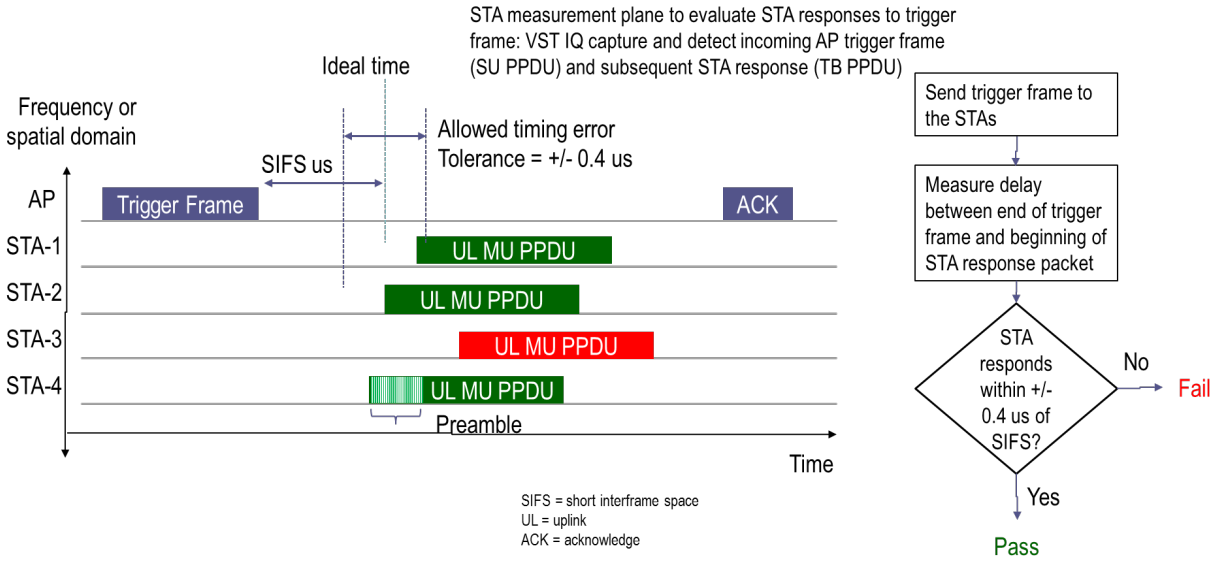

Figure 15: Triathlon-based trigger conformance test for timing pre-correction

5.1.2 OFDMA RU allocation

At a less “standards-based” level, and more of an “algorithmic” level, Triathlon can be used to help developers to make sure that the RUs the APs have allocated to the STAs with which they are communicating are both “correct” and “efficient”.

An example of and AP assigning RUs to various STAs in shown in Figure 16.

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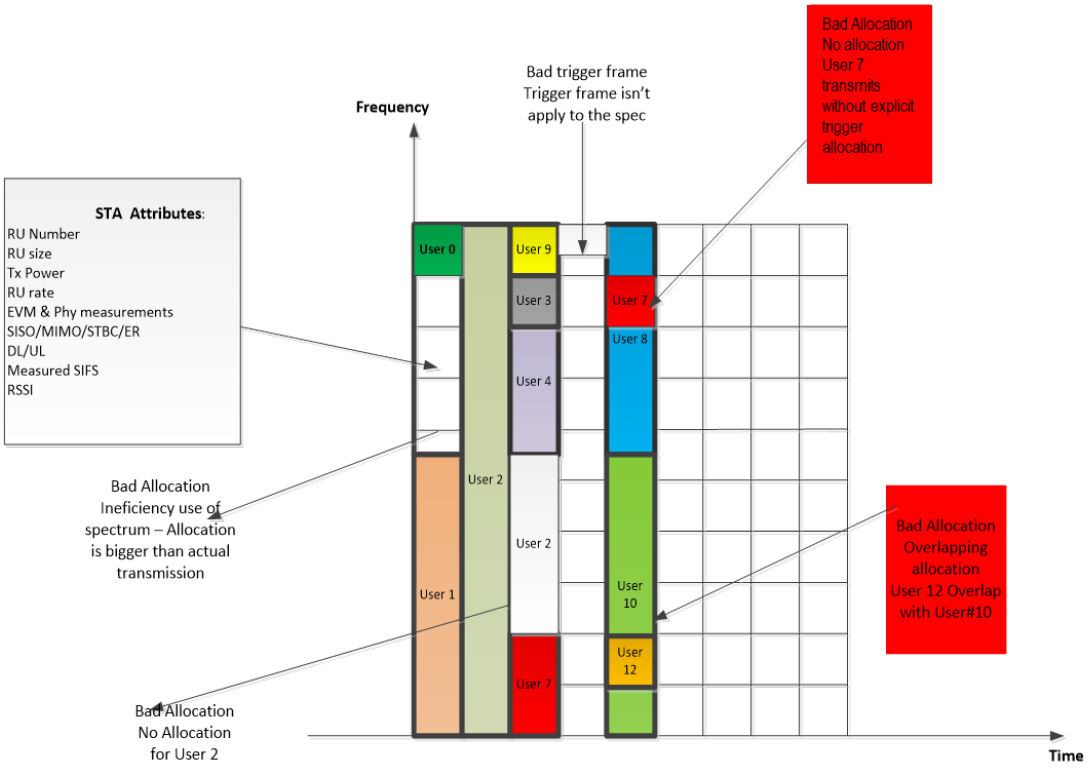

Figure 16: RU allocations to a set of STAs, as a function of time

Correctness

"Correctness" implies that that the RU allocations make sense, and don't conflict with each other. For example, if one STA is assigned an RU consisting of a set of subcarriers, and another STA is assigned, at the same time, an RU that consists of either some, or all, of those same subcarriers, that is an example of an allocation that would not be considered "correct".

Efficiency

"Efficiency" takes another look at those RU allocations and asks whether, even if they are correct, are they the best use of the spectrum? If, for example, there are STAs with data to transmit, but in any given time increment there are RU allocations that leave some subcarriers unused, that would be considered an "inefficient" use of the spectrum.

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Summary

Triathlon make available to developers and testers two capabilities not previously available:

(1) it creates the ability to trigger, in real-time, on protocol captures and to generate I/Q captures based on those triggers. This helps to capture on the PHY layer only those captures that are related to a condition of interest, and
(2) It makes it possible to see easily packet alignment between protocol level sniffer captures and I/Q samples.

This alignment of packets to IQ samples (of interest) makes it possible for developers and testers to focus in on the right place to understand whatever issues they are seeing, as opposed to have to deal with an otherwise unintelligible collection of I/Q samples.

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