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COEXISTENCE IN 2.4 GHz

Co−existence of WLAN, Bluetooth®, ZigBee® and Thread in the 2.4 GHz band

Originally published in Apr. 2019 under the company name Quantenna® Communications, Inc.

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Abstract

This white paper deals with co−existence solutions for wireless technologies operating on the 2.4 GHz ISM band. Many popular wireless technologies like WLAN, Bluetooth, ZigBee, Thread, etc., use the common 2.4 GHz for their operation. Hence, they can cause interference to each other, potentially reducing the overall throughput for all the links involved. Known solutions to such coexistence problems include collaborative and non−collaborative solutions to share the channel. We explore Quantenna's collaborative solution involving the 4−wire packet traffic arbiter (PTA) in detail and analyze its effect on reducing the performance degradation due to interference. Quantenna's PTA can cut down the problematic interference cases by half and potentially more, depending on the amount of in−built safeguards of the coexisting technologies.

Introduction

Many currently popular wireless communication technologies like Wi−Fi®, Bluetooth [1], ZigBee [2], Thread, etc., use the same unlicensed 2.4 GHz frequency band for their operation. Due to the shared nature of the channel, these technologies cause interference to each other when they operate in the same time−frequency−space region. Depending on the strength of the interfering channels and power of transmission, such an interference can cause considerable performance degradation. Some of these technologies have a few built protocol safeguards like carrier sense, adaptive frequency hopping, frequency skipping etc. that can partially guard against interference from other technologies using the same channel.

Figure 1 depicts a canonical co−existence scenario with a WLAN and Bluetooth module co−located on the same QSR10G SoC. The WLAN access point and the Bluetooth master are collocated at the QSR10G. It shows two possible scenarios for the WLAN stations (STA): the *near* case, when the STA is close to the access point and the *far* case, when the STA is far from the access point. In the near case, the STA can hear the co−located Bluetooth master's transmissions and in the far case, the STA cannot hear the master's transmissions, which can give rise to simultaneous WLAN RX (w.r.t. the QSR10G) and Bluetooth TX events. The link between the near WLAN STA and a Bluetooth slave may or may not exist depending on the channel. Interference to either link can be caused by such hidden node scenarios arising due to uncertain network conditions. However, some of the interfering events can be reduced by introducing cooperation between the two technologies that are collocated at the QSR10G. For example, by restricting one link to be active at a given time. Such cooperation can increase the effectiveness of sharing the channel and improve the overall throughput for all the links involved.

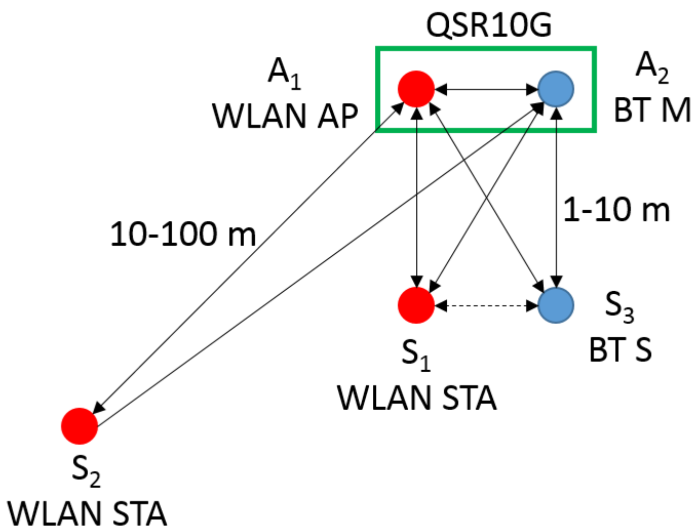

Figure 1. Example Network with WLAN and BT Clients Connected to a QSR10G AP

Existing Solutions for Co−existence

The potential for interference issues and the need for co−existence solutions was realized early on during the development of these technologies. The IEEE 802.15.2 standard [3] (developed by the IEEE 802.15 co−existence task group two) addresses the issue of co−existence between WLAN and WPAN networks. This standard describes recommended practices and provides a computer model for the interference (between 802.11b and 802.15.1). The standard describes collaborative solutions (used when the transmitters are collocated) like the following:

* Alternating Channel Access (MAC Layer Solution)
  This approach divides the beacon interval into two parts and the two technologies used TDMA to avoid interference.

* Packet Traffic Arbitration (MAC Layer Solution)
  A separate PTA block authorizes all transmissions from the different interfaces using the same channel. The PTA block coordinates the sharing of the medium depending on traffic load and priority.

* Deterministic Interference Suppression (PHY Layer Solution)
  This approach uses a programmable notch filter in the WLAN receiver to remove the narrow band Bluetooth interference.

The standard also contains non-collaborative solutions like the following:

* Adaptive Interference Suppression (PHY Layer Solution)
  This approach uses adaptive filtering at the WLAN receiver to remove narrow band interference.

* Adaptive Packet Selection and Scheduling (MAC Layer Solution)
  This approach adaptively selects packet properties (payload length, FEC codes and ARQ) and schedules traffic in low interference regions.

* Adaptive Frequency−hopping
  This approach actively estimates and avoids the channels from the hopping scheme at the WPAN, which have high interference.

As compared to the non−collaborative solutions, the collaborative solutions work better in orthogonalizing the channel access and as a result reducing the potential for interference. However, the collaborative solutions require a tight integration between the corresponding coexisting technologies and frequently hardware or software handshake signals are involved.

In addition to the above−mentioned techniques, a *frequency skipping* collaborative approach can also reduce the chances of accessing the same channel at the same time. In this approach, the collocated radios avoid the common frequencies for their operation. For example, if the WLAN radio is operating on channel 1, the Bluetooth radio avoids channels 0−21 or the ZigBee radio avoids channels 11−14.

Quantenna's 2−wire Arbiter for Co−existence

Quantenna uses a hardware solution based on the PTA recommended in the 802.15.2 standard, for a collaborative coexistence. The interface uses 2−wires to do a handshake between the collocated WLAN and WPAN components to reduce the chances of accessing the common channel at the same time. Figure 1 shows the interface signals between the PTA module and an external (EXT) Bluetooth/ZigBee/Thread module.

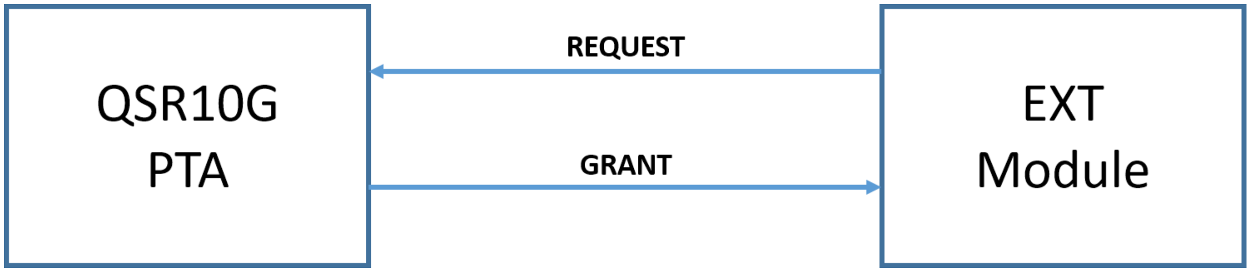

Figure 2. Quantenna's 4−wire Interface between the QSR10G PTA and External Module

The meaning and operation of the different signals shown in Figure 1 are as follows:

1. REQUEST − This is an input signal to the PTA module and it indicates a request from the external module is requesting access of the channel.
2. GRANT − This is an output signal to the external module indicating if the external module is granted access to the channel. This signal is asserted when an external module sends a request signal while the WLAN is neither receiving nor transmitting a frame.

When WLAN has to transmit, it checks if an external module has already been granted access. In case an external module is accessing the channel, WLAN waits until the grant is de−asserted and then transmits. In the normal mode, while the WLAN is transmitting or receiving, any requests from the EXT module is rejected. When the EXT module has to transmit a frame, it sends a REQUEST and waits to get a GRANT before transmitting. When the EXT module receives a frame, it sends a REQUEST and continues to receive the frame irrespective of the GRANT signal.

The above interface can also be run in a 1−wire mode in addition to the above mentioned 2−wire mode. In the 1−wire mode, the only output from the PTA module is the Grant signal. In this mode, the Grant signal is used as an indication of WLAN busy. The PTA de−asserts the Grant signal when WLAN is not using the channel.

The order of the TX/RX events (WLAN TX, WLAN RX, EXT TX, or EXT RX) can cause different working or interference scenarios. Figure 3 shows an example where a WLAN frame is received, while a Bluetooth transmission is in progress. Such a situation can arise if the STA sending the WLAN frame to the access point is far away and hence cannot hear the Bluetooth transmissions done at a lower power (as shown in Figure 1).

Table 1 lists all the possible orders of TX/RX events and its effect when the 2−wire PTA interface is used to reduce interference between the WLAN and EXT modules. The enumeration omits the cases when the channel is idle and when only one interface has TX/RX events and the other interface is idle.

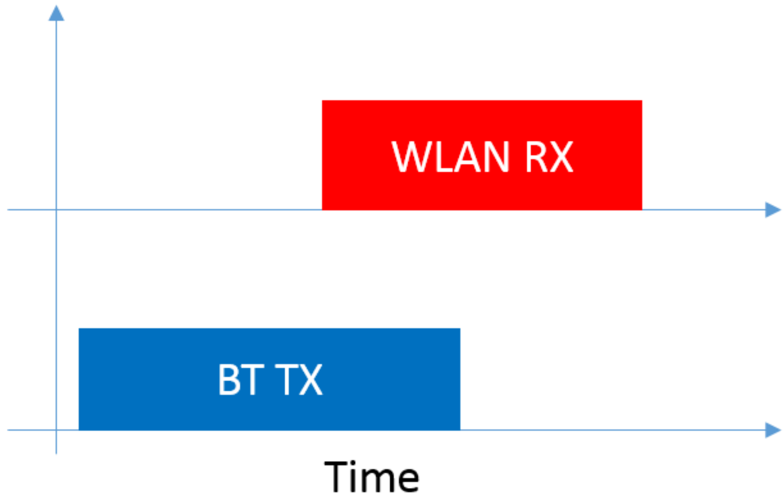

Figure 3. Example of a WLAN RX Event Happening in the Middle of an Ongoing BT TX Event

Note that for hidden node cases (when the WLAN STA and/or EXT slave cannot hear the transmitter), getting frame receptions on one link while a transmission is going on the other link is unavoidable.

Table 1. TABLE

	1st Event	2nd Event	Action	Result (at AP)
1	EXT TX	WLAN TX	Wait until REQ is de−asserted.	Delay in WLAN TX.
2	EXT TX	WLAN RX	Continue WLAN RX. BT TX may or may not stop depending on its mode.	WLAN interference or packet loss.
3	EXT RX	WLAN TX	Wait until REQ is de−asserted.	Delay in WLAN TX.
4	EXT RX	WLAN RX	Continue WLAN RX. BT sends REQ and both continue to receive.	EXT and WLAN interference or packet loss.
5	WLAN TX	EXT TX	BT sends a REQ and waits for GNT. PTA waits for WLAN TX to finish then asserts the GNT. BT either delays the TX or totally misses the window and has to repeat.	Delay in EXT TX.
6	WLAN TX	EXT RX	WLAN does not stop. BT sends REQ and continues to receive.	EXT interference of packet loss.
7	WLAN RX	EXT TX	BT sends a REQ and wait for GNT. PTA waits for WLAN RX to finish to give a GNT. BT either delays the TX or totally misses the window and has to repeat.	Delay in EXT TX.
8	WLAN RX	EXT RX	WLAN does not stop. BT sends REQ and continues to receive.	EXT and WLAN interference or packet loss.

NOTE: Order of TX/RX events and its effect on coexisting interfaces with the 4−wire solution.

Without the PTA module, all the cases mentioned in the table would have caused interference to the active links. The PTA module is able to reduce the number of interference scenarios, even though it might cause delay in the transmission. In general, delays are better than interference/collision since a collision can potentially lose more than one channel time required to send the frame due to retransmissions and cascading error events. Without a PTA, transmissions would have happened when the other link was either transmitting or receiving and could have caused packets to be lost. However, out of the eight co−existence cases considered in the table, the PTA interface is unable to solve four of them. Note that all these remaining issues are when the second interface starts to receive a frame while the PTA has already authorized the first interface for TX or RX. Since a device does not have any control over unscheduled receptions, these kind of error cases are hard to solve. However, these scenarios do not always lead to loss of packets depending on the strength of links. In a later section, we evaluate the probability of such events happening and hence the performance effect they have.

Wi−Fi Pre−emption

Even with the standard PTA mechanism of using requests and grants, the external traffic might have to wait for longer intervals if the current Wi−Fi traffic is high. In many current use cases of ZigBee, Bluetooth, Thread, etc., these external protocols are used on battery operated sensor clients. In such cases, extra delays and collisions cause more retransmissions and in turn affect the client's battery life. Hence, in the presence of such high priority external traffic, it might be useful to stop on−going Wi−Fi transmission right away and let the external traffic take preference. Allowing external traffic even during on−going Wi−Fi traffic is called PTA pre−emption. Quantenna currently supports two modes of pre−emption:

Pre−emption without TX Stop

This mode is meant for the use case when the Wi−Fi and external traffic are on non−overlapping channels. As an example, Wi−Fi channel 1 and ZigBee channel 23 are non−overlapping. In such a use case, since the channels are not overlapping, the two radios can continue their communications at the same time.

Pre−emption with TX Stop

This mode is meant for the use case when the Wi−Fi and external traffic are on overlapping channels. As an example, Wi−Fi channel 1 and ZigBee channel 12 or 13 or 14 are overlapping. In such a use case, since the channels are overlapping, the two radios cannot continue their communications at the same time. Simultaneous transmission might result in collisions.

In this mode, the PTA grants access to the external radio whenever there is a request. If there is an on−going transmission, the PTA stops the transmission right away. In case of Wi−Fi ongoing reception, the PTA does not interrupt it since we do not have control over the transmission. The Wi−Fi does the best it can to recover the signal in the presence of the external traffic.

There is no impact on Wi−Fi traffic for pre−emption without TX stop since it does not share the channel of interference. However, for pre−emption with TCP traffic, slow traffic like 1 ZigBee frame per second may not have any effect on Wi−Fi traffic, but a high throughput like 100 ZigBee frames per second may case up to 60% loss in Wi−Fi throughput.

Performance Impact

Out of all possible scenarios related to the operation of the coexisting devices, some combination of events give rise to interference scenarios. Figure 4 shows the relation between these scenarios. All possible events are depicted by the outermost circle. If the duty cycle of the devices are low enough, a majority of the events will have no contention as shown by the blue part of the outer circle. Out of all the scenarios that can cause interference, some of them can be avoided using the PTA interface as mentioned in Table 1. The innermost circle in red depicts the space of events, which cannot be avoided using the PTA.

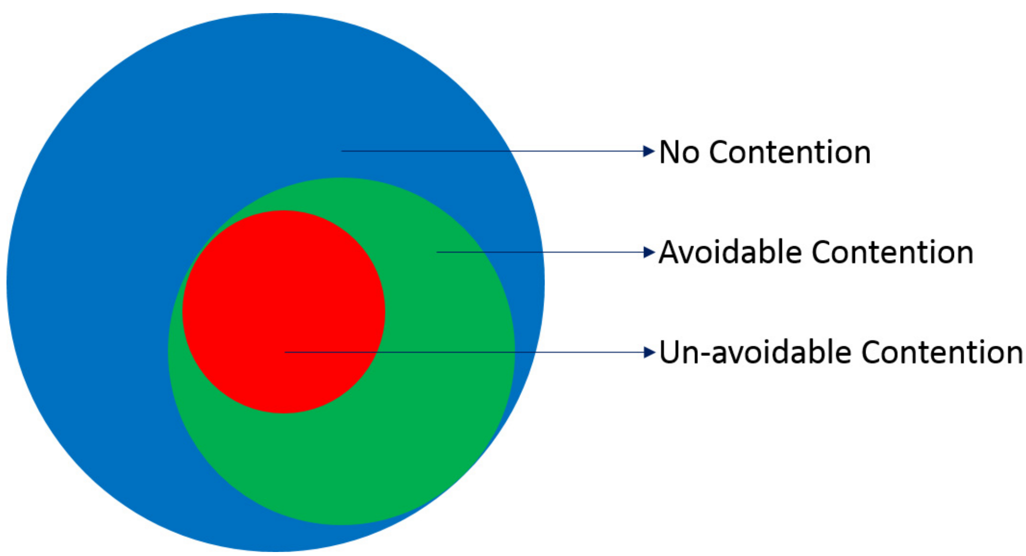

Figure 4. Space of All Possible Co−existence Scenarios

The avoidable and un−avoidable contention events can give rise to delays, retries and packet loss in the traffic of WLAN or WPAN. This can give rise to performance loss. The exact events that give rise to such performance loss depend on the particular solution used to take care of the co−existence. In the next sub−section, we analyze the probability of the avoidable and un−avoidable. Some other analysis of PHY layer performance in co−existence scenarios can be found in [4] and [5].

Probability of Contention Events

To have an idea about the proportion (probability) of the above−mentioned scenarios and their dependence on the WLAN and WPAN duty cycles, we calculate these probabilities as a function of the duty cycles. We consider a network with the following parameters.

- WLAN Traffic Parameters
  - Transmission rate = 60% of WLAN on−time (downlink)
  - Reception rate = 40% of WLAN on−time (uplink)
- EXT Traffic Parameters
  - Transmission and reception rate = 50% of EXT on−time

The probability of all the scenarios are summarized in Figure 5 for two different duty cycles of WLAN traffic. A duty cycle of 10% represents low WLAN traffic and a duty cycle of 90% represents high WLAN traffic. When the duty cycle of the WLAN traffic is low, the probability of contention (avoidable or not) is low and almost all the no−contention scenarios occur when the WLAN is idle. Hence, when the Bluetooth duty cycle increases, the proportion of idle time goes down and proportion of no contention goes up. However, when the WLAN traffic is already high, the probability of no contention goes down with Bluetooth duty cycle. The most important conclusion is however, that the PTA solution is able to take care of more than half of the problematic scenarios.

Now, let us consider some of the variables that were not taken into account in the above calculation. Due to certain built−in safeguard of these WPAN protocols, not all the above unavoidable events can happen in real life. We consider the following four exceptions.

Firstly, for Bluetooth module, if the RX from the slave stations arrive after TX from the master and if the module reserves the time for the entire transaction, the RX event cannot happen in the middle of WLAN events. Therefore, we no longer have the possibility of this unavoidable interference scenario.

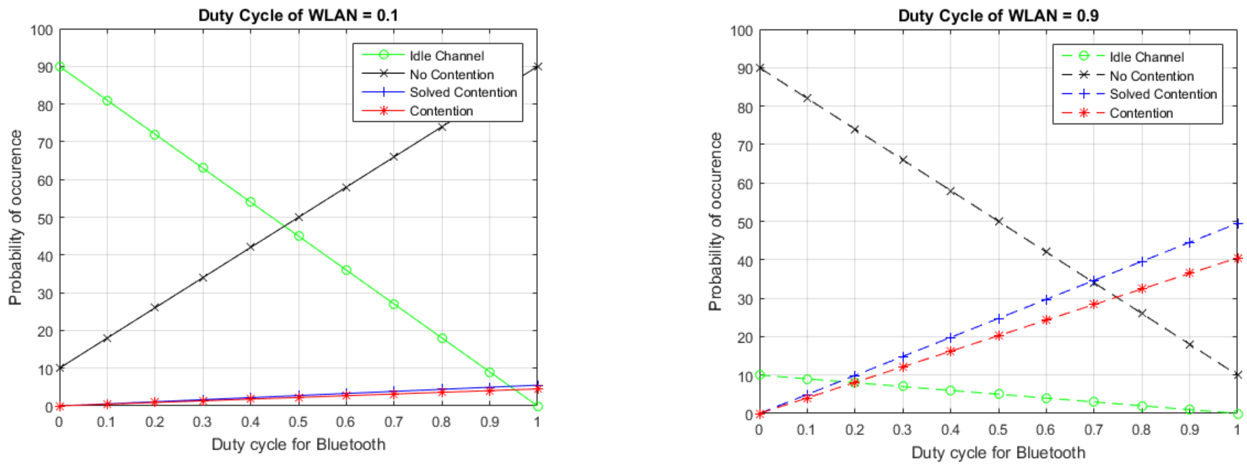

Figure 5. Probability of Events with Varying Duty Cycles of Bluetooth with 0.1 and 0.9 Duty Cycle of WLAN

Secondly, for ZigBee, if the implementation follows CSMA, the stations will be able to hear ongoing WLAN transmissions over the air and hence the RX event cannot happen in the middle of WLAN events.

Thirdly, even if there is simultaneous use of the same channel by the external module and WLAN due to RX events, a Narrow band interference is observed by the WLAN due to the bandwidths used and hopping sequence.

Finally, due to the frequency−hopping scheme of Bluetooth, even if unavoidable contention events happen, the Bluetooth traffic will not overlap with the WLAN bandwidth all the time. The proportion of time, which it overlaps, depends on the hopping sequence and the band of operation of WLAN.

In addition to all the above considerations, cross channel interference due to imperfect radios can also affect the interference, which is outside the scope of this document.

Conclusion

We described and analyzed Quantenna's 4−wire based PTA solution to the co−existence problem to work with different wireless technologies sharing the 2.4 GHz channel. The PTA interface can potentially reduce the contention cases by half and potentially more if the external modules have certain in−built safeguards. As a side effect of the contention cases (avoidable or un−avoidable), there is a performance loss due to co−existence (delays for avoidable cases and retires/losses for un−avoidable cases), which we can minimize but cannot get rid of entirely, especially when the channel is close to full utilization.

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