# White Paper

## Title: BCM4325 Bluetooth® and WLAN Coexistence

The growth of IEEE 802.11™ wireless local area networks and Bluetooth® wireless personal area networks in the 2.4-GHz band has resulted in the need to colocate the circuitry of each technology on a single silicon die. This paper describes the interference mitigation considerations undertaken by Broadcom to make such integration possible.

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# Introduction

Wireless technology is gaining broad acceptance as users opt for the freedom that only wireless networks can provide. This has led to an increase in wireless devices intended for use in IEEE 802.11™ wireless local area networks (WLANs) and Bluetooth® wireless personal area networks (WPANs), both of which support operation in the crowded 2.4-GHz industrial, scientific and medical (ISM) band.

WLAN operates in the 100+ meter range and is often used to augment traditional wired networks in the home, office, and in public areas. WLAN devices operate in accordance with IEEE 802.11 standards (which include 802.11b, 802.11g and 802.11n) and offer data rates in excess of 100 Mbps [1]. In recent years, as voice over IP (VoIP) has been broadly adopted to carry voice traffic, various new technologies such as Unlicensed Mobile Access (UMA) [2] have chosen WLAN as the wireless terminal technology.

WPAN technology is led by Bluetooth [3] and is primarily used to replace short cable runs. Bluetooth supports connectivity to up to 10 meters and offers data rates of up to 3 Mbps (Bluetooth v2.0 + EDR) [4]. The most typical Bluetooth application is the wireless headset.

As WLAN and WPAN are designed for different uses, they often complement each other in personal computers as well as mobile devices such as phones and personal digital assistants. Although WLAN and Bluetooth (BT) are different technologies, they operate in the same 2.4-GHz ISM band and, as a result, they can interfere with each other. The interference issue becomes more serious when the two technologies are implemented on a single chip designed to share some radio components. The end result of interference can be degraded data throughput, reduced voice quality, or even link disconnection.

The interference between WLAN and WPAN networks can be divided into two classes. The interference is said to be external if the interfering devices are physically separated by a distance of more than two meters. The interference is said to be internal if the devices are colocated, which is defined as a distance of less than two meters. A severe internal interference example is one where a transmission from one technology type saturates the receiver's low noise amplifier (LNA) of the other technology type.

The mutual interference between BT and WLAN primarily depends on the physical distances between the two technologies, operating data rates, and transmit power levels.

To address the problem of mutual interference, the IEEE has developed a recommended practice that offers several coexistence mechanisms to enable WLAN and Bluetooth to operate in a shared environment without adversely affecting each others performance. The IEEE 802.15.2 Recommended Practice [5] document categorizes coexistence mechanisms into two classes: *collaborative* and *non-collaborative*. The former requires information exchange between the two technologies, while the later does not. Despite being a big step forward, IEEE 802.15.2 fails to address several important coexistence-related problems, leaving it up to technology providers to develop their own solutions.

## Scope

This document presents Broadcom's novel approach to mitigating interference between colocated BT and WLAN technologies, specifically in situations where components such as the antenna, LNA, power amplifier (PA), etc., are shared. These methods have been successfully implemented in Broadcom's BCM4325 and BCM4329.

## Bluetooth Introduction

Bluetooth technology provides wireless replacements of short cables, offering an untethered operating radius of 10 meters. Each Bluetooth network is organized as a piconet, which has a single master device and a number of slave devices that can only communicate with the master. In this scheme, a single slave device selected by the master may transmit, while others must wait for their turn. The Bluetooth PHY uses frequency hopping spread spectrum (FHSS) technology. At any point in time, the Bluetooth signal occupies 1 MHz of bandwidth, but the center frequency changes, or hops, up to 1600 times per second. The frequency hopping pattern is selected by the piconet master, such that the interference between different piconets is minimized. A time-division duplex (TDD) technique is used to transmit and receive data in a piconet. The transmission channel is divided into 625-microsecond slots. The piconet master transmits during even-numbered slots while slaves transmit during odd-numbered slots. The specification allows multislot transmissions where packets occupy either three or five multiple consecutive slots. A slave must respond to packets addressed to it from the master. If it has no data, it must respond with a *null* packet. The Bluetooth specification defines the following types of links for the support of voice and data applications: synchronous connection-oriented (SCO), extended synchronous connection-oriented (eSCO) and asynchronous connectionless (ACL). SCO and eSCO links are typically used for transmitting real-time voice and multimedia packets, while ACL is most often used for non-real-time data traffic. The SCO packets do not have cyclic redundancy check (CRC) protection and are never retransmitted. eSCO and ACL packets use CRC, and errors are corrected by packet retransmissions.

## WLAN Introduction

IEEE 802.11 defines two different wireless network modes: *ad hoc* mode and *infrastructure* mode. In ad hoc mode, nodes are brought together to form a network on the fly, whereas infrastructure mode uses fixed access points (AP) through which mobile nodes can communicate. These network access points are usually connected to wired networks through bridging or routing functions.

The WLAN medium access control (MAC) layer is a contention-resolution protocol that is responsible for maintaining order in the use of a shared wireless medium. IEEE 802.11 specifies both contention-based and contention-free channel access mechanisms. The contention-based scheme is the distributed coordination function (DCF), and the contention free scheme is the point coordination function (PCF).

The DCF employs a carrier sense multiple access with collision avoidance (CSMA/CA) protocol. In this protocol, when the WLAN MAC receives a packet to be transmitted from its higher layer, the MAC first listens to ensure that no other node is transmitting. If the channel is clear, it then transmits the packet. Otherwise, it chooses a random backoff factor that determines the amount of time the WLAN node must wait until it is allowed to transmit its packet. Only when the channel is clear, does the waiting node decrement its backoff counter. When the backoff counter reaches zero, the WLAN MAC transmits the packet. Because the probability that two nodes will choose the same backoff factor is low, collisions between packets are minimized. Collision detection, as employed in Ethernet, is only possible with full-duplex nodes; devices that can receive while transmitting. IEEE 802.11 nodes are half-duplex, and therefore, while transmitting, they cannot receive from other nodes because the signal power of transmissions drowns out signals from other nodes.

Optionally, when a packet is to be transmitted, the transmitting node can first send out a short request to send (RTS) packet containing information on the length of the packet. If the receiving node hears the RTS, it responds with a short clear to send (CTS) packet. After this exchange, the transmitting node sends its packet. If a directed packet is received successfully, as determined by a cyclic redundancy check (CRC), the receiving node transmits an acknowledgment (ACK) packet. If the transmitting node does not receive an ACK for the directed packet, it assumes the transmission has failed, and error recovery is attempted by retransmitting, also known as retrying, the original packet. Retries are continued until either the ACK packet is received or the retry limit is reached. If the retry limit is reached, the packet is retransmitted at a lower data rate, and if that fails the packet is discarded.

To maintain a reliable data connection at the highest possible data rate, the WLAN transmitter usually employs a dynamic rate adaptation algorithm. This algorithm, which reduces the link data rate when packet success rates drop below a set threshold, converges to the highest supported data rate when noise is dominated by the receiver's noise floor. Unfortunately, the rate adaptation algorithm doesn't converge as desired when interference from a colocated Bluetooth transceiver is introduced. In fact, with such interference and no mitigating actions, the algorithm will increase the likelihood of WLAN packet collisions by lowering the data rate, which equates to an increase in packet transmission times.

When packets are lost, overall network performance degrades as a function of lost packet type. The following examples reveal the affects of specific packet losses:

- Discarded directed frames may result in poorer VoIP link quality or lower TCP throughput.
- Lost, that is not received, multicast packets may result in ARP and DHCP failures.
- Lost beacon frames may result in PHY synchronization loss.

# Concurrent WLAN/Bluetooth Use Cases

Users expect devices with integrated complementary technologies such as WLAN and WPAN to operate simultaneously and flawlessly. Although the use-case scenarios for such integrated products are numerous, Broadcom has assembled a comprehensive use-case list that it uses when evaluating the performance of devices that colocate WLAN and Bluetooth on a single silicon die. The remaining paragraphs of this section comprise this comprehensive list.

## WLAN and Bluetooth Data

In this set of use cases, the distinguishing trait is that the Bluetooth node uses asynchronous connectionless (ACL) links to send and receive data. Bluetooth and WLAN throughput is to be measured with the following configurations:

- Bluetooth configuration:
  - Node type is master or slave.
  - Link type is ACL.
  - Data packet flow is bidirectional.
- WLAN configuration:
  - WLAN mode is ad hoc or infrastructure.
  - Data packet flow is bidirectional and at varying rates.
  - Channel scans or periodic calibrations are included.

These use cases are most forgiving as both Bluetooth ACL and WLAN support packet error detection and retransmission.

## Bluetooth Voice and WLAN Data

In this set of use cases, Bluetooth uses SCO or eSCO links to send high-quality voice to a wireless headset while WLAN data transfers take place. The Bluetooth data is usually limited to 64 Kbps in both directions, and its performance is measured in terms of packet error rate (PER) or voice quality score. See ITU-T P.862 (PESQ) [6] for more information on voice quality score. The WLAN performance is measured in terms of throughput. The following Bluetooth and WLAN configurations apply:

- Bluetooth configuration:
  - Node type is master or slave.
  - Link types are SCO and eSCO.
  - Packet types for SCO links are HV1 and HV3.
  - Packet types for eSCO links are EV1, EV3, EV4, EV5, 2EV3, 2EV5, 3EV3, and 3EV5.
  - Data packet flow is bidirectional.
- WLAN configuration:
  - WLAN mode is ad hoc or infrastructure.
  - Data packet flow is bidirectional and at varying rates.
  - Channel scans or periodic calibrations are included.

## Bluetooth High-Quality Audio Streaming and WLAN Data

The Bluetooth advanced audio distribution profile (A2DP) specifies the protocols and procedures used to distribute high-quality, mono or stereo, audio content on Bluetooth ACL channels. It defines various audio codec settings with a maximum mono channel data rate of 320 Kbps and stereo channel data rate of 512 Kbps. The maximum jitter and minimum throughput requirements for high-quality audio are more stringent than for data. The following Bluetooth and WLAN configurations apply:

- Bluetooth configuration:
  - Node type is master or slave.
  - Link type is ACL.
  - Audio packet streams are bidirectional.
- WLAN configuration:
  - WLAN mode is ad hoc or infrastructure.
  - Data packet flow is bidirectional and at varying rates.
  - Channel scans or periodic calibrations are included.

## Bluetooth Scan and WLAN Data

In this set of use cases, Bluetooth inquiry or page scans are performed while WLAN data transfers take place. The following Bluetooth and WLAN configurations apply:

- Bluetooth configuration:
  - Node type is master or slave.
  - Page or inquiry scans are being performed.

- WLAN configuration:
  - WLAN mode is ad hoc or infrastructure.
  - Data packet flow is bidirectional and at varying rates.
  - Channel scans or periodic calibrations are included.

For this set of cases, the page or inquiry scans must succeed while having a minimal impact on WLAN throughput, scans, and calibration results.

## WLAN and Bluetooth Voice

In this set of use cases, the WLAN serves as a bridge between VoIP internet traffic and a WLAN-enabled phone, while that same phone transfers Bluetooth voice packets to and from a wireless headset. The VoIP packets typically contain 20 ms of compressed voice information and, depending on the voice codec type, they contain 20–160 bytes, not including protocol overhead. The Voice-over-WLAN (VoWLAN) packets are delivered every 20 ms to ensure an uninterrupted voice stream. WLAN and Bluetooth performance is gauged by packet error rates and ITU-T P.862 [6] voice quality scores. Additionally, WLAN packet jitter is measured to judge VoWLAN system performance. The following Bluetooth and WLAN configurations apply:

- Bluetooth configuration:
  - Node type is master or slave.
  - Link types are SCO and eSCO.
  - Packet types for SCO links are HV1 and HV3.
  - Packet types for eSCO links are EV1, EV3, EV4, EV5, 2EV3, 2EV5, 3EV3, and 3EV5.
  - Voice packet flow is bidirectional.
  - Page or inquiry scans are being performed.
- WLAN configuration:
  - WLAN mode is infrastructure.
  - Voice packet flow is bidirectional and at varying rates.
  - Channel scans or periodic calibrations are included.

## WLAN Audio and Video Streaming and High-Quality Bluetooth Audio

In this set of challenging multimedia use cases, WLAN real-time audio and video is streamed to a mobile device, which in turn streams high-quality Bluetooth audio to a wireless headset. The following Bluetooth and WLAN configurations apply:

- Bluetooth configuration:
  - Node type is master or slave.
  - Link types are ACL, SCO, and eSCO.
  - Packet types for SCO links are HV1 and HV3.
  - Packet types for eSCO links are EV1, EV3, EV4, EV5, 2EV3, 2EV5, 3EV3, and 3EV5.
  - Audio packet flow is unidirectional, from the mobile device.
  - Page or inquiry scans are being performed.

- WLAN configuration:
  - WLAN mode is infrastructure.
  - Audio packet flow is into the mobile device, at varying rates, and over up to two channels.
  - Video packet flow is into the mobile device and at varying rates.

# Related Work

IEEE 802.15.2 Recommended Practice for Information Technology [5] defines several collaborative and non-collaborative approaches to coexistence. The two strictly collaborative approaches are alternating wireless medium access (AWMA) and packet traffic arbitration (PTA). Adaptive frequency hopping (AFH) is usually non-collaborative but can be enhanced if the communication between two devices, or two subsystems within a single device, is possible.

AWMA requires WLAN and Bluetooth network coordination to implement time-division multiple access (TDMA), so that WLAN and Bluetooth activity alternates. AMWA's shortcomings, which are serious, include WLAN AP collaboration may not be attainable, and AMWA cannot be used with Bluetooth SCO traffic.

PTA provides for a central WLAN and Bluetooth subsystem arbiter that makes medium access decisions. Each subsystem makes medium requests, and the arbiter decides who gets access. PTA efficiently arbitrates outgoing traffic but does not address the interference caused by incoming packets, and the resulting performance degradation due to incoming packet loss.

AFH is normally used as a non-collaborative approach, where a Bluetooth device detects interference and marks a subset of the available channels as unusable. However, if a communication channel exists between the WLAN and Bluetooth subsystems, the Bluetooth subsystem can mark the WLAN band as *bad* without the need for interference detection.

A number of novel coexistence methods have been proposed. Some of these approaches are Bluetooth carrier sense (BCS) [7], overlap avoidance (OLA) [8], Bluetooth interference aware scheduling (BIAS) [9], and Bluetooth SCO link interfering mitigation (BSIM) [10]. Most of these schemes are primarily non-collaborative and do not provide comprehensive approaches for truly integrated WLAN and Bluetooth solutions.

# The Broadcom Solution

## Hardware Interfaces

The integration of WLAN and Bluetooth technologies onto the same silicon die presents a unique opportunity to take collaborative coexistence methods to a new level.

This section describes the WLAN and Bluetooth colocation architecture that Broadcom uses in its BCM4325. Figure 1 on page 8 demonstrates Broadcom's colocation architecture.

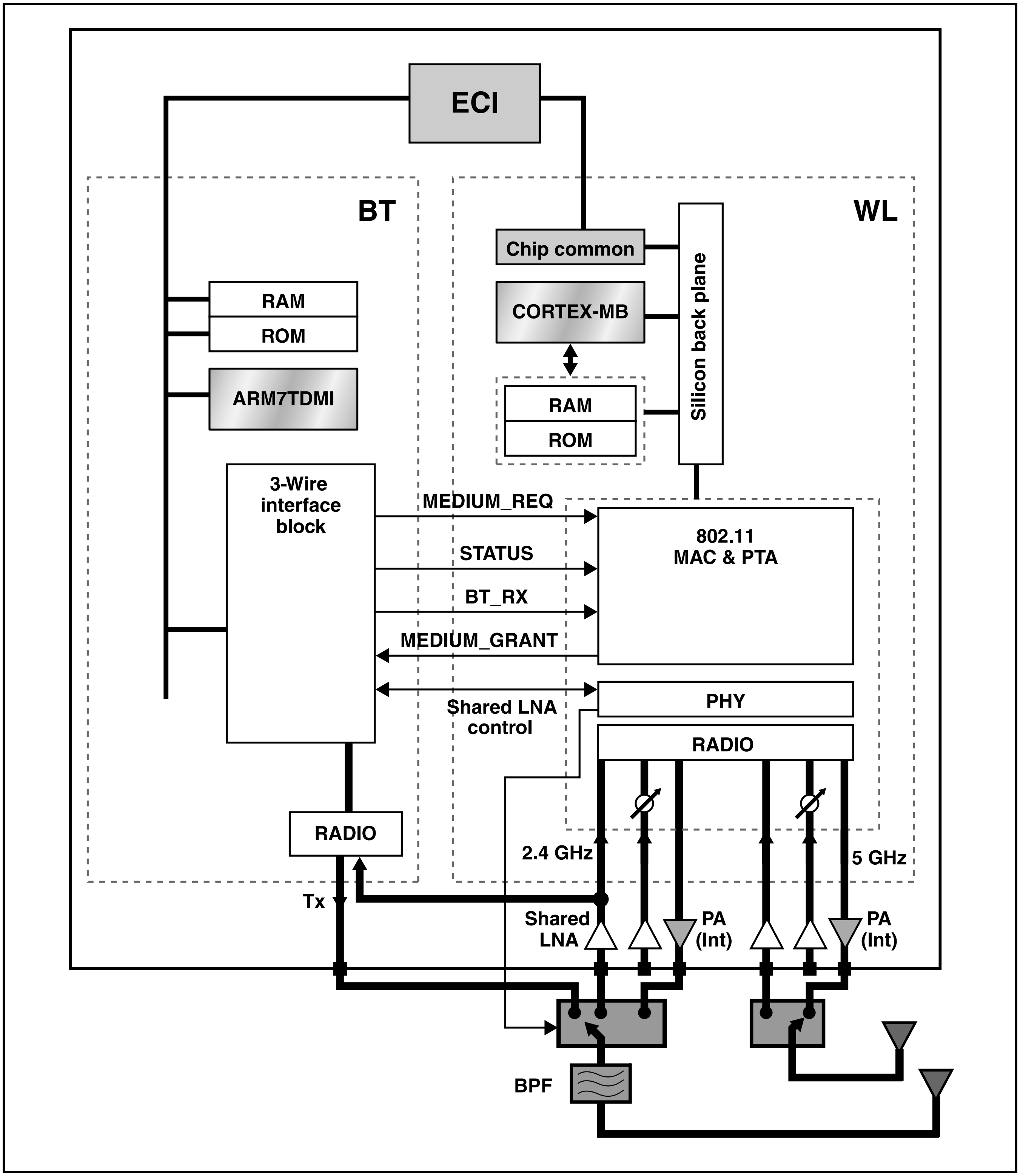


**Figure 1:** WLAN and Bluetooth Colocation Architecture

## Shared Low Noise Amplifier

Mobile devices represent the most prevalent use of highly integrated WLAN and Bluetooth combination devices. In these devices, cost, board space, and form factor dictate the use of a single antenna. To enable simultaneous WLAN and Bluetooth reception without incurring any front-end RF splitter loss, Broadcom employs a shared LNA architecture, where the 2.4-GHz wideband signal is amplified and then split before being routed to each receiver. The shared LNA has programmable gain settings that support a wide dynamic range. Algorithms have been developed to arbitrate shared LNA gain-setting requests from the WLAN and Bluetooth subsystems to minimize receiver noise figure.

### *Packet Traffic Arbitration*

Broadcom's packet traffic arbitration (PTA) approach extends the capabilities recommended by IEEE 802.15.2 [5]. Broadcom's WLAN subsystem implements PTA logic, which relies on signaling between the WLAN and Bluetooth subsystems. The PTA architecture is shown in Figure 2, with the signals coming into and going out of the WLAN subsystem's Bluetooth Coexistence (BTCX) block. The signals between the two subsystems are described in Table 1 on page 10.

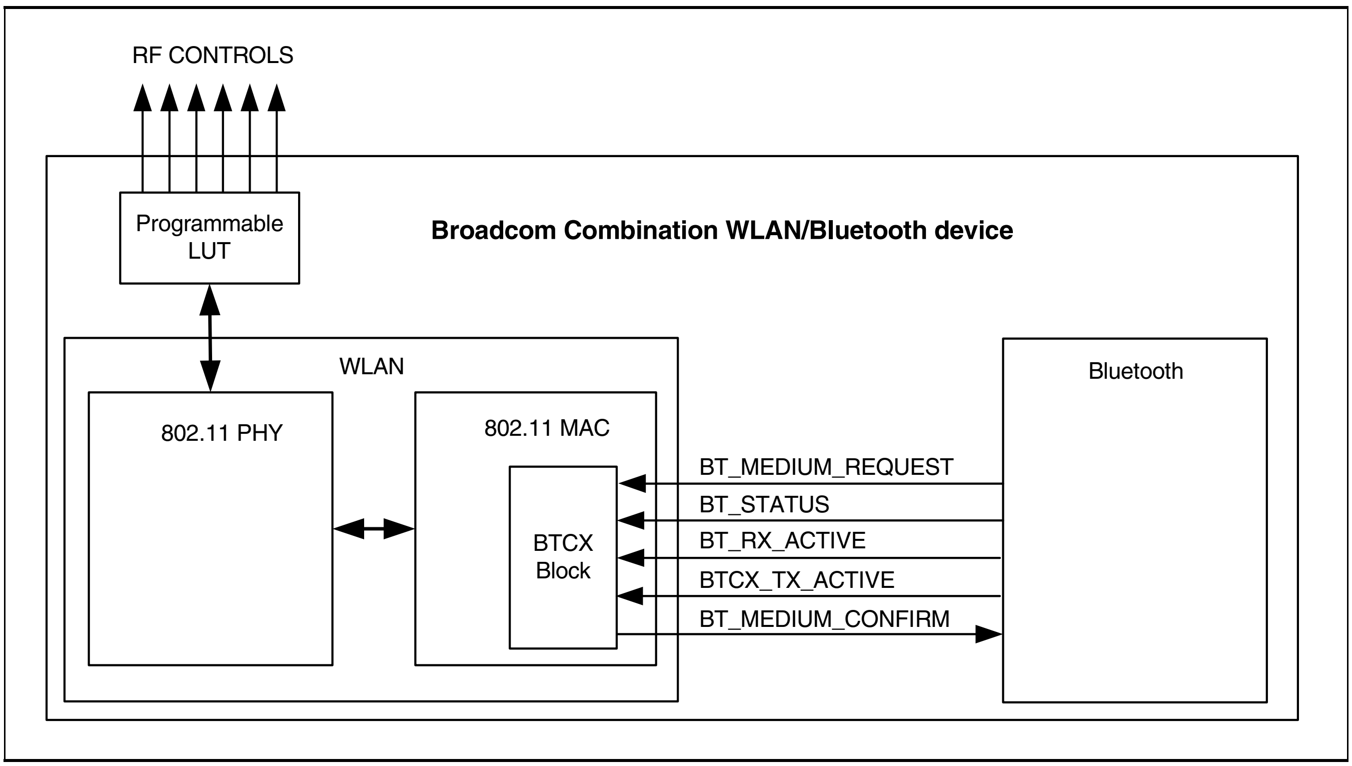


**Figure 2: Packet Traffic Arbitration Architecture**

**Table 1: Packet Transmit Arbitration Signals**

| PTA Signal | Description |
|---|---|
| BT_MEDIUM_REQUEST | Asserted prior to Bluetooth activity. The lead time is programmable. |
| BT_STATUS | Indicates Bluetooth priority status. |
| BT_TX_ACTIVE | Indicates the Bluetooth subsystem has started transmitting. |
| BT_RX_ACTIVE | Indicates the Bluetooth subsystem has started receiving a valid frame. |
| BT_MEDIUM_GRANT | Medium access confirmation. Bluetooth subsystem receive or transmit permission. |
| RF_CONTROLS | Signals to control the shared LNA and various RF switches, including the antenna switch. |

The PTA operates at the WLAN MAC layer. It provides per packet authorization of all WLAN and Bluetooth transmissions. Bluetooth subsystem requests for medium access will be decided by the PTA based on WLAN subsystem status. The WLAN programs the PTA to handle Bluetooth requests in one of the following four ways:

- PTA grants all Bluetooth medium access requests.
- PTA grants high priority Bluetooth requests only. (BT_STATUS signal is asserted when BT_MEDIUM_REQUEST is asserted).
- PTA grants high- and medium-priority Bluetooth requests. (BT_STATUS signal is asserted or BT_RX_ACTIVE signal is asserted when BT_MEDIUM_REQUEST is asserted)
- PTA does not grant any Bluetooth medium access requests.

The PTA setting is changed dynamically by the WLAN subsystem and is dependent on the WLAN activity at the time of the request.

### *Enhanced Coexistence Interface*

Enhanced Coexistence Interface (ECI) is implemented in the BCM4325. ECI augments PTA signaling to enable more advanced collaborative-coexistence methods.

The ECI interface is a wide bidirectional bus between the Bluetooth and WLAN subsystems with provisions for data synchronization and buffering to ensure data validity. ECI messages can also be exchanged using interrupts.

#### *ECI Information Conveyed from Bluetooth to WLAN*

- Packet type for the upcoming slot or slots (e.g., HV3, 3EV3, DM1, etc.)
- Duration of the upcoming transaction
- Hop frequency of the upcoming transaction
- Master/slave role
- Multilevel priority of the upcoming transaction (used by WLAN to augment BT_STATUS signal)
- Transmit power level
- Received signal strength indication

### *ECI Information Conveyed from WLAN to Bluetooth*

- Channel number to be used in defining Bluetooth AFH pattern
- Transmit power level
- Received signal strength

Being a wide bus, ECI also has a provision for extensions to support future coexistence algorithms.

## Preemptive Coexistence Methods

The biggest limitation of 802.15.2 is that it does not address integrating WLAN AP behavior into an overall WLAN and Bluetooth coexistence solution. A WLAN station (STA), whose colocated Bluetooth subsystem is transmitting, will be unable to receive WLAN AP packets destined for it. This is a physical limitation of all coexistence implementations that can only be overcome by AP and STA coordination. Without such coordination, both WLAN and Bluetooth networks suffer from WLAN-induced interference, which gets exaggerated by WLAN retransmissions.

When a WLAN AP transmits a packet to a STA that has colocated WLAN and Bluetooth subsystems, that packet will be lost if the STA's receiver is rendered *deaf* by a concurrent Bluetooth transmission. WLAN AP retransmissions, which normally serve to strengthen WLAN link performance, can have a negative effect on both WLAN and Bluetooth networks by adding packets into the medium; packets that will not be received while the Bluetooth subsystem transmits. The effects of this lack of WLAN AP and STA co-ordination are reduced WLAN and Bluetooth data rates and poor medium utilization. To avoid this out-come, it is desirable to preempt WLAN AP packet transmissions during times when the destination STA is unable to receive packets. To achieve the desired coordination, a combination of two methods is used to preempt AP transmissions. One method uses WLAN self-addressed CTS packets and the other inte-grates Broadcom's PTA approach with its WLAN Power Save mode implementation.

### *WLAN CTS Shared Medium Reservation*

The IEEE 802.11 standard allows WLAN devices to send a self-addressed CTS packet (CTS2SELF). This packet contains a duration field that each receiving WLAN node uses to update its network allocation vector (NAV). The virtual carrier sense (CS) mechanism of the WLAN nodes who receive the CTS2SELF packet will inhibit transmissions in accordance with their newly updated NAVs. The WLAN sender of the CTS2SELF packet, knowing the upcoming transaction duration of a colocated Bluetooth transmitter, will set the duration field accordingly.

This approach prevents the transmission of all WLAN traffic, including beacons, from any WLAN device that receives the CTS2SELF packet. It does not require WLAN APs to do any special packet queuing, and it is compatible with all 802.11 standards-compliant AP implementations. This approach delays beacon and multicast packet transmissions until after Bluetooth subsystem transactions complete. It also denies medium access to all WLAN nodes, leading to the drawback that just a few network devices with colocated WLAN and Bluetooth subsystems can substantially reduce WLAN data rates.

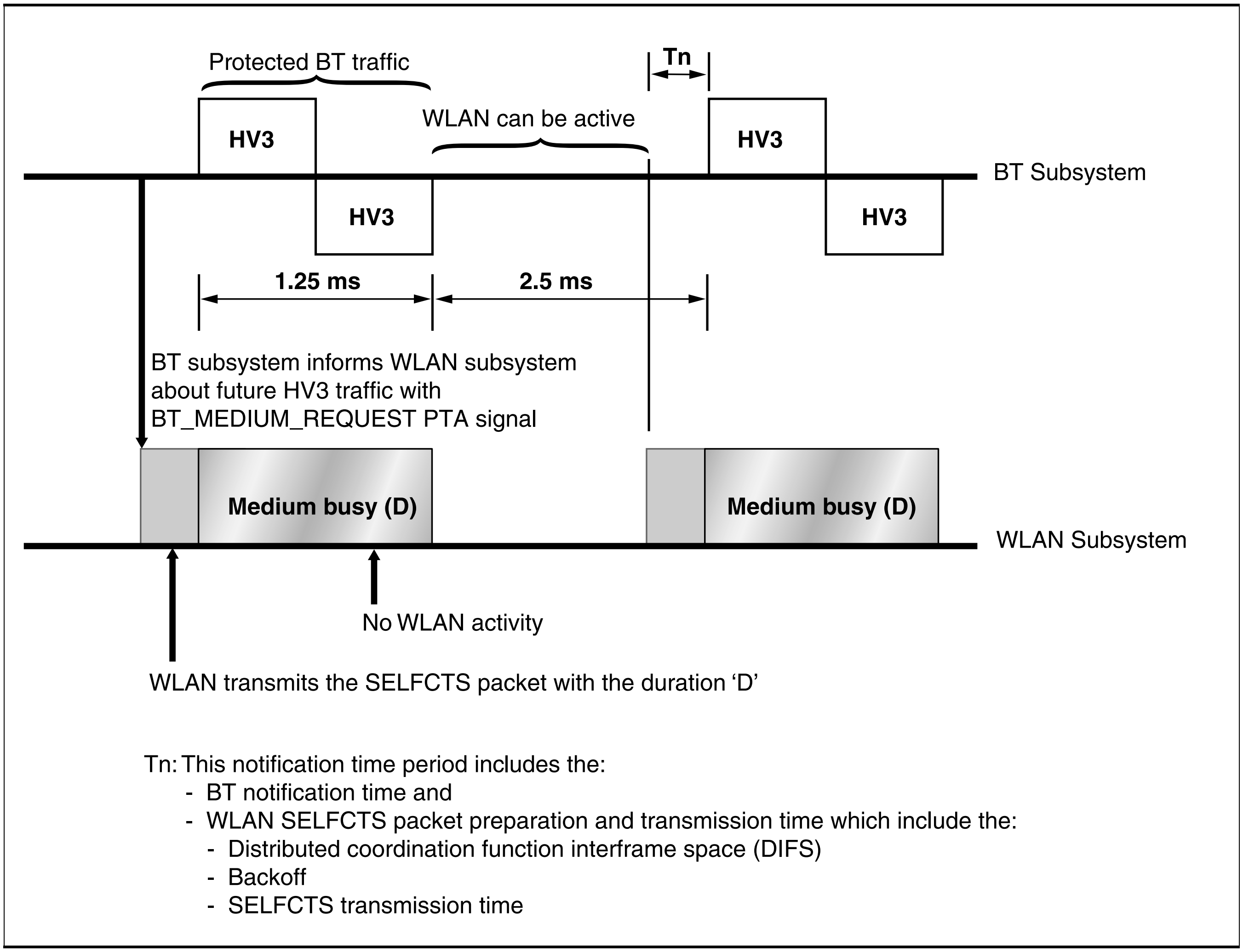


**Figure 3:** WLAN and BT Coordination Using CTS Shared Medium Reservation

Figure 3 shows how the WLAN CTS shared medium reservation method is used to protect a Bluetooth HV3 SCO link. Within a subject node that has colocated Bluetooth and WLAN subsystems, the Bluetooth subsystem informs the WLAN subsystem that there is an imminent HV3 data transfer by asserting the BT_MEDIUM_REQUEST PTA signal. The ECI provides the duration of the upcoming HV3 traffic, which in the example of Figure 3 is 1.25 ms. The WLAN subsystem responds by transmitting a CTS2SELF packet with the duration field set to 1.25 ms. Other WLAN nodes that receive the CTS2SELF packet will inhibit their transmissions for 1.25 ms, allowing enough time for the subject node's Bluetooth transaction to complete. The medium clears once the subject node's Bluetooth transaction completes, allowing WLAN nodes to once again use the medium for approximately 2.5 ms, after which the entire cycle repeats.

Since medium access is non-deterministic, the transmission of the CTS2SELF packet cannot be guaranteed. The protection given by the WLAN CTS shared medium reservation method will be statistical, as it depends upon the number of nearby WLAN devices.

### WLAN Power Save Mode Coordination with PTA

The IEEE 802.11 standard defines the following two WLAN station power states:

- Awake: The STA is fully powered.
- Doze: The STA is not able to transmit or receive.

In addition, it defines the following two power management modes:

- Active mode: The STA may receive packets at any time.
- Power Save mode (PS): The STA listens to selected beacons and polls the AP for buffered packets, if the most recently received beacon indicates that the AP has buffered traffic for it.

A WLAN STA informs APs of its power management mode changes by setting the Power Management bit in the Frame Control field of a given frame exchange.

APs will buffer packets intended for a STA in PS mode until the STA either switches to Active Mode or polls for the buffered packets.

The WLAN power management protocol can be used effectively to mitigate Bluetooth interference. The biggest advantage of this method is that it does not inhibit other WLAN nodes from communicating, and thus it works well even in congested WLAN networks. Its biggest drawback is that WLAN AP traffic buffering overhead causes WLAN throughput degradation.

There are three different WLAN power save methods that can be employed: power save on/off, legacy power save with poll, and wireless multimedia (WMM) power save.

#### Power Save On/Off

In this method, a STA having a WLAN subsystem that is colocated with a Bluetooth subsystem enters PS mode prior to a Bluetooth subsystem transaction and then enters Active mode after the Bluetooth transaction completes. To accomplish this behavior, the Bluetooth subsystem asserts the BT_MEDIUM_REQUEST PTA signal at the start of a transaction, and the WLAN subsystem reacts by transmitting its imminent transition to PS mode and then entering PS mode. At the end of a Bluetooth transaction, the Bluetooth subsystem deasserts the BT_MEDIUM_REQUEST PTA signal, the WLAN subsystem enters Active mode and then transmits a frame indicating its mode change. The advantages of this method are that the AP is inhibited from transmitting packets to the STA during Bluetooth transactions, and no STA polling is required to retrieve buffered AP data. The disadvantage is the bandwidth reduction incurred by power mode state transition packets, which get sent even when APs have no buffered packets for the STA.

#### Legacy Power Save

In this method, a STA having a WLAN subsystem that is colocated with a Bluetooth subsystem remains in PS mode indefinitely, and uses PS-POLL frames to poll an AP for buffered data. If the WLAN subsystem determines, using ECI data, that an AP will have time to respond before the next Bluetooth transaction begins, it will transmit a PS-POLL frame upon BT_MEDIUM_REQUEST signal deassertion. Since AP response times to PS-POLL packets are not deterministic, there is always a chance that polled WLAN packets will collide with the Bluetooth transaction. In addition, polling for every buffered packet will significantly reduce WLAN throughput. An advantage of this approach is that no WLAN packet needs to be sent in the short period of time preceding a Bluetooth transaction.

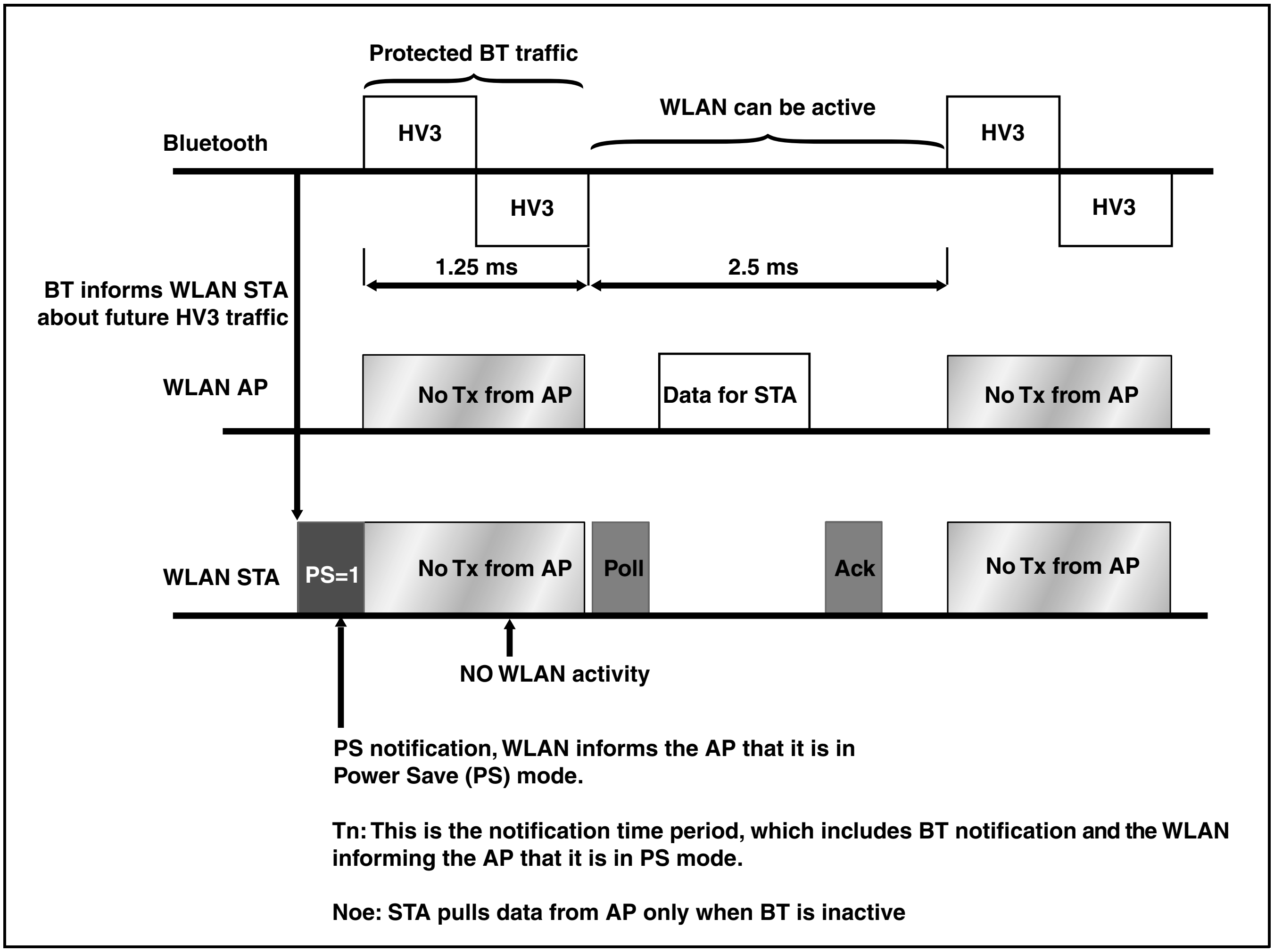


**Figure 4:** WLAN and BT Coordination Using Power Save Method

### *WMM Power Save*

The WMM Power Save method differs from the Legacy Power Save method in that it uses a trigger packet to poll for all AP buffered packets instead of using a PS-POLL for each buffered packet. This method is more efficient at medium utilization but has a higher risk that a set of AP-transmitted packets will collide with a Bluetooth transaction.

## Algorithms

Broadcom has developed algorithms that dynamically switch between the preemptive coexistence methods in order to exploit the advantages and minimize the disadvantages of each.

### Throughput Management

The WLAN CTS shared medium reservation method, also known as the CTS method, provides the best WLAN throughput but inhibits all WLAN traffic during Bluetooth transactions. To avoid inefficient use of WLAN bandwidth, the WLAN subsystem constantly monitors directed packet throughput. If the throughput falls below a threshold, the WLAN subsystem switches to Power Save protection mode. While in Power Save protection mode, the WLAN subsystem periodically switches to the CTS method to check if the volume of the directed traffic justifies using the CTS method.

For cases where both WLAN and Bluetooth traffic occupy close to 100% of the available medium bandwidth, which is the case for concurrent WLAN and Bluetooth ACL data connections, the respective bandwidth allocation is handled by multilevel priority being communicated from the Bluetooth subsystem to the WLAN subsystem over ECI. For a particular connection, both subsystems maintain data throughput targets as well as minimum acceptable throughput requirements. If the Bluetooth subsystem's throughput falls below its throughput target because the WLAN subsystem is not granting medium requests, the Bluetooth subsystem will gradually increases its multilevel priority for the upcoming transaction opportunity. This priority is compared with an equivalent WLAN multilevel priority to ensure fair bandwidth allocation between the two subsystems.

### Congestion Management

The Power Save protection method is Broadcom's default preemptive coexistence method. The CTS medium reservation method, if employed by several devices in the same network, can severely limit network bandwidth. To avoid this situation, the WLAN subsystem monitors CTS-induced medium reservations. The WLAN subsystem will inhibit its own CTS reservations if it determines that other devices are already using too much bandwidth from their own CTS reservations. To prevent a single device from monopolizing the medium, each WLAN device switches back to the Power Save method after using CTS medium reservations for a period of time. The WLAN subsystem uses a congestion-sensing algorithm with random backoff, which is not to be confused with carrier sense, to determine when it can once again attempt a CTS medium reservation.

CTS medium reservations are only used to protect short-duration Bluetooth traffic. Page and inquiry scans are always protected using the Power Save method.

### WLAN Beacons and Multicast Packets

When a WLAN STA is in Power Save mode, it is still expected to receive DTIM beacons and subsequent multicast traffic. If the WLAN subsystem is using the Power Save preemptive coexistence method, it will switch to the CTS method around DTIM beacon time. In a congested network with multiple devices that have colocated WLAN and Bluetooth subsystems, not all devices will have the opportunity to access the medium to send a CTS2SELF packet. If a WLAN subsystem is unable to send a CTS2SELF packet to protect a Bluetooth transaction around a DTIM beacon interval, it must deny medium access to the Bluetooth subsystem to prevent loosing the beacon.

## Limitations

There are two cases where WLAN and Bluetooth coexistence cannot be achieved without the help of a network-wide solution.

### *Coexistence with Bluetooth SCO HV1 Traffic*

Some older Bluetooth headset models use SCO HV1 packets. Since these packets only carry 10 data bytes, every Bluetooth slot is used to support 64-Kbps symmetric voice traffic. This leaves no bandwidth available for WLAN communication, so the WLAN connection will terminate when SCO HV1 packets are used.

### *Low Data Rate WLAN Coexistence with Bluetooth SCO Traffic*

When a WLAN link can only be supported using a low data rate, coexistence with Bluetooth SCO traffic becomes a challenge. For example, if HV3 SCO packets are used by the Bluetooth subsystem, the maximum WLAN subsystem transaction time must be less than 2.5 ms to avoid Bluetooth packet loss. Devices with colocated WLAN and Bluetooth subsystems have no control of transmitted WLAN AP packet sizes, and in the case of WLAN network traffic, the maximum packet size is likely to be used. This makes WLAN communication at data rates below 9 Mbps impossible without loosing Bluetooth packets and adversely affecting voice signal quality. The VoWLAN traffic uses much smaller data packets and is not affected as much. However, communicating at 1Mbps concurrently with a Bluetooth HV3 SCO connection is challenging even for VoWLAN traffic.

## Conclusion

This paper presented novel methods employed by Broadcom to improve WLAN and Bluetooth coexistence. These methods offer significant advantages over the traditional coexistence schemes recommended by IEEE 802.15.2, and they address the strict requirements of modern mobile devices while providing simultaneous use of WLAN and Bluetooth technologies integrated on the same silicon die.

# Acronyms and Abbreviations

| Item | Definition | Item | Definition |
|---|---|---|---|
| A2DP | Advanced Audio Distribution Profile | ISM | Industrial, Scientific and Medical |
| AP | Access Point | LNA | Low Noise Amplifier |
| ACK | Acknowledgement | MAC | Medium Access Control |
| ACL | Asynchronous Connectionless | NAV | Network Allocation Vector |
| AM | Active Mode | PA | Power Amplifier |
| AWMA | Alternating Wireless Medium Access | PCF | Point Coordination Function |
| AFH | Adaptive Frequency Hopping | PER | Packet Error Rate |
| BT | Bluetooth | PHY | Physical layer |
| BPF | Band Pass Filter | PTA | Packet Transmit Arbitration |
| BSS | Basic Service Set | PS | Power Save |
| CRC | Cyclic Redundancy Check | RSSI | Received Signal Strength Indicator |
| CS | Carrier Sense | RTS | Request To Send |
| CSMA/CA | Carrier Sense Multiple Access with Collision Avoidance | RX | Receive |
| CTS | Clear To Send | SCO | Synchronous Connection Oriented |
| DCF | Distributed Coordination Function | STA | Station |
| DTIM | Delivery Traffic Indication Map | SIFS | Short Inter Frame Space |
| ECI | Enhanced Coexistence Interface | TDD | Time-Division Duplex |
| EDR | Extended Data Rate | TDMA | Time-Division Multiple Access |
| eSCO | Enhanced Synchronous Connection Oriented | TSSI | Transmit Signal Strength Indicator |
| FHSS | Frequency Hopping Spread Spectrum | TPC | Transmit Power Control |
| FTP | File Transfer Protocol | TX | Transmit |
| IBSS | Independent Basic Service Set | UMA | Unlicensed Mobile Access |
| IGMP | Internet Group Management Protocol | VoIP | Voice over IP |

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