Bluetooth LE/IEEE 802.15.4 Coexistence

nRF70 Series

Application Note

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Contents

Revision history

Date	Description
2023-06-08	Added Coexistence combinations on page 17
2023-03-02	Updated: • Kconfig usage • Coexistence APIs
2023-01-31	First release

1 Introduction

Devices operating in the 2.4 GHz frequency range can experience coexistence issues. There are several techniques to improve Wi-Fi® coexistence.

This application note describes a specialized coexistence mechanism designed for the Nordic nRF70 Series devices, giving recommendations to help harmonize spectrum use fairly between competing radio interfaces. Along with the detailed sample implementation at `<ncs-repo>/nrf/samples/wifi/sr_coex`, this document assists the writing of an application utilizing concurrent Wi-Fi and Bluetooth Low Energy/IEEE 802.15.4 operations.

2 Generic coexistence problems

The 2.4 GHz ISM (Industrial, Scientific, and Medical) band is a range of radio frequencies that are globally available for the use of unlicensed wireless devices. The 2.4 GHz band is popular for use in wireless technologies such as Wi-Fi, Bluetooth, and the IEEE 802.15.4 standard.

The concurrent and co-located operation of different 2.4 GHz radio standards cause mutual interference, degrading each other's performance. In addition, the 2.4 GHz band is susceptible to interference from other types of electronic equipment, such as microwave ovens, cordless phones, and certain types of medical equipment.

The interference between devices can cause disruptions to wireless communication and affect the reliability of Wi-Fi networks. To minimize interference, devices that use these technologies must be designed to share the available spectrum in a way that minimizes disruption.

3 IEEE recommendations for Wi-Fi coexistence

The IEEE 802.15.2 standard recommends *Packet Traffic Arbitration (PTA)*-based architecture for coexistence between Wi-Fi and Bluetooth technologies.

The IEEE standard recommends a centralized coexistence logic that accepts prioritized transmit and receive requests from Wi-Fi and Bluetooth devices. The logic then determines whose request is granted to ensure fair allocation amongst the two. The Nordic coexistence design follows this approach and is enhanced with proprietary algorithms and software that mitigate different coexistence scenarios.

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4 nRF70 Series PTA-based coexistence

The nRF70 Series devices offer highly configurable coexistence hardware to help mitigate interference between Wi-Fi and devices like Bluetooth LE, Thread®, and Zigbee®.

The coexistence hardware for the nRF70 Series has a *PTA* module connected to coexistence hardware logic functions that facilitate mitigating various interference scenarios through a highly programmable fabric. This enables flexible output signals supporting multiple interface configurations such as:

- 3-wire interface without multiplexed PRIORITY signal
- 3-wire interface with multiplexed PRIORITY signal
- 4-wire interface

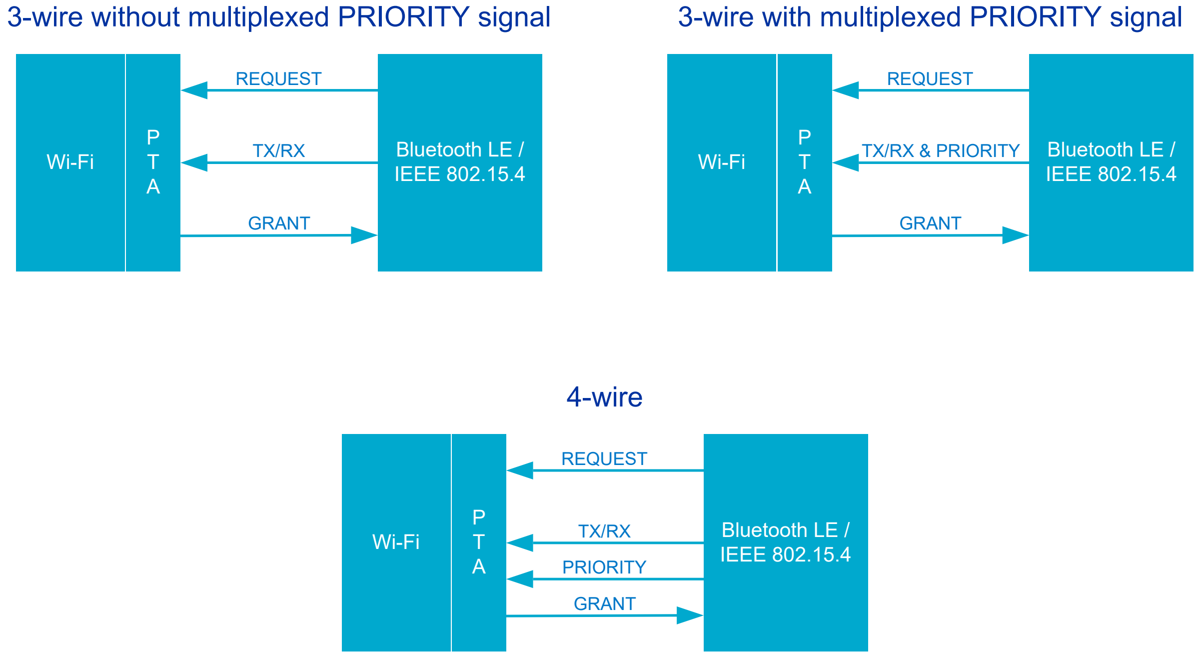

Figure 1: Interface configuration

The following are supported antenna configurations:

- Shared Antenna mode—The PTA makes priority decisions and controls the switch between Bluetooth LE/IEEE 802.15.4 and Wi-Fi. The PTA also grants TX/RX requests from the Bluetooth LE/IEEE 802.15.4 device. Only one interface, either Bluetooth LE/IEEE 802.15.4 or Wi-Fi, is connected to the antenna at any time.
- Separate Antenna mode—The PTA makes priority decisions, granting TX/RX requests from Bluetooth LE/IEEE 802.15.4. Each interface is permanently connected to its own antenna.

The following figure shows the architecture of the coexistence hardware with the details of the PTA control lines.

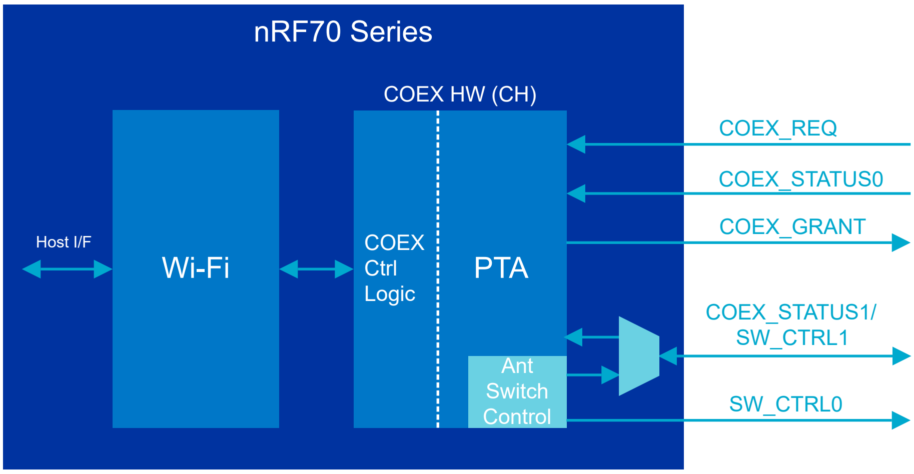

Figure 2: Coexistence hardware architecture

Signal name	I/O	Mandatory/ Optional	Bluetooth LE/IEEE 802.15.4 signal (3-wire/4-wire)	Description
COEX_REQ	Input	Mandatory for 3-wire and 4-wire	SR_REQUEST	Bluetooth LE/IEEE 802.15.4 device requesting a TX/RX transaction.
COEX_STATUS0	Input	Mandatory for 3-wire and 4-wire	SR_STATUS	Indicates if the Bluetooth LE/ IEEE 802.15.4 transaction is TX or RX. If the device supports a PRIORITY signal, it is multiplexed with TX/RX on this signal.
COEX_GRANT	Output	Mandatory for 3-wire and 4-wire	SR_GRANT	Indicates that the Bluetooth LE/IEEE 802.15.4 device is granted access for this transaction.
COEX_STATUS1/ SW_CTRL1	Input/ Output	Optional for 3-wire	SR_PTI/ RF_SW_CTRL1	In 4-wire mode, this carries the Bluetooth LE/IEEE 802.15.4 1-bit PRIORITY signal. In 3-wire Shared Antenna mode, this can be optionally used as a second antenna switch control signal.
SW_CTRL0	Output	Mandatory for 3-wire and 4-wire Shared Antenna mode. Optional otherwise.	RF_SW_CTRL0	Used for antenna switch control in Shared Antenna mode.

Table 1: Coexistence hardware signals

Note: The behavior of SW_CTRL0/1 is programmable and dependent on the configured coexistence mode and switch control interface.

4.1 nRF7002 DK antenna configuration

The nRF7002 *Development Kit (DK)* has two antenna switches: SW1 (*PTA* controlled) and SW2 (*General-Purpose Input/Output (GPIO)* controlled). These are specifically designed to facilitate test and development of both separate and shared antennas between Bluetooth LE/IEEE 802.15.4 and Wi-Fi radios.

Switch SW1 connects nRF7002 to antenna A1 and switch SW2 connects nRF5340 to antenna A2. Switch SW2 is configured based on the setting of `CONFIG_COEX_SEP_ANTENNAS`:

- Separate antennas—when `CONFIG_COEX_SEP_ANTENNAS=y`, nRF5340 is connected to A2.
- Shared antenna—when `CONFIG_COEX_SEP_ANTENNAS=n`, nRF5340 is connected to SW1 and A1 through SW2.

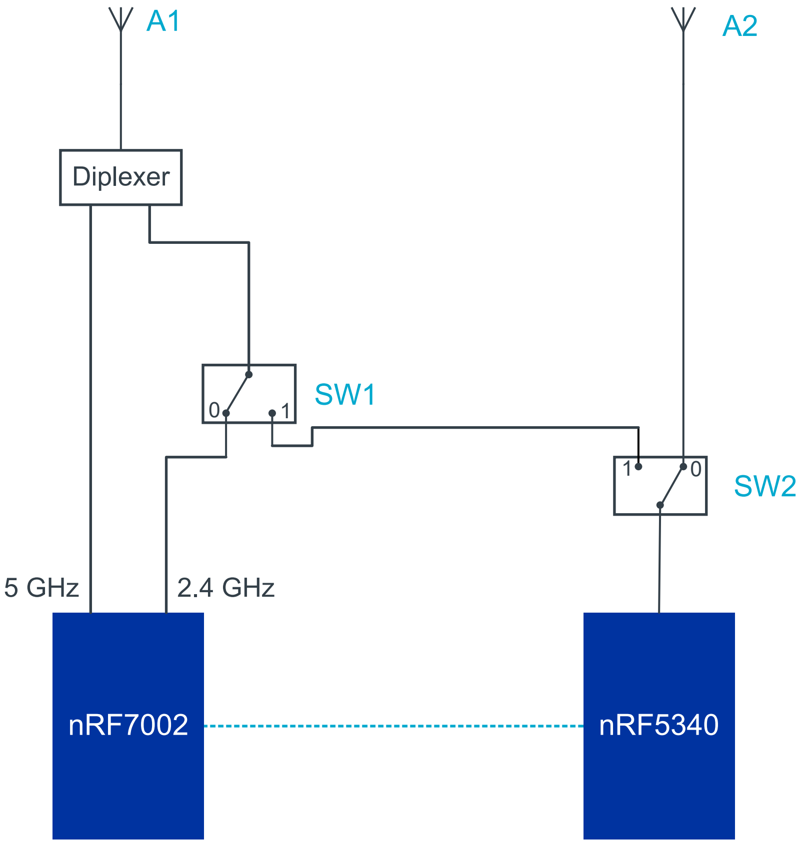

Figure 3: nRF7002 DK antenna configuration

4.2 Coexistence configuration

The following table shows the possible combination of *PTA* modes and antenna configurations, including configurations supported in the current NCS release.

PTA mode	Hardware support	Firmware support	Remarks
3-wire without multiplexed PRIORITY signal	Yes	Yes	Supported
3-wire with multiplexed PRIORITY signal	Yes	No	Firmware support will be added in future
4-wire	Yes	No	Firmware support will be added in future

Table 2: Combination of PTA modes and antenna configurations

Antenna configuration	Hardware support	Firmware support	Remarks
Separate antennas	Yes	Yes	As per nRF7002 *DK* hardware
Shared antenna	Yes	Yes	As per nRF7002 DK hardware

Table 3: Hardware and firmware support for antenna configurations

The following conditions are true in combination mode:

- In the Shared Antenna mode, the switch (SW1) is pointing to either Wi-Fi or Bluetooth LE/IEEE 802.15.4. There is no option to connect both radio interfaces to the antenna concurrently.
- When Wi-Fi is operating in the 5 GHz band, the PTA is not utilized and hence there is no attempt to restrict Wi-Fi or Bluetooth LE/IEEE 802.15.4 operation. This applies to both separate and shared antenna cases.
- IEEE 802.15.4 standard/Thread requires continuous RX and hence does not support Shared Antenna mode when Wi-Fi is operating in the 2.4 GHz band.

4.3 Kconfig usage

Use Kconfig to configure different coexistence options for Bluetooth LE/IEEE 802.15.4.

Kconfig symbol `CONFIG_COEX_SEP_ANTENNAS` is set to enable the use of the separate antenna configuration. If shared antenna configuration is required, set `CONFIG_COEX_SEP_ANTENNAS=n`.

To enable or disable coexistence in Bluetooth LE/IEEE 802.15.4, set Kconfig symbol `CONFIG_MPSL_CX` in configuration files `prj.conf` (application core) and `hci_rpmsg.conf` (network core) as follows:

- `CONFIG_MPSL_CX=y` to enable coexistence
- `CONFIG_MPSL_CX=n` to disable coexistence

4.4 Coexistence APIs

The APIs assume that the correct Kconfig symbols are setup as required for the application. Include files `zephyr_fmac_coex.h` and `mpsl_cx_nrf700x.h` to access these APIs.

Configure PTA table

```
int nrf_wifi_coex_config_pta(enum nrf_wifi_pta_wlan_op_band
wlan_band,bool antenna_mode)
```

This function initializes the PTA table in the coexistence hardware for either separate antennas or shared antenna as per the configuration. This function is to be called immediately after successful Wi-Fi connection or reconnection and returns 0 on success. The PTA table configurations are different when Wi-Fi is in the 2.4 GHz band or 5 GHz band, where `wlan_band` specifies which Wi-Fi band is present:

- NRF_WIFI_PTA_WLAN_OP_BAND_2_4_GHZ
- NRF_WIFI_PTA_WLAN_OP_BAND_5_GHZ

Set the input parameters:

- Separate antennas—`antenna_mode = 1`
- Shared antenna—`antenna_mode = 0`

Configure non-PTA registers

```
int nrf_wifi_coex_config_non_pta(bool antenna_mode)
```

This function is used to configure non-PTA registers of coexistence hardware to cater for either separate antennas or a shared antenna. This function is to be called during application initialization and returns 0 on success.

Set the input parameters:

- Separate antennas—`antenna_mode = 1`
- Shared antenna—`antenna_mode = 0`

Configure switch SW2

```
int nrf_wifi_config_sr_switch(bool antenna_mode)
```

This function configures SW2 to A2 for the case of separate antennas and to SW1 and A1 for a shared antenna. This function is to be called during application initialization and return 0 on success.

Set the input parameters:

- Separate antennas—`antenna_mode = 1`
- Shared antenna—`antenna_mode = 0`

This API is based on the nRF7002 *DK* where **P0.24** is connected to SW2. Verify that this configuration is correct on your board or make appropriate changes. This switch and the corresponding control are only for the purposes of supporting configurations of both shared and separate antennas on the DK as reference. Typically, a final product would support one or the other.

Reset coexistence hardware

```
int nrf_wifi_coex_hw_reset(void)
```

This function resets the coexistence hardware and returns 0 on success. Configuration APIs `nrf_wifi_coex_config_non_pta()` and `nrf_wifi_coex_config_pta()` must be called after this function to initialize coexistence in the required mode. This effectively disables coexistence module.

Enable or disable nRF70 Series Coexistence Interface

```
void mpsl_cx_nrf700x_set_enabled(bool enable)
```

This function enables or disables the nRF70 Series Coexistence Interface from the Bluetooth LE/IEEE 802.15.4 controller device. Clients of MPSL CX APIs are granted or denied access depending on the state of the nRF70 Series GRANT signal.

The Coexistence Interface is disabled by default. It can be enabled by calling this function with `enable=true` or disabled by calling `enable=false`.

4.5 Coexistence API example

The following example is for a typical application *Application Programming Interface (API)*.

```
If shared antenna use case, set CONFIG_COEX_SEP_ANTENNAS=n in the prj.conf file

Initialization -

 /* Reset the coexistence hardware */
      if(nrf_wifi_coex_hw_reset()){
          LOG_ERR("Error resetting coex hardware");
          return -1;
      }

 /* This enables the proper antenna configuration.
  * It can be called anytime independent of other coexistence APIs
  */
      if(nrf_wifi_config_sr_switch(antenna_mode)){
          LOG_ERR("Error switching antenna mode");
          return -1;
      }

 /* One time initialization of register in the coex control
       * logic around PTA
       */
      if(nrf_wifi_coex_config_non_pta(antenna_mode)){
          LOG_ERR("Error in non-pta coex config");
          return -1;
      }

 ....
 ....

 /* Connect Wi-Fi to an Access Point. Get wlan_band once connected */
 ...
 ...
In appropriate function/task of application code -

 /* Configure the PTA coexistence table based on whether Wi-Fi
       * is in 2.4GHz or 5GHz band
       */
      if(nrf_wifi_coex_config_pta(wlan_band, antenna_mode)){
          LOG_ERR("Error in pta coex config");
          return -1;
      }

During Wi-Fi shutdown mode -
      /* Put Wi-Fi in shutdown mode */
      ....
      ....
      /* Disable SR coex */
      mpsl_cx_nrf700x_set_enabled(false);
      ....
```

```
        /* continue with Bluetooth LE/IEEE 802.15.4 operation */
        ....
        /* Power up Wi-Fi */
        ....
        /* Enable SR coex */
        mpsl_cx_nrf700x_set_enabled(true);
        /* Normal concurrent Wi-Fi, Bluetooth LE/IEEE 802.15.4 operation with coex enabled */
        ....
        ....
```

5 Use case and characterization

A detailed sample, `<ncs-repo>/nrf/samples/wifi/sr_coex`, using coexistence *API*s for an application requiring concurrent Bluetooth LE and Wi-Fi operations is available at nRF Connect SDK.

The sample documentation also details the application build, reference test setup used, and representative results for the given use case and test scenario.

6 Coexistence during Wi-Fi shutdown and Power Save mode

This section describes the behavior of the coexistence module when Wi-Fi is shutdown or in a Power Save mode.

- Wi-Fi is shutdown (BUCKEN is de-asserted)—The GRANT signal (input to the Bluetooth LE/IEEE 802.15.4 device) will be floating. The Bluetooth LE/IEEE 802.15.4 firmware must function in coexistence disabled mode by calling the `mpsl_cx_nrf700x_enabled(false)` function as described in Kconfig usage on page 10
- Wi-Fi in Power Save mode (relevant for Wi-Fi in any of the supported Power Save modes)—GRANT signal on the nRF7002 is asserted to ensure Bluetooth LE/IEEE 802.15.4 operation is not inhibited, which means that Bluetooth LE/IEEE 802.15.4 always gets access.

7 Coexistence combinations

This section describes the concurrent or mutually exclusive operations of Wi-Fi and Bluetooth LE/IEEE 802.15.4 in the 2.4 GHz and 5 GHz RF bands with single and dual antenna configurations.

The behavior is differentiated based on the following Wi-Fi states:

- Connected state
- Scan state

7.1 Connected state

When Wi-Fi is in the connected state, coexistence is managed on a packet basis which is determined by the coexistence logic.

7.1.1 Wi-Fi in the 2.4 GHz band

The combinations and expected behavior when Wi-Fi is operating in the 2.4 GHz band in the connected state depend on the transmit (TX) and receive (RX) status of the Wi-Fi and Bluetooth LE/IEEE 802.15.4 devices.

Depending on the antenna configuration, the Wi-Fi and Bluetooth LE/IEEE 802.15.4 devices can have the following operations:

- Concurrent operation
- Single or concurrent operation – determined by coexistence logic, based on TX/RX and priority
- Single operation – determined by coexistence logic, based on TX/RX and priority

The following table describes the coexistence behavior for the different RX/TX combinations when Wi-Fi is operated in the 2.4 GHz band in the connected state.

Wi-Fi (2.4 GHz)	**Bluetooth LE/IEEE 802.15.4 (2.4 GHz)**	**Coexistence behavior**	
		Shared antenna	**Separate antennas**
RX	RX	Single	Concurrent
TX	RX	Single	Single or concurrent[1]
RX	TX	Single	Single or concurrent[1]
TX	TX	Single	Single[2]

Table 4: Coexistence with Wi-Fi operating in the 2.4 GHz band in connected state

[1]Depending on signal strength some TX/RX related performance effects can occur.

[2]Concurrent TX/TX is currently not supported.

When both interfaces are operating concurrently (TX/RX or RX/TX), depending on relative signal strengths, there can be some TX/RX related performance effects. For example, receiving short range signals close to the sensitivity limit while Wi-Fi is transmitting results in the 2.4 GHz noise floor being elevated and hence short-range demodulation being degraded.

Concurrent TX/TX is not supported for separate antennas because the coexistence logic assumes that both Bluetooth LE/IEEE 802.15.4 and Wi-Fi signals are overlapping in frequency. This is a worst case scenario as the channel information is not currently shared from the Bluetooth LE/IEEE 802.15.4 interface to the coexistence logic.

7.1.2 Wi-Fi in the 5 GHz band

When Wi-Fi is operating in the 5 GHz band, both the shared and separate antenna configuration support concurrent operation with Bluetooth LE/IEEE 802.15.4 for all RX/TX modes in the connected state.

Wi-Fi (5 GHz)	Bluetooth LE/IEEE 802.15.4 (2.4 GHz)	Coexistence behavior	
		Shared antenna	Separate antennas
RX	RX	Concurrent	Concurrent
TX	RX	Concurrent	Concurrent
RX	TX	Concurrent	Concurrent
TX	TX	Concurrent	Concurrent

Table 5: Coexistence with Wi-Fi operating in the 5 GHz band in connected state

Note: For concurrent operation with a shared antenna, use a diplexer instead of a switch.

7.2 Scan state

When Wi-Fi is in the scan state, coexistence is managed at a session level.

During a 2.4 GHz Wi-Fi scan operation, which in the worst case takes about 750 milliseconds, Bluetooth LE/IEEE 802.15.4 is denied access. There are no restrictions during a 5 GHz Wi-Fi scan.

8 Comparison of shared and separate antennas

Various factors influence the selection of shared antenna versus separate antennas for Wi-Fi and Bluetooth LE/IEEE 802.15.4 devices in a product.

Criteria	Shared antenna	Separate antennas	Remarks
Printed Circuit Board (PCB) area	Lower	Higher	Shared antenna products need smaller PCB area.
Aggregate throughput	Lower	Higher	Additional opportunities exist for concurrent 2.4 GHz Wi-Fi and Bluetooth LE/IEEE 802.15.4 operation with separate antennas.
RF performance	Degraded	Not degraded	Insertion loss due to switch can result in marginal performance loss in Shared Antenna mode.
Support for IEEE 802.15.4 standard (Thread/Zigbee)	Not supported	Supported	IEEE 802.15.4 standard devices need their RX to be ON all the time. Need to use solution for separate antennas.

Table 6: Comparison of shared and separate antennas

9 Optimize coexistence performance

This section describes additional factors that enhance combined Wi-Fi and Bluetooth LE/IEEE 802.15.4 performance.

- Maximize channel frequency separation between Wi-Fi and Bluetooth LE/IEEE 802.15.4 devices to minimize mutual interference. Use 5G Hz band for Wi-Fi wherever possible.
- For Bluetooth LE, implement adaptive frequency hopping. Mark Wi-Fi overlapping channels as bad channels in the channel map so that Bluetooth LE does not use these in its hop pattern, minimizing mutual interference.
- Maximize antenna isolation between Wi-Fi and Bluetooth LE/IEEE 802.15.4 devices (relevant for separate antennas case).

Glossary

Application Programming Interface (API)

A language and message format used by an application program to communicate with an operating system, application, or other service.

Development Kit (DK)

A hardware development platform used for application development.

General-Purpose Input/Output (GPIO)

A digital signal pin that can be used as input, output, or both. It is uncommitted and can be controlled by the user at runtime.

Packet Traffic Arbitration (PTA)

A collaborative coexistence mechanism for collocated wireless protocols.

Printed Circuit Board (PCB)

A board that connects electronic components.

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